THE XMM ATTITUDE DETERMINATION AND CONTROL SUB-SYSTEM TWO YEARS OF IN-FLIGHT EXPERIENCE

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ABSTRACT *– The X-ray Multi-mirror Mission (XMM) Flight Dynamics System consists of four subsystems: Mission Planning, Attitude Determination and Control, Orbit Determination and Prediction, Orbit Control. The present paper describes the operational experiences and lessons learned, the in-flight performance and the enhancements made to the Attitude Determination and Control subsystem components since the launch on 10th December 1999.*

KEYWORDS: X-ray multi-mirror observatory, flight dynamics system, attitude determination, calibrations, in-flight experience, in-flight enhancements

INTRODUCTION

ESA's X-ray multi-mirror observatory XMM-Newton was launched on 10th December 1999 by Ariane flight 504. For a complete overview of the mission as well as a description of the Attitude and Orbit Control System (AOCS) of XMM-Newton, see [1]. The XMM Flight Dynamics System (FDS), residing on a Sun/Solaris 8 platform, consists of four subsystems:

- Mission Planning, see [2], [4]
- Attitude Determination and Control, see [3] for a summary of the design
- Orbit Determination and Prediction
- Orbit Control, see [6].

The Attitude Determination and Control (ADC) subsystem is further decomposed into:

- Database import/maintenance
- Telemetry access
- Attitude determination and attitude history file generation
- AOCS units calibration
- RCS model, RCS calibration and fuel book-keeping.

The present paper describes for the ADC subsystem components:

- experiences and lessons learned during design and operations

- in-flight performance
- calibration activities
- modifications and improvements in response to additional customer or operational requirements during the first two years in orbit.

DATABASE IMPORT/MAINTENANCE SUB-SYSTEM

Import of Operational Database

The FDS resides on a physically different platform to the main mission control system (MCS). It thus cannot take advantage of the MCS TM handling facilities and must rely on a mirror system. The TM definition tables are imported from the MCS to the FDS in order to allow the FDS to correctly extract individual parameters from the AOCS and system housekeeping TM packets. The operational database (ODB) is maintained via Oracle, however the FDS does not support this package. The relevant tables of the ODB are thus dumped via SQL scripts to ASCII files, which files are further filtered and recombined in a manner most suitable for the FDS. This seemingly backward step – moving the data from a relational DBMS to combined plain-text files – is actually a robust and operationally simple solution from the point-of-view of FDS operatives. As we do not maintain the ODB ourselves and are only an end-customer, the functionality offered by a DBMS such as Oracle in terms of data input and management are not relevant to the *operation* of the FDS – indeed, the elementary readability of the plain-text files is an advantage in this context. We would reconsider this approach, were the ODB to be maintained via a DBMS which was i) genuinely platform-independent ii) easy to use and maintain iii) robust and fast – we have yet to find a DBMS that satisfies *all* these criteria.

Import of manufacturer's Flight Dynamics Database

In the past, ESOC Flight Dynamics have gathered data pertaining to the spacecraft on an as-needed basis, mainly from acceptance test reports. For XMM we have adopted a new approach whereby at an early stage the data needed by the FDS are defined and then collected and provided by the prime-contractor as a single data-package. We don't have the space to describe the detailed pros-and-cons of the two approaches (and hybrid and alternative approaches) here, but will summarise our top-level experience.

The original approach had the clear advantage of restricting the data-gathering only to that which was needed at the time – the new approach forces us to specify what we *think* we *might* need as well as that we know we will need, since the contractual/financial implications of changes to a signed-off ICD can *severely* inhibit later additions/deletions.

The major disadvantage of the original approach was that of data-verification close to launch. By that time, much of the prime-contractor's expertise will have moved on to new projects (and this is even more true of sub-contractors). Similarly, ESA project-management will have its hands full with other critical pre-launch activities and thus has little time to devote to this topic. By making the prime-contractor responsible for data-collection and verification at an early stage, it was hoped to avoid this serious problem.

Our experience is as follows:

1. In an understandable effort to cut costs, the prime-contractor will manage the data via an off-the-shelf DBMS (MS-Access in the case of XMM and INTEGRAL) and will also use the same mechanism to keep track of data for spare hardware units. This presents Flight Dynamics with the need to transfer the data from a platform-dependent DBMS to the "operational flight dynamics database" and at the same time ensure that data for non-flight units are filtered out. As long as the prime-contractor is willing to maintain an up-to-date configuration table of units actually mounted on the flight model and also to provide queries to allow Flight Dynamics to filter out non-flight units on the basis of this table, then this approach is acceptable.

2. In contrast to the majority of other cases, from the Flight Dynamics point-of-view it is an advantage to finalise the ICD at as late a stage as possible! The reason for this is that modifications to signed-off ICDs normally have a formal cost impact. The temptation is thus to include *every* datum, which *might* be necessary, in the initial specification. Of these data, many might never be used in practice but nevertheless must be verified and agreed both by prime-contractor and Flight Dynamics, for *every new release of the database*.
3. It is essential that the database be populated with measured data from an early stage – there should thus be an initial release with nominal data and subsequent releases as further subsystem and system level data become available.
4. Were an industry-wide standard available, covering the mission-independent areas such as mass-properties and sensor/actuator positions/alignments then a core "flight dynamics database" could be specified, the format and content of which would be largely mission independent. This could be agreed upon and finalised at an *early* stage between the prime-contractor and Flight Dynamics. A more flexible approach *must* be taken however with regards collection of highly mission-specific data, in order to avoid the inefficiencies and hidden effort implied in points 1 and 2 above.
5. In some exceptional cases where a large effort was concerned and the operational justification *appeared* to be of very low priority, the prime-contractor refused (on cost-grounds) to provide the data via the database and instead referred Flight Dynamics to the relevant test reports and procedures … Effectively forcing us to use our original data-gathering method.

Import of Star-tracker-Instrument Alignment Matrices

Direction cosine matrices defining misalignments between the operational star-tracker and the payload instruments are generated by the Science Operations Centre (SOC) for use by the FDS when generating mission-planning products. These data are provided to Flight Dynamics in a plain-text file for import into the operational flight dynamics database. From the database-maintenance point-of-view, this is a straight-forward task.

TELEMETRY ACCESS SUB-SYSTEM

As noted above in the database section, the FDS resides on a different platform to the main mission control system (MCS) but nevertheless requires access to the service-module TM filed on the MCS. For this reason, the FDS is equipped with a subsystem for retrieval of TM from the MCS and management of these data.

The packets retrieved (Ref. [14]) are

- The 4 periodic AOCS packets
- The non-periodic AOCS clustered event reports, task parameter reports and memory dumps (of which only the clustered events are retrieved during routine operations)
- The 7 periodic system housekeeping packets (of which only system HK 5 is retrieved during routine operations)
- The time-correlation packets generated by the ground-segment

The TM retrieval and management by the FDS is, by-and-large, quite straight-forward. However, our experience with XMM and its "twin mission" INTEGRAL is as follows:

1. Although the spacecraft transmits the event reports in clusters, the MCS decomposes these clusters into individual records, each holding a single event. The FDS however, works much more efficiently if the packets of clustered events can be processed directly, rather than having to retrieve each separate record from the MCS – which was not foreseen in the original ground-segment design, with the result that the clustered-event packets were eventually made available to the FDS only after artful

manipulation of the MCS configuration files to allow this. The moral here is that whilst it may be user/application-friendly to break down the transmitted data into ever more manageable portions, access to the original/intermediate data-formats should also be possible without traversing three sides of the square. The FDS developers had a similar experience with respect to the task parameter reports – in this case, the MCS developers provided a "merge" facility to channel the several dozen distinct report IDs into a single file for retrieval by the FDS.

2. Although INTEGRAL boasts much the same spacecraft service-module hardware (same attitude control computer, sensors, actuators, etc.), the TM of interest to the FDS is nevertheless transmitted in 4 packets instead of a maximum 12 for XMM. The data-rate (modest kilobits per second) is similar for this subset of service-module TM, for both missions. Whilst this may seem a trivial difference in this day-and-age of fast processors and cheap memory, the human effort required to monitor and verify the extra TM packets of XMM plus extra design effort entailed in synchronising TM from separate packets leads us to the conclusion that the INTEGRAL approach to a higher degree of TM grouping has much to recommend it.

3. For XMM we are using a venerable piece of software (dating back over 10 years) as part of the MCS-to-FDS TM-retrieval. Said SW utility was not designed for modern packet telemetry and we are consequently experiencing recurring but comparatively minor performance problems characterised by an occasional lag behind real-time, which are currently under investigation. These problems did not show up during the extensive and rigorous testing phase, when the system was loaded to a much greater extent than during the current routine operations. Our experience here is that care should be taken with older SW utilities implemented on different platforms with more relaxed performance requirements. Whilst the functionality may still be identical, such SW should perhaps be singled out for extra testing.

4. The original ground-segment specification was such that the FDS was not formally required to provide any real-time TM monitoring facilities on the grounds that the MCS already had this functionality in abundance. Flight Dynamics has developed a generic TM-access tool which allows on or off-line display of telemetry. For our own benefit (e.g. as a useful tool for debugging in the course of FDS implementation) we configured our TM monitor to handle XMM TM. This "unofficial" tool quickly became indispensable and is now an operational part of the routine FDS. In particular, we have added functionality to allow plotting of predictions of reaction-wheel speed variation which are displayed together with the measured data (see figure below) to provide the spacecraft controllers a valuable indication of whether the spacecraft is manoeuvering according to plan. The lesson learned is that the advantages of displaying the same basic and processed data in different ways should not be underestimated.

The following figure shows the measured and predicted speeds in RPM for reaction-wheel 1 around a slew (30/10/2001 12:20 to 12:45), reaction-wheel bias (15:02) and perigee passage (16:17).

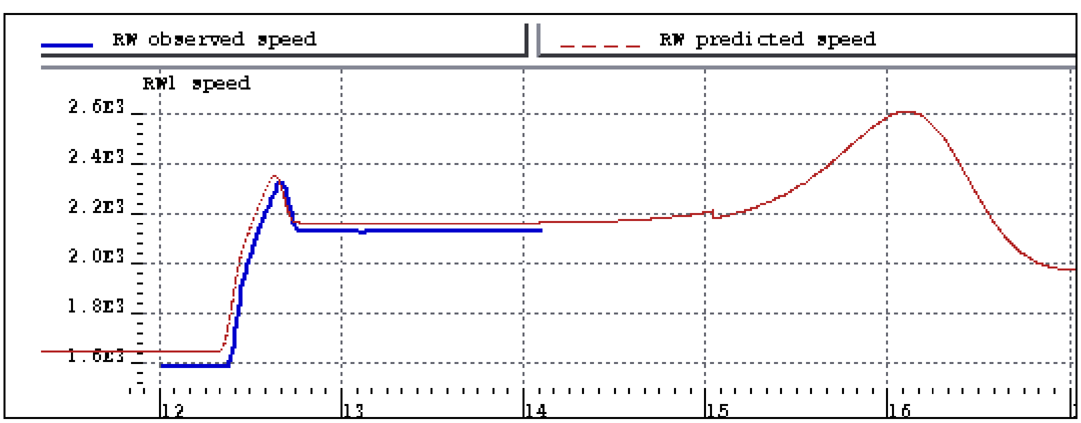

Fig. 1. Observed vs. Predicted Wheel-1 Speeds Showing Slew & External-Torque Effects

The agreement of our predictions with the observed speeds is sufficiently close that any discrepancy will attract the attention of the spacecraft controller. The slight offset between predictions and measurements in the plot is due to the transition from thruster-based to wheel-based attitude control … The residual body rates caused by the thrusters following a reaction-wheel momentum unloading are cancelled out by the wheels. Our prediction SW does not model the behaviour of the on-board-controller with regards to this effect.

ATTITUDE DETERMINATION AND ATTITUDE HISTORY FILE GENERATION

Attitude Determination

The attitude determination subsystem has been extended to routinely perform other tasks in addition to determining the attitude of the spacecraft at a single epoch [3]. These tasks consist of the generation of a database of matched star information from the XMM mission star catalogue, which has been derived mainly from the HIPPARCOS and Tycho source catalogues using the star catalogue facility [5]. The database also includes instrumental magnitudes as measured by the star tracker. This database will be used to produce calibration curves that relate instrumental magnitude to visual magnitude, (B-V) and (V-I) colour indices. These relationships are required to refine the predictions of instrumental magnitude in the XMM mission star catalogue, which are currently based on corrections to visual magnitude given as a function of spectral type. These magnitude corrections tables were obtained from the ISO mission.

In addition, the reduced accuracy star position measurements from every star tracker mapping are used to provide a list of suspect 'lit' pixels. One of the confirmed 'lit' pixel positions is routinely reported during star tracker mappings.

Finally, the software now provides accurate positions and magnitudes for the major planets, asteroids and comets. For comets and asteroids the ephemerides are downloaded from the Minor Planet Center web site (*http://cfa-www.harvard.edu/iau/Ephemerides/index.html*). The positions of the asteroids and comets are derived based on the universal time of flight algorithm in [7]. Predictions for the position in star tracker coordinates and magnitude, for the comet C/2001 A2 LINEAR, were used to search and track this comet with the operational star tracker during two planned scientific observations of this comet on 2001/06/27.

Star Tracker Window Dump Processing

The star tracker window dump processing is required as part of the in-orbit star tracker CCD maintenance. It is used to confirm the presence of faulty pixels on the star tracker CCD.

The XMM star tracker, whilst in it's primary mode of operation (tracking stars), does not provide access to the raw pixel measurements in telemetry. In order to access this information, the star tracker has to be commanded into a specific mode of operation, called the star tracker window dump mode. When in this mode, the spacecraft attitude is maintained by the FSS and IMU. Then it is possible to dump several specified acquisitions of a 9x9 array (window), which can be placed over the entire 384x288 CCD using a specified acquisition gain. The starting points for positioning these dumps are areas of the CCD where search/track commands have failed or bad pixels identified using the routine attitude determinations. A tool has been developed to analyze the window dumps and to provide a graphical output to visualise the pixel outputs during the dumps on a 3D bar plot animation using PV wave. Confirmed and potential bad pixels are then placed in a database for use by the mission planning guide star selection software. The tool is also used to perform various computations to assess the uniformity and to look at trends in the CCD dark current. Figure 2 shows a typical plot with a confirmed bright 'lit' pixel. Normally a star image is de-focussed by the star tracker optics and is spread over 4 pixels.

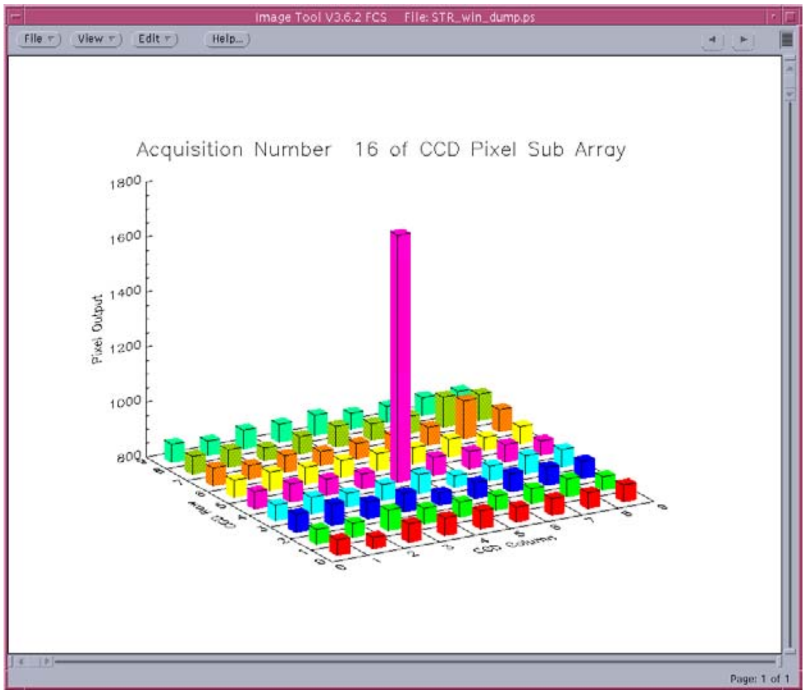

Fig. 2. Confirmed 'Lit' Pixel

Attitude History File Generation

In September 1998, the interface between the FDS and the XMM science operations center (SOC) for providing an AHF per revolution was finalised in an ICD. During the Commissioning and Verification Phase (CVP) of the mission, the SOC realised however, that they would prefer to have the attitude reconstituted by the FDS at the same frequency as the 2 Hz star tracker and fine sun sensor data. It was also realised, early in these mission phases, that FSS quantisation (3.1-7.5 arcsec) and residual bias errors, corrupted significantly the attitude solution. Now the attitude is determined from 5 continuously tracked stars widely separated in the 3°x4° star tracker field-of-view. With the data provided in this way the SOC have the freedom to apply there own filtering algorithms which is required particularly around periods where the spacecraft attitude is disturbed by star tracker SEU. Figures 3a and 3b show plots of the star tracker boresight deviation with respect to the planned attitude over a complete revolution and in the case where the spacecraft attitude is disturbed by a star tracker SEU.

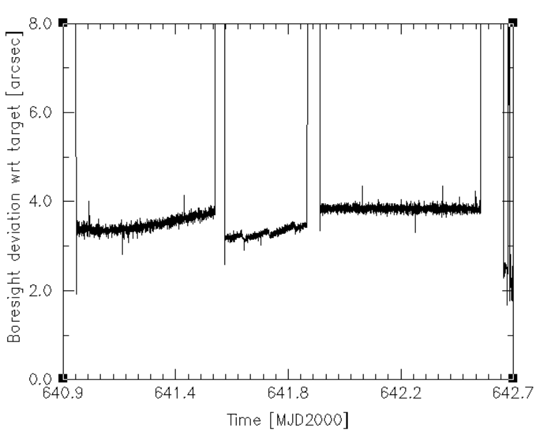

Fig. 3a. Boresight Deviation w.r.t. Planned Attitude for Rev. 333

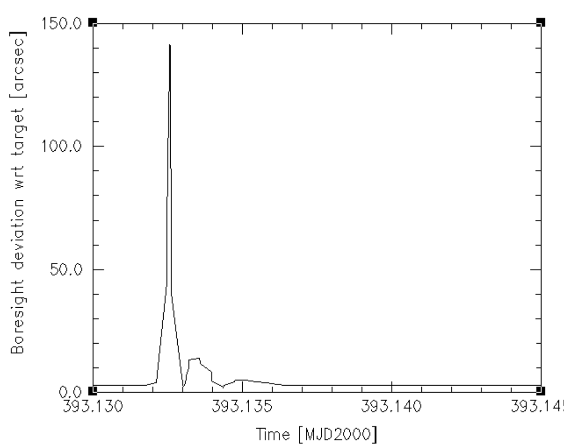

Fig. 3b. Boresight Deviation w.r.t. Planned Attitude in Rev. 208 with STR SEU

In August 2001, a patch to the star tracker software was uploaded to reduce the sensitivity of the sensor to SEU. This has consequently reduced significantly the effects due to SEU.

AOCS UNIT CALIBRATION

Inertial Measurement Unit Drift Bias Calibration

This subsystem continues to be used prior to every eclipse season. Even though the IMU remains powered off for periods of several months, prior to use during the eclipse season, the drift stability of these units is quite good. Typically the drift biases have remained very stable with absolute drift biases of less than 1.5°/hour, with a small switch on to switch on variation. The main problem with accurate IMU drift bias compensation is that shortly after switch on, there is a temperature stabilization period (typically 5 hours or more), where the drift is clearly non-linear. Due to constraints on IMU usage, the IMU drift bias must be calibrated soon after switch on for a period of 1 hour. Since this is typically how the IMU is used prior to eclipses, there is no use in waiting for the temperature to stabilise prior to calibration. This drift is then used for the subsequent eclipse season and provides adequate performances in terms of attitude drift when the spacecraft is under IMU control.

Open-Loop Slew Performance Calibration

Slew manoeuvres are performed open loop about the yaw axis and closed-loop about the roll and pitch axes using FSS outputs. The control law inputs are the predicted sun positions and wheel momentum vector as a function of time, to give the required slew about the eigenaxis. The computation of the wheel momentum profiles assumes a knowledge of the spacecraft moments and products of inertia, the reaction wheel moments of inertia and the alignments of the reaction wheels with respect to the spacecraft functional reference frame (defined by the operational star tracker).

A new algorithm has been developed, [9], which uses a linear least square formulation to solve for the unknown 15 parameters (spacecraft inertia matrix, reaction wheel inertia and alignment matrices). This algorithm shows an improvement of about 1 order of magnitude over the original algorithm, [8], in the square of the residuals. It is shown in [9] with zero external torque that the system has rank 14 with a typical condition number of $2x10^6$.

As mentioned in [3], a simulation of the open-loop slew mode was developed which calls the environmental torque model described in [4]. Slew manoeuvres started early/late in the revolution are significantly affected by large variations in the gravity gradient torque. This simulator in conjunction with software to determine the attitude during open-loop slew manoeuvres has proved an accurate tool to predict open-loop slew errors (Figures 4a and 4b). As a result the slew simulation has been incorporated into the mission planning software to predict the slew errors and to configure the on-board slew controller accordingly. This is usually sufficient to reduce slew errors to a level (<2.5°) so that an attitude correction slew can be performed in closed-loop. The prediction error of the simulator has been shown to be better than 1°.

This simulator has recently been enhanced with the capability to minimise the slew error, by modifying the slew eigenaxis and angle. The minimisation scheme is based on the NAG Fortran library routine E04UCF [12]. This method has only been tested operationally with 2 slew manoeuvres to date, where the errors have been reduced from predicted errors of above 2° down to 0.3° and 0.6° respectively.

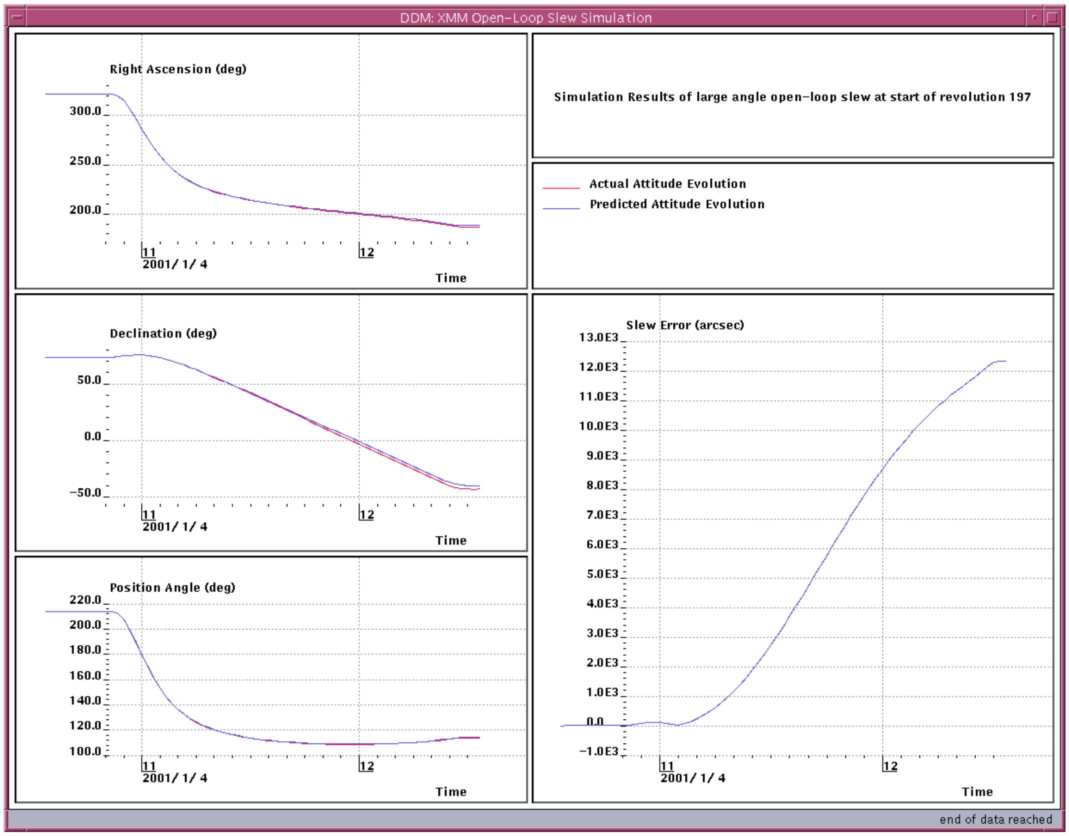

Fig. 4a. Slew Simulator Predictions

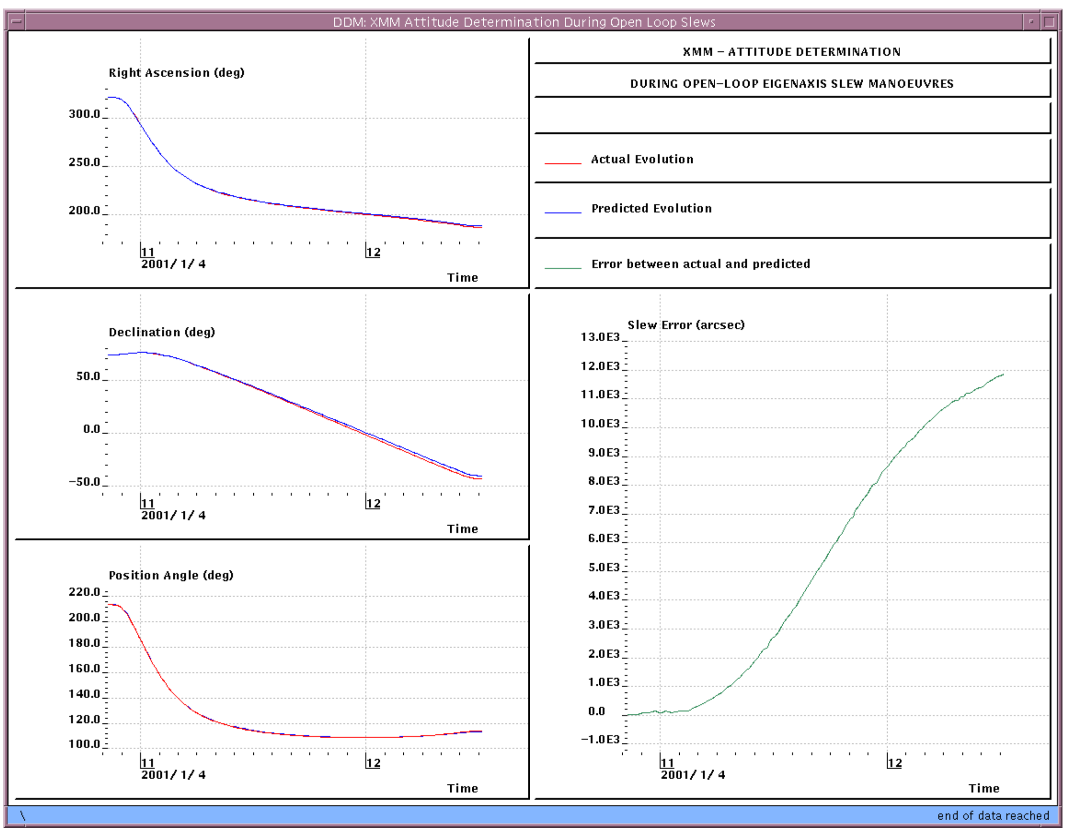

Fig. 4b. Slew Attitude Determination Results

Star Tracker/Fine Sun Sensor Misalignment Calibration

This subsystem was executed several times during LEOP and CVP but only one calibration has been executed during the routine phase. The following equations show the full transfer function as implemented within the XMM ACC flight software. The coefficients A_1 to A_8 and B_1 to B_8 are obtained from the FSS manufacturer (Adcole Corporation), and are not calibrated in flight. The remaining coefficients are a function of the misalignments of the particular FSS head with respect to the spacecraft functional frame defined by the operational star tracker

$$\alpha_T = \tan^{-1}\left[A_1 + A_2 N_\alpha + A_3 \sin\left(A_4 N_\alpha + A_5\right) + A_6 \sin\left(A_7 N_\alpha + A_8\right)\right] + A_9$$

$$\alpha = \alpha_T + A_{10} \tan \beta_T \cos^2 \alpha_T + A_{11} \tan \beta_T \sin 2\alpha_T$$

$$\beta_T = \tan^{-1}\left[B_1 + B_2 N_\beta + B_3 \sin\left(B_4 N_\beta + B_5\right) + B_6 \sin\left(B_7 N_\beta + B_8\right)\right] + B_9$$

$$\beta = \beta_T + B_{10} \tan \alpha_T \cos^2 \beta_T + B_{11} \tan \alpha_T \sin 2\beta_T$$

Table 1 shows the time history of the estimated misalignment terms of the FSS transfer function. In revolutions 1, 2, 3 and 4 only the terms A_9 and B_9 are estimated, by placing the spacecraft in an attitude such that the FSS α and β angles are close to zero. In revolutions 6 and 10 the 6 misalignment terms of the transfer function are estimated by processing data from 4 pointings with the sun placed near the extreme sun constraints (±20º, ±20º) in the FSS field-of-view.

Run Time	Rev	STR	FSS	FSS_A9	FSS_A10	FSS_A11	FSS_B9	FSS_B10	FSS_B11
1999/12/10 16:02:00	0001	A	A	113.67	-1033.43	-651.05	-26.85	-154.52	11.32
1999/12/10 22:55:27	0001	A	A	-27.05	-1033.43	-651.05	201.46	-154.52	11.32
1999/12/10 22:58:54	0001	A	A	-26.64	-1033.43	-651.05	199.69	-154.52	11.32
1999/12/11 22:40:06	0001	A	A	-47.35	-1033.43	-651.05	231.26	-154.52	11.32
1999/12/11 23:24:41	0001	A	A	-47.58	-1033.43	-651.05	231.48	-154.52	11.32
1999/12/12 18:42:08	0002	A	A	-58.42	-1033.43	-651.05	218.87	-154.52	11.32
1999/12/14 19:42:37	0003	A	A	-59.16	-1033.43	-651.05	223.72	-154.52	11.32
1999/12/16 18:32:47	0004	A	A	-31.84	-1033.43	-651.05	220.74	-154.52	11.32
1999/12/16 18:51:35	0004	A	A	-31.33	-1033.43	-651.05	220.70	-154.52	11.32
1999/12/29 09:24:01	0006	A	A	-50.16	-1069.72	-456.72	210.76	-71.04	-146.29
1999/12/29 17:10:14	0010	A	A	-39.52	-1135.59	-532.93	207.90	-91.54	-142.24
2000/06/08 12:35:48	0080	A	A	-85.29	-1017.97	-597.47	215.40	-64.28	-194.19
2000/06/08 12:42:27	0080	A	A	-86.15	-1016.33	-592.44	215.61	-63.72	-194.48

Table 1: Time History of FSS Transfer Function (Alignment) Terms (arcseconds)

When roll slew manoeuvres in the CVP were processed, where the IMU was powered on, it was noticed that there was an oscillation on the spacecraft roll axis during the constant rate phases of the slew. The amplitude and frequency of these rate signals were obtained using a Fractional Fourier Transform, [13], and are shown to be related to errors in the coefficients of the harmonic terms in the FSS transfer function, [11]. These coefficients have not been calibrated and therefore introduce a spatial bias on each FSS measurement axis, which are not considered as part of the current misalignment calibration algorithm, [10]. This phenomenon was also observed during a roll slew performed on the Infrared Space Observatory (ISO), during the end of mission technology test phase [11].

Star-tracker-Instrument Alignment Matrices

The requirement is that all instrument bore-sights should be co-aligned within a 60 arcsecond half-cone and this is indeed the case. However, to our surprise we find that the misalignment of the instruments with respect to the star-tracker around the spacecraft roll-axis is significantly larger than the original requirement of 0.5°, varying from 1.25° to 2.43° for the EPIC instruments and 1.35° for the RGS. The optical monitor misalignment is within bounds.

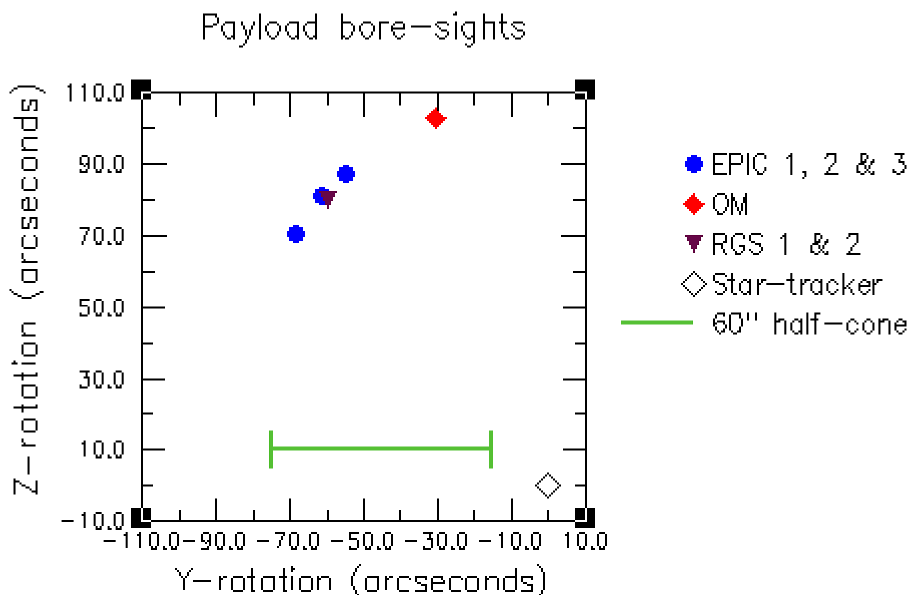

Fig. 5. Instrument Bore-sights Relative to the Star-tracker

RCS MODEL, RCS CALIBRATION AND FUEL BOOK-KEEPING

XMM possesses reaction-wheels and a reaction-control-system (RCS) of hydrazine thrusters. In the routine phase, attitude slews are performed solely with the wheels and the thrusters are used for orbit manoeuvres and reaction-wheel biasing.

There are four reaction wheels mounted in the usual "skew" mounting configuration such that if one wheel fails the remaining three can always provide 3-axis control. Wheels 1,2,3 have been used since launch, with wheel 4 in reserve.

The principle hardware components of the RCS are 8 hydrazine thrusters in two redundant branches of four, operating in blow-down mode (23N BOL to 7N EOL), plus four propellant tanks. During thruster-control mode, attitude control is facilitated via off-modulation or on-modulation.

RCS Calibration

The calibration of the thrusters is initially based on data supplied by the manufacturer. These calibration terms are subsequently modified by a multiplicative term, based on the differences between predicted and observed manoeuvre performance. The calibration for the major post-launch manoeuvres (the perigee-raising burns) is listed below for the active thruster branch:

Table 2. Thruster Calibration

Time	1A	2A	3A	4A	Comment
1999-12-08T00:00:00Z	1.0000	1.0000	1.0000	1.0000	Initialisation
1999-12-11T12:20:00Z	0.9482	0.9958	0.9143	0.8746	Valid for PRB 1.1, 1.2
1999-12-13T12:24:59Z	0.9332	0.9592	0.9162	0.9177	Valid for PRB 2
1999-12-15T12:09:59Z	0.9562	0.9829	0.9074	0.9177	Valid for PRB 3

The above calibration terms are also used in the calculation of fuel-used during a given thruster manoeuvre. A conservative approach is adopted whereby the calibration term is only applied if greater than unity (i.e. we assume the fuel flow rate is always equal to or greater than the rates measured during ground-tests).

The thruster in-flight torque-calibration is as follows:

Table 3: Thruster On-board Torque Calibration (1/Nm)

Time	Roll	Pitch	Yaw	Comment
1999-12-10T14:32:00Z	0.1422	0.0312	0.0333	At launch
1999-12-11T09:34:00Z	0.1644	0.0361	0.0386	Intermediate
1999-12-11T13:33:00Z	0.2234	0.0491	0.0524	Intermediate
1999-12-11T16:33:00Z	0.2618	0.0575	0.0614	Intermediate
1999-12-13T09:02:00Z	0.2977	0.0654	0.0698	Intermediate
1999-12-13T14:04:00Z	0.3182	0.0699	0.0746	Intermediate
1999-12-15T11:10:00Z	0.3169	0.0696	0.0743	Intermediate
1999-12-15T13:15:00Z	0.3342	0.0734	0.0784	Intermediate
1999-12-16T09:46:00Z	0.3379	0.0742	0.0793	Intermediate
1999-12-16T12:23:00Z	0.3383	0.0743	0.0794	Intermediate
1999-12-17T10:30:00Z	0.3140	0.0691	0.0728	Routine-phase

Fuel Book-keeping

ESOC Flight Dynamics has significant experience in the management of hydrazine-based reaction control systems. This experience has shown that the most reliable method of keeping track of available fuel is the estimation of fuel used during individual manoeuvres, based on observed manoeuvre performance. The total fuel remaining (initially known accurately at the tank-filling at launch) is then decremented by this fuel-usage estimate.

Of the 530 kg hydrazine loaded prior to launch, approximately 380 kg were used during the pre-operational orbit and attitude manoeuvres, as shown by the following figure. The majority of fuel was used during perigee-raising burns 1.1, 1.2, 2 and 3, which are clearly visible on the figure.

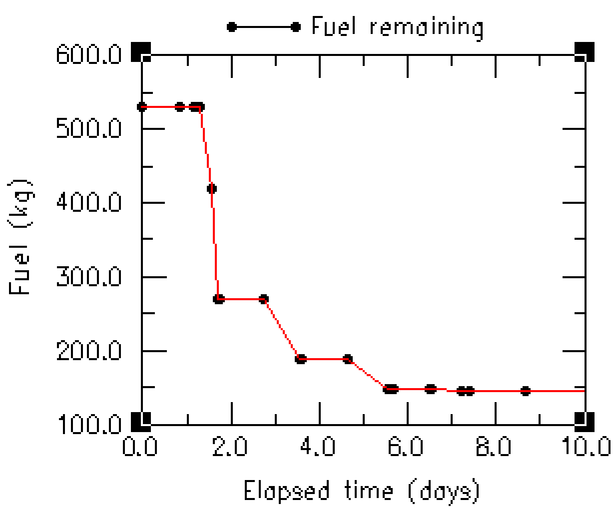

Fig. 6. Fuel Usage During Launch and Early Orbit Phase

A subsequent 13 kg have been used during routine operations, leaving 133 kg 700 days into the mission. The figure below shows the fuel usage on a daily basis. Of the five excursions into emergency sun-acquisition mode (ESAM), the four ESAMs at days 56, 91, 114 and 369 used slightly more fuel than for the equivalent routine operations. The fifth ESAM on day 522 used no more fuel than a normal daily reaction-wheel biasing. During the routine phase, the average thruster manoeuvre (approximately one per day) has consumed 20g of fuel.

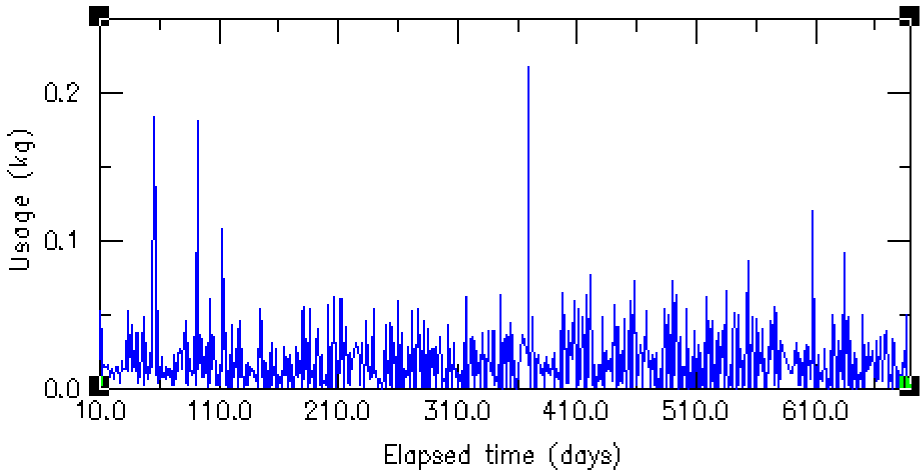

Fig. 7. Fuel Usage per Manoeuvre in the Routine Phase

In principle we have enough fuel for approximately 20 further years of operation. In mid-March 2003, a drift-start orbit manoeuvre (3kg) followed 12 days later by a drift-stop (2.8kg) are foreseen. Regardless of such occasional orbit manoeuvres, the original budgeting for a 2.25 year nominal mission with possible extension to 10 years is more than guaranteed.

In addition to derivation of fuel usage, the fuel book-keeping SW calculates the Δ**v** effects of all thruster manoeuvres as input for orbit determination. A summary of the routine-phase Δ**v** magnitudes is shown below, the average being approximately 7cm/s.

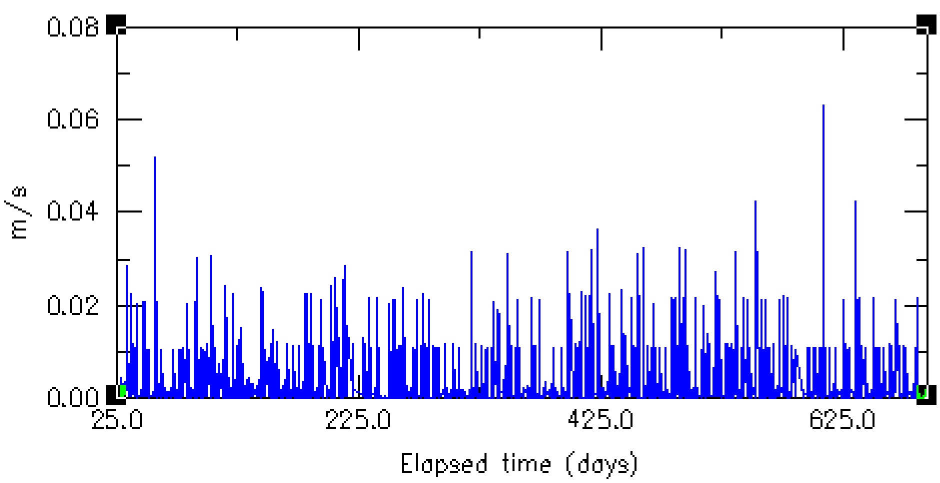

Fig. 8. Δv Effects of Reaction-Wheel Biasing Manoeuvres

A discrepancy of 14% on average, has been observed between the Δ**v** estimate from the FDS RCS SW and the observations based on orbit determination. An investigation is under way to determine whether the manufacturer's calibration data were inaccurate, the calibration procedures are in error or the FDS SW is incorrectly applying data or procedures.

OVERALL RELIABILITY OF THE FDS

The XMM Flight Dynamics routine anomaly reporting system was introduced on 22/5/2000. To date (3/11/2001), 109 reports were filed and processed:

- 68 had no impact on science time
- 41 resulted in a loss of science time
- 30 were related to the ADC system
- 11 related to the ADC system resulted in a loss of science time.

SUMMARY

The first two years in orbit have proven that the Flight Dynamics Attitude Determination and Control subsystem is a very reliable subsystem; only very few non-conformances did show up. The chosen approach for populating the Flight-Dynamics database proved to be not 100% workable. The newly provided TM-access subsystem is working flawlessly and a great deal of commonality between XMM and INTEGRAL has been maintained, despite the differing on-board approaches to TM-packet data population. Ironically, one of the tried-and-trusted existing TM-access utilities appears to be giving us problems. The attitude determination sub-system functions were extended: Database of measured star magnitudes, reporting of 'lit' pixels, solar system objects position and magnitude, star tracker window dump processing). For the attitude history file, at the request of the Science Operations Centre, a new concept (raw attitude file at 2 Hz) was implemented in Feb. 2001. IMU calibration activities went according to plan; for the slew performance calibration a second approach was implemented. After the STR/FSS calibrations, LEOP roll slew manoeuvres revealed some unexpected effects of the FSS transfer function provided by the unit manufacturer. To predict and eventually reduce the large slew errors due to variation of gravity gradient torques, we have implemented a new simulator and slew parameter optimisation software.

The main lessons learned are:

- The peculiar design of the XMM AOCS requires substantial and continuous attention by Flight Dynamics experts.
- To improve the modest slew accuracy of the spacecraft, considerable enhancements of calibration s/w and mission planning s/w were needed.
- The organisational and operational approach taken in ESOC Flight Dynamics enabled us to respond changing or new operational requirements and allows continuous improvement based on operational experience.
- The XMM/INTEGRAL project decision to deliver all Flight Dynamics data in a relational database has some advantages over the traditional approach to collect the data from test reports, but causes significant extra effort on prime contractors and Flight Dynamics' side.

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LIST OF ACRONYMS

ACC	Attitude Control Computer
ADC	Attitude Determination and Control
AHF	Attitude History File
BOL	Beginning Of Life
CVP	Commissioning and Verification Phase
EOL	End Of Life
EPIC	European Photon Imaging Camera
ESAM	Emergency Sun Acquisition Mode
FDDB	Flight Dynamics DataBase
FDS	Flight Dynamics System
FSS	Fine Sun Sensor
ICD	Interface Control Document
IMU	Inertial Measurement Unit
INTEGRAL	INTErnational Gamma Ray Astrophysics Laboratory
ISO	Infrared Space Observatory
LEOP	Launch and Early Operations Phase
MCS	Mission Control System
ODB	Operational DataBase

PRB	Perigee Raising Burn
RCS	Reaction Control System
RGS	Reflection Grating Spectrometer
RWB	Reaction-Wheel Bias
SEU	Single Event Upset
SIAM	Star-tracker/Instrument Alignment Matrix
SOC	Science Operations Center
STR	Star TRacker
XMM	X-Ray Multi-Mirror