XMM-Newton's operational challenge of changing the attitude control to 4 active reaction wheels, after 12 years of routine operations

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The AOCS of XMM-Newton was designed to use three reaction wheels (RW) with a fourth wheel in cold redundancy. The three wheels configuration has been used for more than 12 years for the momentum management, to re-orientate the S/C with slews in order to achieve the required science pointing. With 3 wheels, frequent reaction wheel unloading is used both to compensate the external torque and to re-orientate the angular momentum to allow the slew execution, which results in fuel consumption of around 6 Kg per year. A fourth wheel in control gives the advantage of a higher momentum envelope and introduces the null space in the wheels matrix, allowing a wheel speed variation without changing the total angular momentum. With four wheels the reaction wheel bias will compensate only for the accumulation of angular momentum due to the external torque, resulting in saving a significant amount of fuel and extending the mission lifetime. The use of all four RW implies the development of new attitude control algorithms and a software change on board which needs to be made in parallel to execution of the science mission. A design phase of this change has already started, and an initial test to check the functionality of the redundant wheel has already been successfully completed. A review of the safety failure detection criteria and thresholds will be needed. From operations point of view this is a major change, since the review of the nominal and contingency procedure will be needed, together with mission control system (MCS) changes. The Flight Dynamics System (FDS) as well needs to be adapted to the new four-wheel drive concept, with the new algorithm reflected in its system. At the end of the development of the algorithm and of the software patch, after the necessary changes on the MCS and on the FDS side, an end-to-end test campaign needs to be implemented. This paper describes the process and the challenge to implement and validate such a change.

I. Introduction

XMM-Newton is a cornerstone ESA mission, and the most powerful X-ray space observatory currently operated. The design of the Spacecraft has been defined in the late 90's when the standard practice for the design of the AOCS subsystem was to use three active wheels for momentum exchange management and a fourth one inactive as cold redundancy. The main reason of this choice is to simplify the design, as long as it meets the required performance specification. This concept has been changed later on, in the more modern missions, where the nominal configuration of the AOCS usually has four active wheels, to achieve higher performances, and in case of failure of a reaction wheel, the AOCS is reconfigured in a degraded configuration with three wheels and reduced performance.

A. Spacecraft status

XMM-Newton, after more then 12 years of operations, has still 65 Kg of fuel left in the tanks (data of April 2012), even if the original designed lifetime was 10.25 years. This abundance of fuel is due to the fact that the fuel budget was fixed while the launcher and the final operational orbit were not yet decided. The amount of fuel had to envelope the worst-case launcher and orbit scenario: some launchers would have put the spacecraft in a low transfer orbit with low perigee, requiring a high amount of fuel for perigee raising to achieve the final orbit. Eventually the launcher chosen was Ariane 5, which managed to bring the spacecraft in an optimal transfer orbit, such that the amount of fuel used to achieve the target orbit was less than originally expected.

The spacecraft is in good shape, since all the redundancies are still available. Only some degradation on two reaction wheels has been noticed, which is the well-known problem of bearing cage instability [(1)]. To cure this problem a re-lubrication of the wheel's ball bearings will be performed in summer 2012. The recommendation from industry regarding the prevention of the bearing cage instability is to run the wheels at lower speed, as far as possible. The option of running three wheels at low speed has some drawbacks: a significant reduction of the angular momentum available, and therefore setting some constraints for the achievement of the science pointing, and the need of many more wheel unloading which would translate in a much higher fuel consumption.

B. The 4WD project to extend the XMM-Newton's lifetime

In term of science return, XMM-Newton has very high requests from the X-ray science community, with an over-subscription factor of 6.7 times the actual available observing time. Responding to this high interest, we analysed some ways to extend the lifetime of the mission, trying to save fuel in nominal operations. Some analyses were performed by the Flight Dynamics team and it turned out that the best approach to save fuel is to use the whole set of reaction wheels as active wheels. This would allow having a wider momentum envelope, which would reduce the number of wheel unloading needed. Flight Dynamics performed some simulations that showed how the mission could save 50% of the fuel with this new strategy and potentially extending its lifetime from the current 2020 limit up to 2026. That is how the "four wheel drive" project started.

The degradation of RW1 and RW2 due to the bearing cage instability was spotted some times during the feasibility study of the 4WD project. It turned out that using four wheels for active control would allow running the wheels at a lower speed, which reduces the risk of bearing cage instability. This gives an additional justification to develop the 4WD, not only with the aim to extend the spacecraft lifetime but to improve the safety, reducing the impact of unit degradation.

II. Current design of XMM-Newton's AOCS

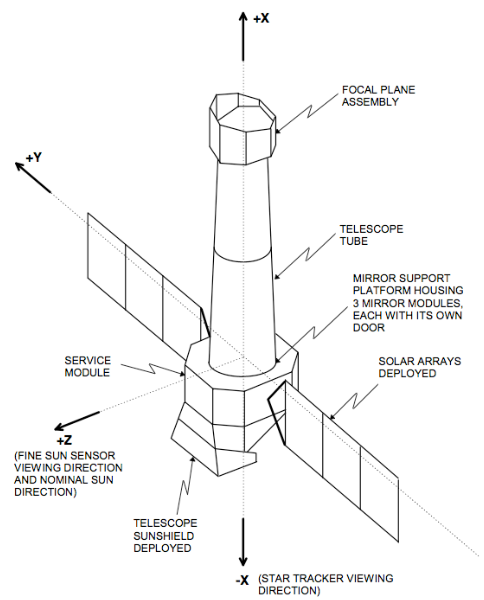

Figure 1. XMM-Newton's spacecraft axes and configuration.

C. General description of XMM-Newton's AOCS

The Attitude and Orbit Control System (AOCS) provides 3-axis stabilisation during all modes. The AOCS architecture is formed around the Attitude Control Computer, running the software for mode control and the attitude and thrust control laws [(3)]. The AOCS uses the Star Tracker and Fine Sun Sensor to provide the absolute reference. The star tracker is a small telescope with 3 deg on Z and 4 deg on Y field of view and thermoelectrically 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. 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 is usually off and is used as cold redundancy unit.

During eclipses, the roll reference from the sun sensor is obviously not available, so it is replaced by rate information from a gyro. The star tracker continues to supply pitch and yaw reference. Whilst eclipses generally occur at low altitude where radiation levels are high, it is expected that without special measures, single event upsets may frequently disturb the star tracker output. Therefore the star tracker has memory error detection and correction and uses sophisticated software filters to avoid loss of its guide star. Also, the redundant computers have memory error detection and correction as a precaution against the radiation environment.

D. AOCS operative modes

The modes used in the nominal phase of the mission are the following:

Sun Sensor Acquisition (SSA) Mode: this mode can be entered from any other mode, including recovery from the emergency safe attitude mode. The sun pointed attitude is maintained from the processed outputs of the Fine Sun Sensor, sun angles α and β, for roll and pitch axes. Yaw rate is controlled from the processed output of the IMU. Yaw rate demand is nominally 0°/sec. Thrusters are used for actuation.

All three operational reaction wheels are spun up in this mode to speeds suitable for the next phase of the mission through the use of wheel momentum control loops.

Note that, when the wheel speeds are zero, the spacecraft may be "spun up" about the yaw axis to 0.5°/sec by updating the yaw rate demand to this value, by telecommand. This is to accommodate a period, sometime in the mission, of high solar activity when STR data cannot be used. Fine Sun Sensor sun angle data is processed by software in the ACC and used to drive roll and pitch control loops. IMU yaw channel data is processed by software in the ACC and the yaw control loop ensures that nominal yaw rates are below 60"/sec.

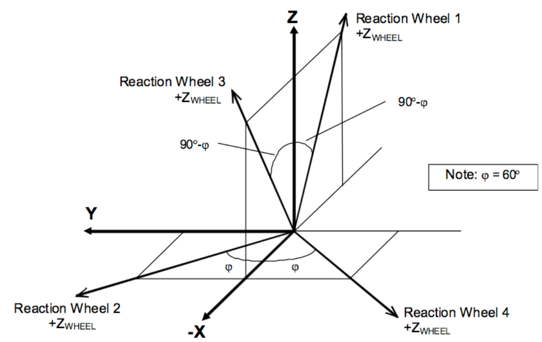

Figure 2. Reaction wheels spin axes orientation.

Star Tracker Acquisition Mode (STA) Mode: this mode establishes 3 axis spacecraft attitude control with the +Z axis nominally sun pointing. The mode uses the Fine Sun Sensor for control of the spacecraft sun pointing axis for roll and pitch attitude control. Yaw attitude control is initially performed using IMU data, and once the STR detects and tracks a star, the ACC software automatically changes the source of the yaw attitude data from the IMU to the STR. Reaction wheels are used for actuation during this mode, with wheel momentum control loops being used to drive the wheel speeds to their demanded values.

Inertial Pointing and Slew (IPS) Mode: this is the central AOCS mode and it maintains accurate star pointing and sun pointing (the Fine Pointing phase) and it provides the facility to slew the spacecraft to the attitude required for scientific observations, orbit maintenance manoeuvres and perigee passage (the Slew phase). In each case, reaction wheel actuation is used.

In the Fine Pointing phase, three axes attitude control is maintained through the use of FSS and STR processed outputs for inputs to the three control loops. When scientific observations are performed, a roll sun steering law is included to compensate for the roll motion of the sun. The fundamental requirement is that the control star does not leave the STR FoV (the STR is a non-autonomous type, from the 90's, without star pattern recognition).

In sunlight, inputs to the roll control loop will be derived from the FSS, whilst inputs to the pitch and yaw loops will normally be based on STR outputs. However, if the STR stops tracking its control star, then the pitch input will be derived from the FSS (instead of the STR) and the yaw controller will be driven by the IMU data.

During eclipses, inputs to the pitch and yaw loops continue to be derived from the STR. The input to the roll loop is obtained from the IMU. The eclipse period is defined using a timer in the ACC software and incorporates the penumbra regions as well as a small extra safety margin either side of the real eclipse.

The Slew phase is entered whenever the spacecraft is required to perform a slew. The software generates profiles of the required wheel momenta and the required, processed FSS outputs (α and β) consistent with the desired slew. The wheel momentum profiles are effectively feed-forward commands to the three wheel momentum control loops. The yaw error signal is set to zero. At the end of the slew, an automatic transition back to the Fine Pointing phase occurs. Note that the slew phase does not make use of IMU data.

Thruster Control Manoeuvre (TCM) Mode: the purposes of this mode are to impart linear momentum to the spacecraft if a delta-V manoeuvre is required to carrying out orbit phasing manoeuvres throughout the mission, and to control the spacecraft attitude during wheel momentum management operations. Sensor usage in this mode is the same as in IPS mode.

The ACC software includes a timeline, which is initiated on entry into TCM Mode. Initially, thrusters are used for attitude control, using normal on-modulation. Subsequently, the ACC software automatically switches control parameters and finally switches from thruster control to reaction wheel control. TCM mode may therefore be considered as comprising two sub-modes, one using thrusters for attitude control TCM(A) and one using reaction wheels TCM(B).

E. 3 wheels momentum management: current design

The wheel to spacecraft body transformation matrix is given by:

$$
\begin{pmatrix} h_x^{sc} \\ h_y^{sc} \\ h_z^{sc} \end{pmatrix} = \begin{bmatrix} \cos 60° & -\cos 60° & -\cos 60° & -\cos 60° \\ 0 & \sin 60° & 0 & -\sin 60° \\ \sin 60° & 0 & \sin 60° & 0 \end{bmatrix} \begin{pmatrix} h_{RW1}^{wheel} \\ h_{RW2}^{wheel} \\ h_{RW3}^{wheel} \\ h_{RW4}^{wheel} \end{pmatrix} \tag{1}
$$

Reaction wheel actuation is used for attitude control in STA, TCM (B) and IPS. Both TCM (B) and IPS have the capability of autonomous wheel momentum off-loading. Nominal wheel momentum off-loading is performed under ground control in the thruster mode.

Attitude control laws generate body axis angular momentum demands in spacecraft body frame. This is done by passing the roll, pitch and yaw error signals through a second order phase advance filter (for the roll axis this is in series with an elliptic filter). The roll, pitch and yaw error signals are also input to a parallel integrator. The outputs of these are summed and integrated to give the angular momentum demand.

Feed-forward momentum is added to the spacecraft angular momentum demand, which then is transformed into the 3 active reaction wheel axes. This is done with a straightforward matrix, from 3 dimensional spacecraft body frame to 3 dimensional reaction wheel frame. The transformation matrix, from the 3RW axis frame to the spacecraft body frame, is obtained from the matrix in Eq. (1), ignoring the column corresponding to the inactive wheel, resulting in a 3x3 matrix. The transformation from spacecraft body frame to 3RW axis frame is then easily obtained by the matrix inverse.

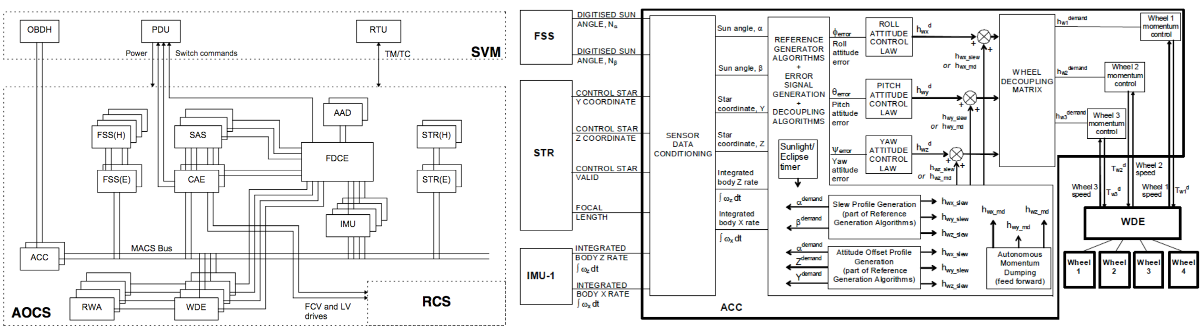

Figure 3. AOCS block diagram (left) and IPS mode logic (right).

In the on-board software the matrix A is used to transform from spacecraft frame to reaction wheel frame. This is a [4 x 3] matrix which has the row corresponding to the inactive wheel set to zero. There are 4 values of A and 4 values of B, according to the 4 possible wheel sets which are available using 3 active wheels. The wheel momentum control loops are used to drive the wheel speeds to their demanded values.

For the slew guidance profiles used in IPS, a feed-forward momentum is added to the system in spacecraft body frame before the transformation to the active 3RW. The slew guidance profile feed-forward angular momentum in spacecraft body frame is illustrated in Figure 3 (right block diagram) where it is output from the 'Slew Profile Generation' block.

As part of the reference generation algorithm the measured angular momentum of the 4 wheels needs to be transformed to spacecraft frame. This is done using the [3x4] B matrix: $\underline{h}^{sc} = B\underline{h}^{wheel}$. The values of the B matrix are depending on which wheels are active.

The wheel momentum unloading can be carried out either via ground control or autonomously on board. The autonomous wheel momentum "dumping" (AMD), takes place while the AOCS is in IPS or TCM(B) (wheel based control) mode, using momentum feed-forward and thruster firing. The feed-forward is added to the system in spacecraft body frame, before the transformation to the active 3RW axes. The AMD feed forward angular momentum is in spacecraft body frame as illustrated in Figure 3 (right block diagram), where it is output from the 'Autonomous Momentum dumping (feed forward)' block and then added to the control loop momentum demand.

III. 4 wheel drive new algorithm

The structure of the preliminary 4WD design is shown in Figure 4 [(4)]. Using 4 active RW provides an extra degree of freedom. Unlike using 3 active RW, there is no longer a unique mapping between spacecraft body frame and the 4RW axes frame. A control method can therefore use the extra degree of freedom (DOF) to optimize quantities in 4RW frame given a desired torque or momentum vector in spacecraft body frame.

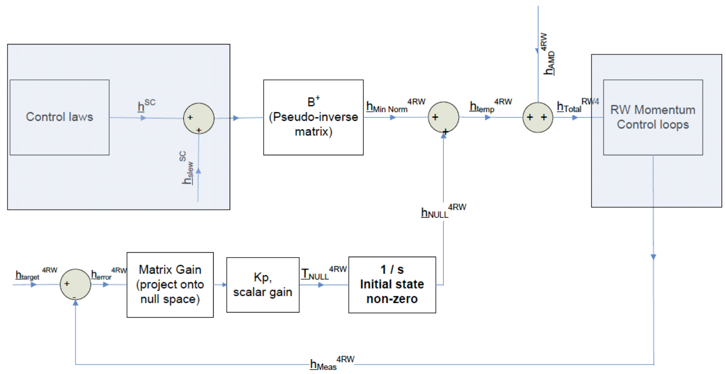

Figure 4. Control Block Diagram of the 4WD design.

This way the torque and angular momentum can be optimized separately. The obvious solution is to use the extra DOF to:

1. Minimize the wheel torque (whilst imparting the spacecraft axis torque needed for control).
2. Control the wheel angular momentum towards a desired or target momentum value. The separation between the wheel actual 4-momentum and a target 4-momentum vector is minimised. This is done by moving in 4-dimensional space along the line parallel with the vector belonging to the null space of B, since this keeps the angular momentum in spacecraft body frame unchanged.

The equation describing the angular momentum transformation and null vector control is:

$$\underline{h}^{4RW} = B^{+} \cdot \underline{h}^{sc} + \underline{h}_{null}^{4RW} \qquad (2)$$

where

1. $B^{+} \cdot \underline{h}^{sc}$ is the Moore-Penrose pseudo-inverse transformation: frame transformation from spacecraft body frame to 4RW frame using B^{+} = the pseudo-inverse of B. This term gives the minimal norm solution for the wheel torque.
2. $\underline{h}_{null}^{4RW}$ is the null vector control: to control the angular momentum in 4RW frame to a desirable target, a correction $\underline{h}_{null}^{4RW}$, along the line parallel to null vector is added to the angular momentum in 4RW frame.

The equation describing the angular momentum feed-forward for AMD is:

$$\underline{h}_{total}^{4RW} = \underline{h}^{4RW} + \underline{h}_{AMD}^{4RW} \qquad (3)$$

3. $\underline{h}_{AMD}^{4RW}$ is the Autonomous Momentum Dumping feed-forward: the autonomous momentum dumping, $\underline{h}_{AMD}^{4RW}$, needs to be added to the system in 4RW frame, since information would be lost if this is done purely in spacecraft body frame (i.e. prior to the pseudo-inverse transform).

F. Null vector control

A transformation from spacecraft body frame (3 dimensional space) to 4RW frame (4 dimensional space) has an infinite number of solutions since the system is underdetermined (4 unknown and 3 equations). All solutions will lie on a line parallel to the vector belonging to the null space of B (where B is the transformation matrix between 4RW frame and spacecraft body frame). Hence adding a correction, $\underline{h}_{null}^{4RW}$, along the direction of the null vector in 4RW frame does not change the outcome in spacecraft body frame.

The correction $\underline{h}_{null}^{4RW}$ will be calculated such that the distance between the current measured angular momentum $\underline{h}_{meas}^{4RW}$ and the target angular momentum $\underline{h}_{target}^{4RW}$ is minimized when the control reaches its steady state. This means that the measured angular momentum, $\underline{h}_{meas}^{4RW}$, is driven to the achievable target solution. The achievable target is the point, within the solution space, with the shortest distance to the target angular momentum.

Changing the wheel momentum by moving parallel to the null space direction changes the wheel momentum without changing the spacecraft axes momentum.

The correction $\underline{h}_{null}^{4RW}$ is obtained by first calculating the torque correction, $\underline{T}_{null}^{4RW}$, in the null space direction.

The torque correction is then integrated to get the angular momentum correction. The integration introduces a memory to the system, which enables the angular momentum vector to be initialized to a non-zero value.

The torque correction, $\underline{T}_{null}^{4RW}$, is obtained by :

1 - Calculate the error vector between the current measured angular momentum $\underline{h}_{meas}^{4RW}$ and the target angular momentum $\underline{h}_{target}^{4RW}$, i.e. $\underline{h}_{error}^{4RW} = \underline{h}_{target}^{4RW} - \underline{h}_{meas}^{4RW}$

2 - Project this error vector onto the null space

3 - Scale the error vector by the proportional gain k_p (with the unit [s^{-1}]), to give a torque vector (which lies parallel to the null vector).

G. Feed-forward modifications

To enable the 4WD design changes to the onboard software need to be implemented for both the slew feed-forward generation and the AMD.

1. Slew

The slew feed-forward shall, just like in the 3RW design, be added to the control-loop in spacecraft body frame.

The guidance reference generation needs to be updated to enable the use of four active reaction wheels. As part of both these guidance laws angular momentum is transformed into spacecraft body frame $\underline{h}^{sc} = B\underline{h}^{wheel}$. The current onboard software for the 3WD design has a set of 4 different B matrices available depending on which 3 wheels are active. For the 4WD design a new B matrix needs to be available in the on-board software to perform the transformation from 4 active wheels to spacecraft frame.

2. AMD

The demanded AMD is directed to a (or several) specific reaction wheels. In the 3WD design the mapping between spacecraft body frame and 3RW frame is unique hence the AMD can be added to the system in spacecraft body frame and result in the desired AMD in 3RW frame.

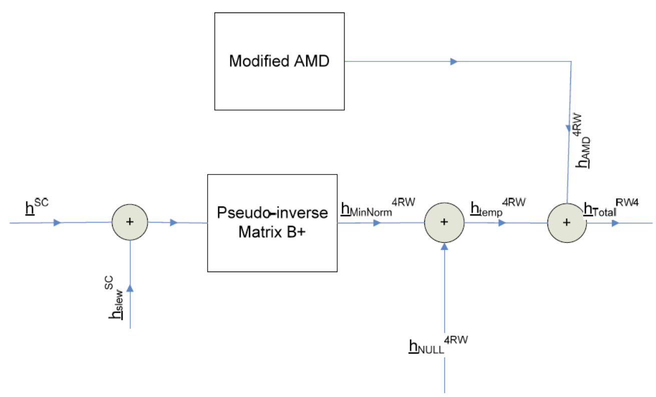

Figure 5. Schematic over 4WD design of AMD

The same approach is not suitable for 4WD design, since there is no longer a unique mapping between spacecraft frame and 4RW frame. Performing the transformation with the Moore–Penrose pseudo-inverse would result in the minimal norm solution, which does not give the desired AMD in 4RW frame.

The chosen solution for the AMD with 4RW is to add the total AMD after the transformation to 4RW frame. The total AMD is obtained from scaling the already existing SW parameter H_AMD, which is the delta angular momentum in body axis for each wheel. This implementation avoids making changes to the existing quite complex AMD function.

H. Architectural 4WD design

In term of architecture change, the preference is to make the 4WD changes in such a way that if there is ever a reason to return to 3WD, it can be done using mode transitions from a 4WD mode to a current mode, without requiring un-patching of the software changes for 4WD. Thus is preferable to preserve the existing TCM and IPS modes, and effectively add new 4WD modes, namely TCM4W and IPS4W, shown in Figure 6.

3. Transition path for 3WD to 4WD

The software is patched for all updates in IPS (3WD). After the patch the AOCS is commanded from IPS to TCM4W. RW4 is spun-up in TCM4W. After spin-up, with all 4 RW spinning, the sub-mode transition from TCM4W(A) to TCM4W(B) occurs. This is where the transition from thruster control to 4WD wheel control occurs. 4WD is first initialised at the start of TCM4W(B). After settling in TCM4W(B), IPS4W is commanded, and used for IPS operations using 4WD. TCM4W is used for periodic momentum dumping.

The transition from 3WD to 4WD would be:

IPS => TCM4W => IPS4W => TCM4W (when wheel unloading are necessary) => IPS4W

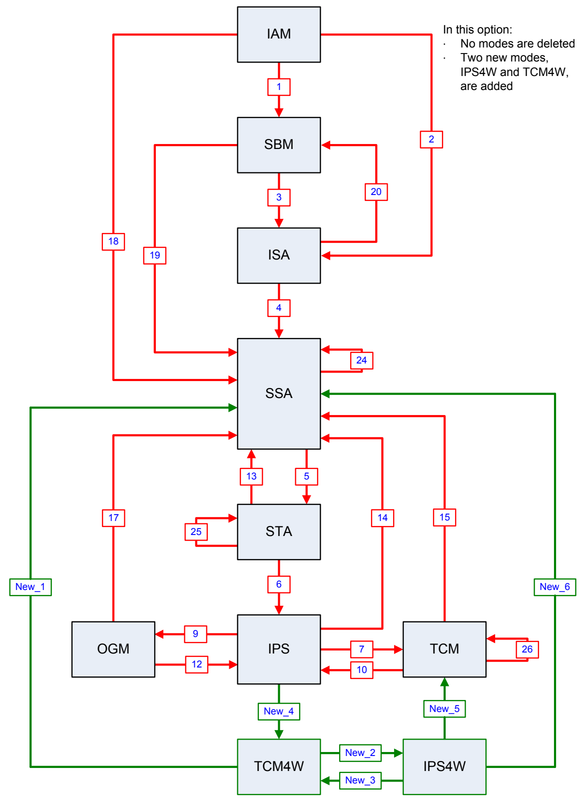

Figure 6. Architecture of the AOCS modes with the new TCM4W and IPS4W for 4WD.

I. Location of the patch

The 4WD on board software change is localised in the ACC, which is the core of the AOCS. Since the original version of the software is burned in a hard-coded PROM (not a more flexible EEPROM), every modification needs to run in RAM, and updated with a dedicated software patch. This is the only way to implement such a change on-board, even if it has some disadvantages: at every ACC restart the baseline software in PROM is reloaded and the patch needs to be uploaded again. The 4WD patch will include modification to the following objects:

- CLAWS function, which executes the control laws and the sub-mode logic
- WDE function, which provides interface to the wheels
- TCASW function, which controls the execution of the telecommands
- TMASW function, which gathers the software telemetry data
- MODE function, which defines modes and control mode transition

IV. Fuel saving with 4 wheel drive

With 3 wheels, frequent reaction wheel unloading is used both to compensate the external torque and to re-orientate the angular momentum to allow the slew execution, which results in fuel consumption of around 6 Kg per year.

Using a momentum management concept based on 4 active wheels can reduce the fuel consumption due to the fact that the wheel unloading would eventually compensate only for external torques since the wider angular momentum availability would allow the slew execution to change the scientific pointing, with less frequent wheel momentum biases. This can be achieved when the redundant reaction wheel is permanently activated in the spacecraft control. The fuel saving potential in this configuration has been analysed, with a simplified simulation: the attitude sequence of a significant number of revolutions was analysed and the angular momentum that was accumulated due to the influence of external torques was recalculated. The fuel consumption of the hypothetical bias used to compensate for that amount was then estimated by comparing the change in angular momentum to bias history data of the real spacecraft and the associated measured fuel consumption. This analysis showed that limiting the change in angular momentum only to compensate the external torques can reduce the average fuel consumption per revolution from the current 0.023 kg to 0.012 kg, which is a saving of almost 50% of fuel consumption.

In Figure 7 the result of the simulation is shown, where the fuel consumption in Kg is plotted against the requested change in angular momentum. The blue dots are the measured fuel consumption per revolution – therefore AOCS based on 3 wheel drive – from rev. 400 (13 February 2002) to rev. 1990 (20 October 2010), which average is 0.023 kg, represented by the blue dashed line. To simulate the behaviour with 4 wheel drive, the fuel consumption to compensate only for the external torques has been estimated, based on data from rev. 1000 (25 May 2005) to rev. 1982 (4 October 2010). Also in this case every dot represents average fuel consumption per revolution. The total average over the simulated period gives a fuel consumption of 0.012 kg, which is represented by the red dashed line. The difference in the time span for the two simulations was done for data retrieval convenience, but it does not affect the generality of the result.

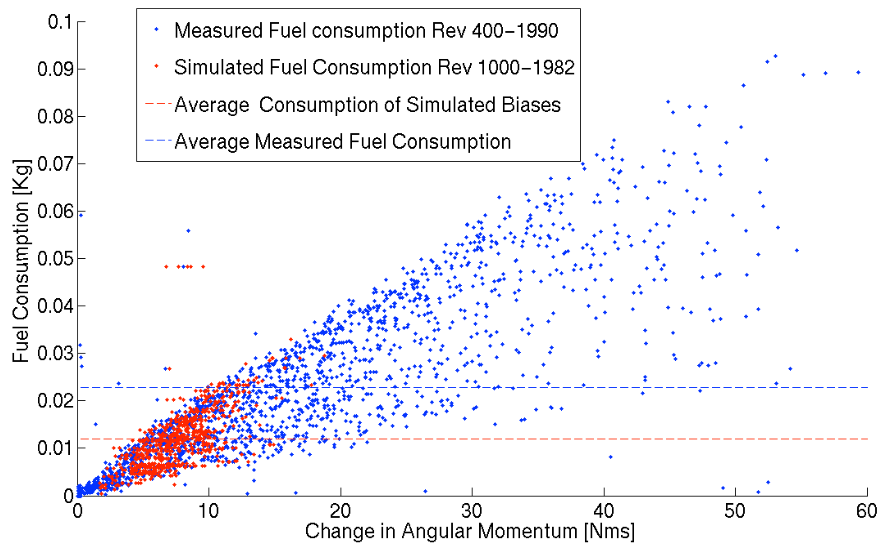

Figure 7. Comparison between the 3WD fuel consumption and simulated 4WD fuel consumption

J. 4 wheel drive and orbit maintenance

Currently the wheel unloading is also used for orbit control, by taking advantage of the delta-V generated while firing the thrusters and selecting a convenient position in the orbit to perform the wheel unloading. The orbit control consists essentially to maintain the size of the semimajor axis of the orbit such that the orbit period remains exactly two days. This strategy avoids to have dedicated Delta-v's for orbit control. A significant reduction of fuel spent on RWBs will reduce the size and the frequency of the manoeuvres and therefore reduce the control authority of the current orbit control concept, but it will still be sufficient for orbit control purposes assuming to select an optimised perigee passage attitude in term of orbit control. The transition to such an attitude in the planning sequence is foreseen before the introduction of the 4 wheel control. Independent of the wheel control strategy, special attitudes can be defined to increase orbit control authority, in case some orbit correction is needed.

V. Impact of the 4WD on operations

The operations of XMM-Newton after more than 12 year in orbit are pretty much consolidated. The concept of the operations has not changed during the years. The major changes in the operations of XMM-Newton, implemented so far were the following:

- delta-V manoeuvre to change the orbit, in early 2003 to improve the ground station coverage,
- upgrade of the mission control system to SCOS-2000 in 2005 (9),
- change of the antenna handover strategy, due to a problem in the antenna switch in 2008 (11),
- tank1 and tank4 temperature control taken over by ground after a problem on a low temperature protection of the tank heater circuit, occurred in July 2009 for tank1 and in Nov 2010 for tank4 (10).

Besides the above changes in the operations baseline, no other major modifications were done to the original mission concept. The 4WD will be the most important change since launch, with a significant improvement of the spacecraft performance.

In parallel with the on-board software algorithm and patch development, the ground segment needs to be prepared to be able to manage the new operations based on 4WD. Hereafter an overall assessment on every ground segment module is presented, to identify the areas affected by the 4WD. An implementation plan will be produced, with a test and validation phase, before the actual upload of the new software patch.

K. Procedures update for the 4WD

A set of new procedures for the 4WD change has to be implemented in the flight operations plan. New procedures are related to the patch upload activity and to the patch roll-back to the 3WD. We will write a system level procedure, describing the overall operation from the deviation from the 3WD timeline to the new 4WD routine operations, including the tests on the spacecraft which have to be done before declaring the 4WD modification operational on-board.

We will implement a contingency procedure in case something does not work as expected, in order to be able to abort the operation safely at any point and be able to roll-back to 3WD and resume nominal operations.

The existing procedures for the wheel management have to be updated as well, to reflect the new strategy, but the 3WD has to remain in the procedures structure as additional option, this time as a contingency situation, in case of failure of one reaction wheel. The contingency procedures for the wheel management have to be updated to reflect the new baseline of 4 active wheels (e.g. one RW out of four has always been considered off by default, which will not be applicable anymore with 4WD).

L. Database

The 4WD will have a impact in the Mission Control System database: new telecommands need to be coded to uplink to the spacecraft the following quantities:

- the desirable target vector $\underline{h}_{target}^{4RW}$ as input for the null space control, computed on-board,
- the proportional gain for the null vector control,
- the unity vector of the null space of B, the transformation matrix between the four wheel reference frame and the body frame,
- the components of the transformation matrix A between the body frame and four wheel reference frame (i.e. the pseudo inverse of B),
- the components of the transformation matrix B between the four wheel reference frame and the body frame.

There is also a number of new telemetry parameters related to the 4WD: the most important one is the $\underline{h}_{null}^{4RW}$, which is the output of the null vector control calculation. This new parameter can be added to existing packets: it could be included in the slowest XMM AOCS telemetry (e.g. within HK1 or HK2) with sampling period of 12 s. this additional telemetry affects the size of the existing packet, and the mission control system has to be able to decode it. A longer packet can be handled in several ways, for example with a new SCOS-2000 packet identifier (SPID) for the extended packet and a condition in the database (PIC table) selecting the correct packet identifier, depending on the length of the received packet [12].

Another useful quantity that shall be monitored is the null space torque correction $\underline{T}_{null}^{4RW}$, which quantity can be included as new telemetry parameter or derived on ground from the measured wheel speed and knowledge of the desired target $\underline{h}_{target}^{4RW}$.

New alphanumeric and graphical displays will be created to show the new quantities in telemetry. The existing displays will be revisited to be consistent with the 4WD.

M. Mission Control System

There is no modification foreseen to the mission control system due to the 4WD. In case the variable length packet cannot be handle with a modification in the database, some specific mission control system software change will be needed. A possible solution is to change the packetiser application to create a new packet containing the additional data. Another option is to extend the existing SPID to the new length while filling the packet with zeros in the archived data until the moment of 4WD change.

N. On Board Software Maintenance System

The on board software maintenance system will be used to produce the actual commands for the 4WD patch, starting from the built version (i.e. an ICD image file) of the ACC code containing the 4WD software modification. Using the OBSM software application, a series of commands are created to upload the patch and to dump the relevant memory addresses (for verification purposes).

The 4WD will be the most important and longest patch generated to the ACC: the correctness of the commands generated by the OBSM application will be verified at the simulator before the final upload on board.

O. Impact on Flight Dynamics

The flight dynamics system has to be updated for the 4WD patch on the following functions:

- GTP retrievals: the task that retrieves the housekeeping packet, which will be extended by the 4WD patch, has to be updated to be able to gather the extra data.
- Wheel speed prediction: the wheel speed evolution tool has to be updated to predict the speed of all 4 wheels. This will be function of initial angular momentum, null space offset, and pointing sequence.
- Command Generation: this module generates command files entry (TPF/APF) and they need to be updated according to the new 4WD momentum management concept and the null space offset.
- Bias optimisation: this module finds an optimum combination of angular momentum and null space offset for a given observation pointing sequence.
- EPOS generation: adapt EPOS generation script to use the enhanced modules for 4WD listed above.
- HPTDG update: the flight dynamics High Precision Test Data Generation, used for specific FD test and validation purposes, will be also updated to include the 4WD patch.

P. Timeline of implementation and validation

The 4WD project has been divided in two major phases:

Phase 1: preparation phase

The 4WD preparation phase was kicked off in September 2011 and finalised in April 2012.

During Phase 1 systems necessary for developing AOCS algorithms and implement/validate on-board software changes has been reactivated. A study of how to implement the 4WD in the on-board software architecture, and an identification of compatibility with FDIR and stability margin of the control has also to be performed. The go-ahead for the start of Phase 1 was given after successful health test of the fourth wheel, performed on 27th July 2011.

During Phase 1 the feasibility of the 4WD algorithm was demonstrated and a new control algorithm was proposed. The original algorithm development environment XMMSIM was reactivated and modified to be able to simulate 4 wheel momentum management and used to demonstrate the 4WD features. A preliminary FDIR assessment was performed, which analysis will be finalised during the implementation phase.

Phase 2: implementation phase

During Phase 2 the 4WD design will be finalised, tuning the algorithm data values, revising the operational constraints that may change due to 4WD and identifying the new FDIR thresholds. A simulation campaign will be carried out to support the 4WD analyses and design. All the features will be implemented in a software patch to the ACC, which will be developed, verified and validated at unit level using the Software Development Environment (SDE) and at system level using the XMM Operational Simulator.

The nominal and contingency procedures for AOCS and system will be updated. The modifications to the Database will be implemented and as soon as the patch is delivered, they will be tested with the Operational Simulator. In parallel the changes needed to the Flight Dynamics system will be implemented.

After all the changes specified above will be implemented, verified and validated, the actual patch will be uplinked to the spacecraft and after a period of commissioning of the changes it will be used for nominal operations.

The Phase 2 of the 4WD project is in course of approval by XMM-Newton management and will possibly start in summer 2012 and it will last one year.

According to this plan XMM-Newton will run with four active wheels by end of 2013.

Q. 4WD verification and validation

The new design will be verified and validated at various levels and using a variety of methods including

- review of design,
- controller performance verification using XMMSIM and stability assessment using Matlab,
- software validation using the SDE,
- verification of modes and mode transitions, including operational procedures, using the operational simulator.

The review of design is a continuous activity, in particular for the algorithm design. Details concerning validation and the validation approach can be found in [(6)].

For the software, a tailored set of reviews will be done:

- URR – User Requirements Review,
- DDD – Detailed Design Review,
- PAR – Preliminary Acceptance Review.

On software level, the software will undergo

- unit tests using the SDE,
- integration test using the SDE and the operational simulator,
- verification and validation test mainly performed with the operational simulator.

VI. Conclusions

In this paper an overview of the 4WD changes and its impact on XMM-Newton operations was presented. The foreseen saving of 50% of fuel after implementing the new momentum management strategy will potentially extend the lifetime of XMM-Newton up to 2026. The preparation phase was successfully completed, demonstrating the feasibility of the 4WD project. The implementation phase is foreseen to start in summer 2012 and according to this plan XMM-Newton will run with four active wheels by end of 2013.

Appendix A
Acronym List

3WD	3 Wheel Drive
4WD	4 Wheel Drive
ACC	Attitude Control Computer
AOCS	Attitude and Orbit Control System
AMD	Autonomous Momentum Dump
APF	Attitude Parameter File
DOF	Degree Of Freedom
EEPROM	Electrically Erasable Programmable Read Only Memory
EPOS	Enhanced Planned Observation File
FD	Flight Dynamics
FDIR	Failure Detection Isolation and Recovery
FSS	Fine Sun Sensor
GTP	Generic Telemetry Processor
HK	HouseKeeping telemetry
HPTDG	High Precision Test Data Generator
IMU	Inertia Measurement Unit
IPS	Inertial Pointing and Slew mode
MCS	Mission Control System
OBSMS	On Board Software Maintenance System
PIC	SCOS-2000 Packets Identification Criteria
RW	Reaction Wheel
SDE	Software Development Environment
SPID	SCOS-2000 Packet IDentifier
SSA	Sun Sensor Acquisition mode
STA	Star Tracker Acquisition mode
TCM	Thruster Control Mode
TPF	Task Parameter File
XMM	X-ray Multi-Mirror
XMMSIM	XMM AOCS algorithm SIMulator

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