The Attitude and Orbit Control of XMM

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Attitude and orbit control of the XMM spacecraft relies on two subsystems on-board: the Attitude and Orbit Control Subsystem (AOCS) and the Reaction Control Subsystem (RCS). Together they must provide:
- **stable Sun-pointing after the spacecraft's separation from the launcher and during solar-array deployment**
- **increase the spacecraft's perigee altitude by means of a chemical propulsion delta-V of about 210 m/s**
- **provide undisturbed, high-accuracy, three-axis pointing during scientific observations lasting up to 40 h**
- **slew the spacecraft between observations, and before and after perigee**
- **ensure that the Sun remains more than 15 deg away from the telescope at all times.**

The Attitude and Orbit Control Subsystem (AOCS)

The AOCS on XMM supports six different operational modes, as indicated in Figure 1. The first three acquisition modes are transitional. The Initial Sun Acquisition mode is used exclusively after XMM's separation from the launcher, to support rate damping, Sun acquisition and solar-array deployment. The Sun Sensor Acquisition mode handles transitions from the use of the wide-angle Sun Acquisition Sensors to the Fine Sun Sensor. It is also used for recovery from the Emergency Sun Acquisition mode (an entirely hardware-supported mode activated by particular failure detection criteria). Finally the Star Tracker Acquisition mode supports the transition from gyroscope to star tracker and from thrusters to reaction wheels.

The two main modes for routine operations, described in more detail in the following paragraphs, are the Inertial Pointing and Slew mode and the Thruster Control Manoeuvre mode.

The various units of the AOCS are shown in Figure 2. In addition, it makes use of the propulsion capabilities of the Reaction Control Subsystem (RCS), which is described below.

The attitude and orbit control design is influenced by four main drivers:
- the high-accuracy inertial pointing
- the delta-velocity injection of about 210 m/s
- no failure or ground-control error may point the telescope closer than 15 deg to the Sun
- 'gyro-lean' operations.

High-accuracy inertial pointing

The high-accuracy attitude information is provided by a star tracker, co-aligned with XMM's telescope, giving accurate star-position data on up to five stars every 0.5 sec. In addition, there is an accurate Sun sensor for precision Sun-line determination around the telescope line-of-sight. The sensor information is processed by the attitude-control computer, on which the operation mode logic and control algorithm software is executed. The resulting control demand is achieved by accurate spin-rate control of three extremely well-balanced reaction wheels. Since the telescope must be inertially pointed in all three axes, a so-called 'Sun steering law' is implemented to compensate for the orbit progression around the Sun.

Thanks to the low noise in the star-tracker measurements, a narrow-bandwidth controller and accurate momentum control of the reaction wheels, the pointing is very stable, being ~1 arcsec over a 2 minute period. The absolute accuracy of the reconstructed attitude based on star-tracker measurements is also very high, at typically 1 arcsec.

Slew manoeuvres are used to reorient the telescope between observations and before and after perigee passages. For large slews outside the star-tracker field of view of 3 x 4 deg, a so-called 'open-loop slew' strategy is implemented. Based on the ground slew tele-commanding, the on-board software generates a three-axis momentum reference profile and a two-axis Sun-sensor reference profile. During the slew, a roll and pitch controller is super-imposing momentum correction onto the reference momentum profile, based on the actual Sun-sensor measurements.

Since no absolute measurements are available for the yaw axis, a residual yaw attitude error

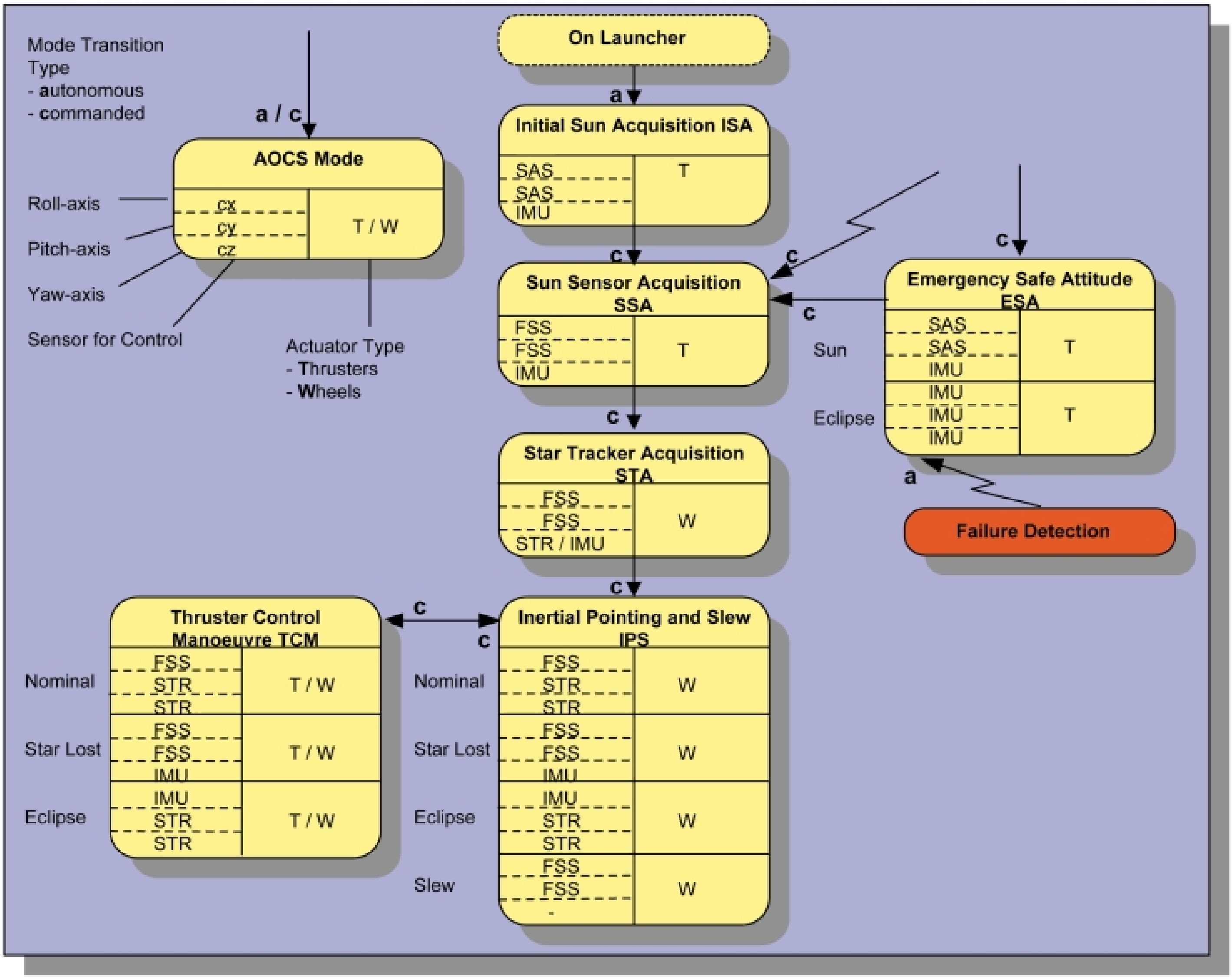


Figure 1. The AOCS operational modes

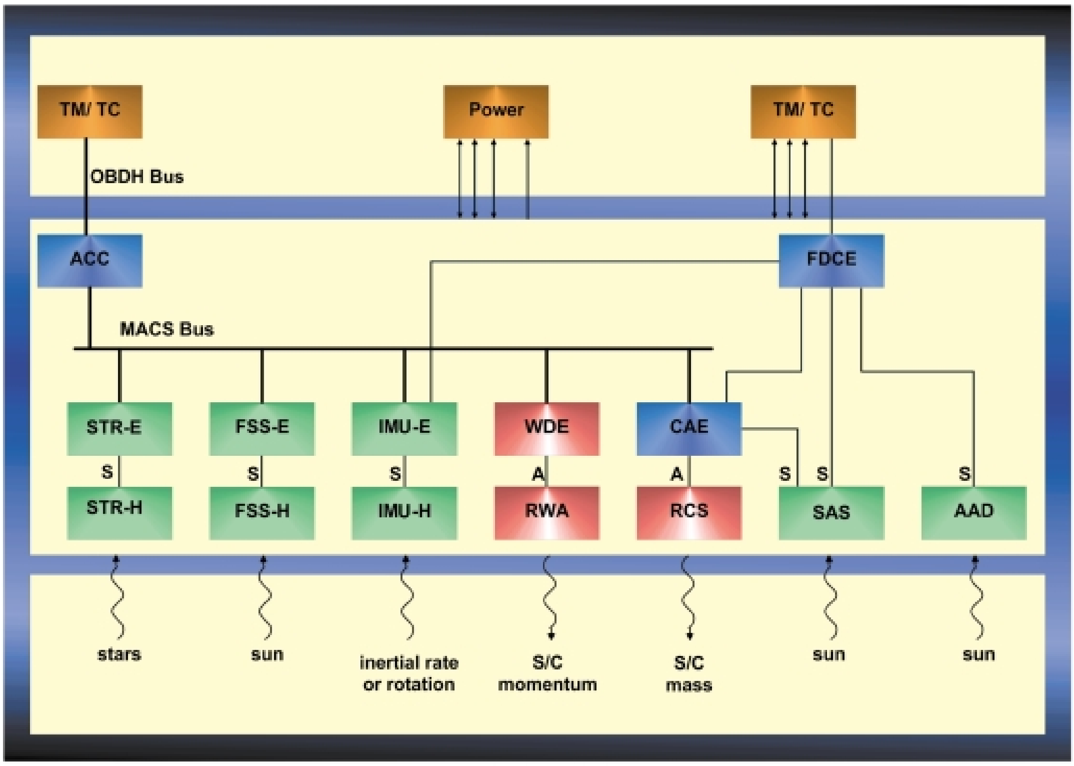


Figure 2. The constituent units of the AOCS

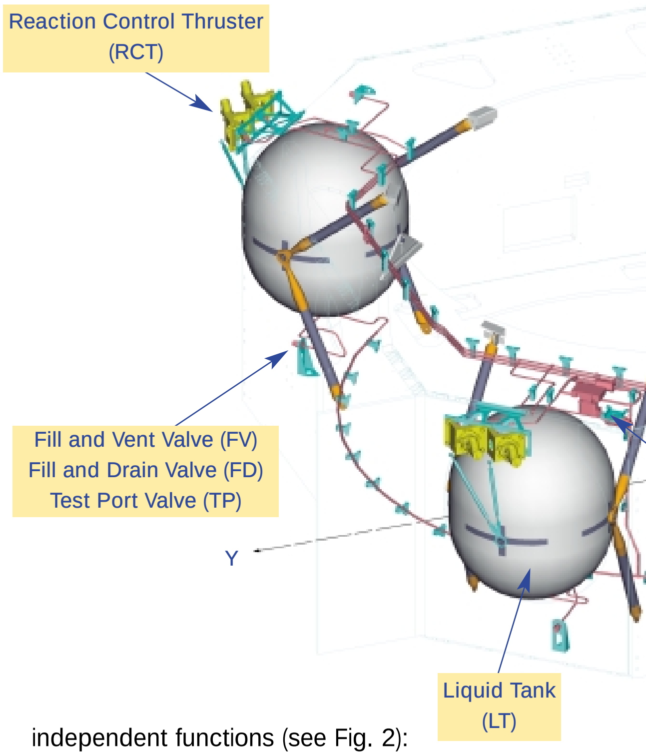


Figure 3. The constituent units of the RCS (courtesy DaimlerChrysler Aerospace)

will exist at the end of each slew. The size of this error is primarily driven by the uncertainty in the estimate of the spacecraft yaw inertia, with uncertainties in reaction-wheel inertia and mounting alignment as secondary contributors. For small slews within the field of view of the star tracker and for the correction of residual open-loop slew errors, measurements from the star tracker are used in addition to the Sun-sensor measurements to provide a closed-loop controlled slew about all three axes.

At regular intervals, typically twice per orbit, the spin rate of each reaction wheel will have to be adjusted, to avoid 'near-zero-speed' operation or speed saturation. The spacecraft is then commanded into thruster-control manoeuvre mode. This mode utilises the Control and Actuation Electronics (CAE) to command (in so-called 'on-modulation') the four thrusters of the propulsion subsystem whilst the reaction-wheel spin rates are changed. The minimum-opening-time limitation of the thrusters sets the limit to the residual spacecraft rates that can be controlled in this mode. To avoid the reaction wheels saturating in terms of torque, the thrusters are operated in a cross-firing mode just prior to transition to reaction-wheel control. To ensure that the wheels remain within their operational range also for ground outages of up to 36 hours, a so-called Autonomous Momentum Dumping (AMD) function is provided. As soon as the spin rate of a reaction wheel reaches its 'near-zero' or 'near-saturation' region, appropriate thruster pulses are fired in 'open loop' to restore the spin rate to the nominal region.

Delta-velocity injection

Delta-velocity manoeuvres will have to be performed at each apogee of the first three or four orbits of the mission. These are designed to increase the perigee altitude from 850 km in the injection orbit to 7000 km in the operational orbit. Also these manoeuvres are supported by the thruster-controlled manoeuvre mode, but here the thrusters are commanded in 'off-modulation'. Nominally all four thrusters are continuously firing, providing a total force of about 90 N along the telescope axis. The attitude control is super-imposed on top of the steady-state firing by means of short closure commands to individual thrusters. To ensure control stability, there is a smooth ramp-up and ramp-down transition between the on- and off-modulation stages.

Protecting against single failures

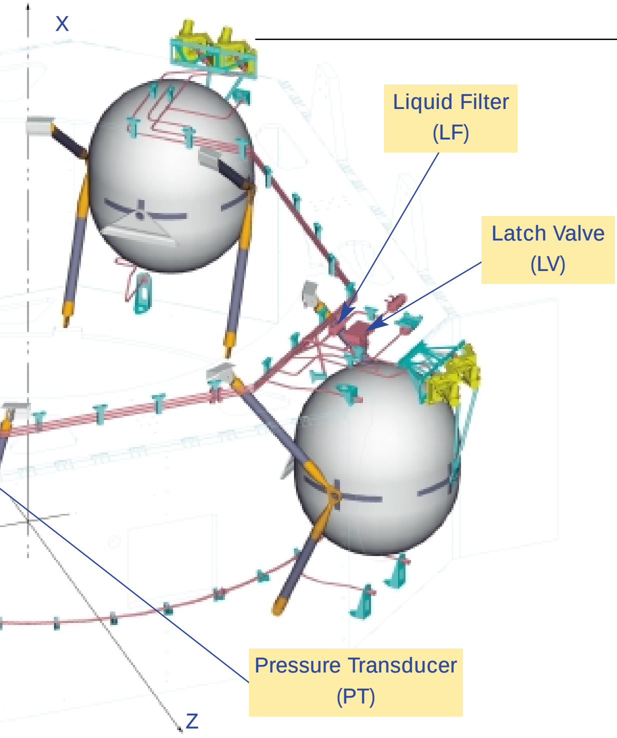
The requirement to guarantee that the telescope never points closer than 15 deg from the Sun regardless of any system failure or operator error is fulfilled by means of three independent functions (see Fig. 2):

– nominal control, implemented around the attitude control computer (ACC) and a set of sensors and actuators communicating through a digital bus (MACS)
– failure detection, implemented around the failure-detection electronics (FDE) and a set of sensors with point-to-point data exchange
– failure correction, implemented around the failure-correction electronics (FCE) and a set of sensors and actuators with point-to-point data exchange.

These three functions are implemented via independent hardware and software and commanded from the ground by independent telecommands to ensure that any single anomaly cannot propagate between the functions, and thereby ensure the telescope's safety. If, for example, a gyroscope used by the nominal control is faulty, the failure detection, which monitors the attitude or rate of the telescope through a different gyroscope, will in case of danger trigger the failure correction to restore a safe attitude.

'Gyro-lean' operations

XMM has four gyroscopes on-board, each providing integrated rate measurements about two axes. Apart from during the Launch and Early Operations Phase (LEOP), which will last approximately 10 days, and during eclipses, with a total duration of less than 2% of the total mission time, the spacecraft will not rely on any gyroscope information. As described above, the slew and on-modulated thruster manoeuvres are carefully designed not to require gyroscopes. During LEOP and eclipses, two gyroscopes are used for failure detection. In eclipse, the nominal control uses one channel of these gyroscopes for roll control. Throughout



the mission, two other gyroscopes are available in cold stand-by to be used by the safe-attitude controller in case of identified danger.

For the full mission lifetime of 10 years, the estimated in-orbit operating time for 'the most used' gyroscope is less than 1600 h and 700 on/off cycles. Each gyroscope is qualified for well over 4000 h and 4000 on/off cycles.

The Reaction Control Subsystem (RCS)

The RCS is a mono-propellant hydrazine system made entirely of titanium and operated in 'blow-down' mode. Its layout, shown in Figure 3, is characterised by four tanks and two branches, each with four thrusters, a pressure transducer, a liquid filter and an isolation latch valve. The tanks have a maximum capacity of 530 kg of N_2H_4 and the fuel expulsion is achieved through surface-tension techniques. Three of the tanks feed their fuel into the fourth main tank, which acts as the main supplier to the thrusters. The flow-control valve of each thruster has dual seats and is self-closing when electrical power is removed.

Subsystem verification

The functionality of XMM's AOCS has been verified by testing at all levels, i.e. unit, subsystem and spacecraft. Performances have been verified by testing at unit level and by analysis and simulation at subsystem and spacecraft level. The operational procedures have been verified by review at subsystem level and by testing at spacecraft level.

Functional 'closed-loop' testing

In order to test all of the functions of such a complex control system, there is a need to provide the sensors with representative stimuli, either electrically or optically. These stimuli must be a reflection of the dynamic spacecraft motion under the influence of the actuators. For this purpose, a dedicated test environment, the AOCS-SCOE, was constructed which performs the following main sequence of tasks 40 times per second:

- Monitoring of the drive-current requests to the reaction wheels and the thrusters, signals marked 'A' in Figure 2.
- Calculation of the dynamic motion of the spacecraft as a result of these drive requests.
- Translation of this motion into angles and angular rates relevant to each of the different sensors.
- Electrical stimulation of the respective sensor electronics, signals marked 'S' in Figure 2.

In addition, the test environment developed supports a powerful test language that enables repetitive execution of complex test scenarios. Telecommands can be called-up from the operational database and the test execution flow can be made dependent on the results of actual telemetry processing. A version of this test environment was used by the subsystem contractor for the subsystem function verification before delivery to the spacecraft. Figure 4 shows the subsystem tests in progress at Matra Marconi Space (UK) in Bristol with all AOCS flight hardware and flight-representative harnesses mounted on a test table. Later, a second version has been used by the spacecraft prime contractor to support subsystem integration onto the spacecraft and to verify functional integrity before and after various environmental tests. Finally, the test environment has also been extensively used for operational-procedure validation and to support System Validation Tests conducted by ESOC.

Schedule constraints and achievements

In line with the original schedule, the total time taken to design, procure, integrate and verify the AOCS as a subsystem has been 44 months. Three main phases can be distinguished; subsystem design and engineering-model unit procurement (23 months), electrical-model integration and testing (10 months), and flight-model integration and testing (11 months). A total of 88 hardware units have been produced, including 30 flight units and three types of units containing a considerable amount of software.

The main challenges in terms of unit procurement have been to ensure correct interpretation of the unit specifications, timely access to high-reliability EEE parts, and maintaining a continuous focus on schedule-critical tasks. Not surprisingly, the electrical-

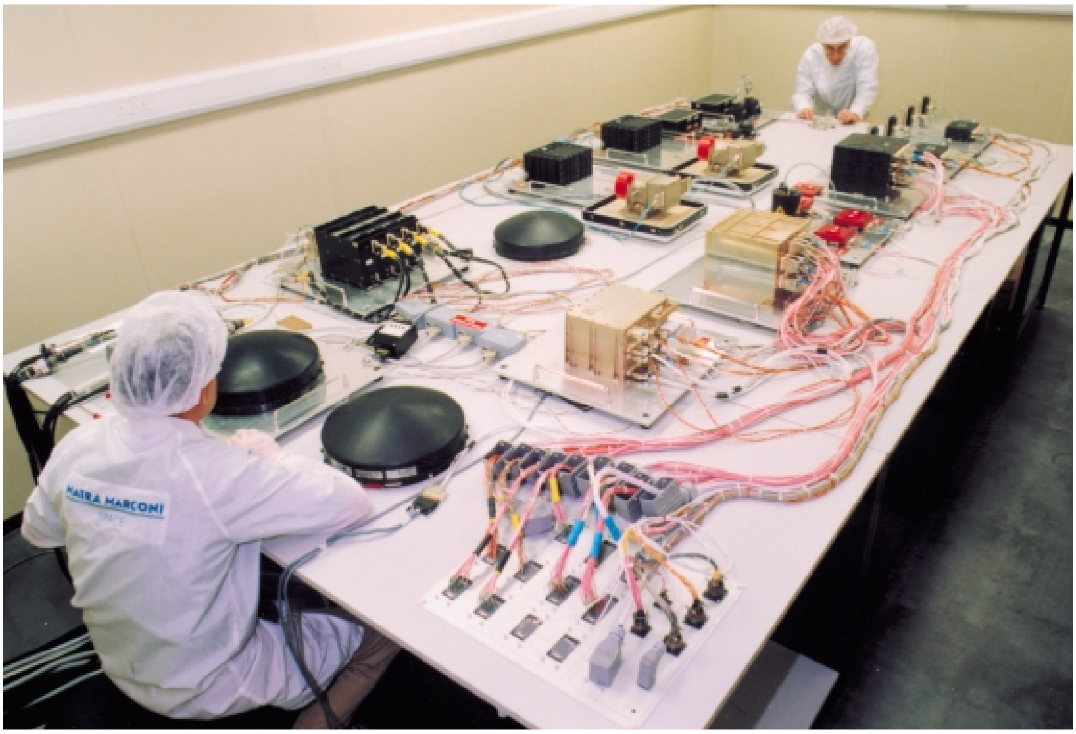


Figure 4. Subsystem testing in progress at Matra Marconi Space, in Bristol (UK)

model integration phase was characterised by 'debugging' of the electrical ground-support equipment (EGSE) to get it operationally stable, and the discovery of a number of short-comings in the on-board software logic. Ultimately, however, the flight-model integration and testing phase clearly demonstrated the completeness of the test coverage and confirmed the subsystem's functionality.

Knowledge transfer from design to operation

One lesson learned is the importance of early involvement of the ground operations team in the AOCS design and verification process, and in particular in the development of flight procedures. The concept of three independent functions for nominal operations, for failure detection and for failure correction relies on the ground segment ensuring a context-consistent configuration on-board. This is a demanding task for the ground segment and has been a focal point during the system verification tests and the mission-rehearsal campaign.

The importance of correct, consistent and complete documentation must not be underestimated. In a project of this size, the only effective means of ensuring adequate knowledge transfer is through proper documentation. This was particularly so in this case because the contractor's site in Bristol was closing during the flight-model delivery phase and access to many key engineers could not be maintained. The AOCS and RCS user manuals, comprising well over 200 documents, have been collected on a dedicated CD-ROM with full-text retrieval capability. Having all design and procedure documentation 'to hand' has been essential during the test campaign, and will be no less important during the launch campaign and LEOP phases.

Acknowledgement

The author would like to extend his gratitude to all personnel in the more than 16 companies who have contributed to the timely delivery, testing and launch readiness of the AOCS and RCS subsystems for XMM. Without detracting from the value of any individual's contribution, I would like to mention a few key colleagues by name: T. Strandberg of Dornier for his infinite energy in fulfilling his responsibilities as subsystem manager; A. Kolkmeier of Dornier, W. Holmes of SATASINT, and W. Davis of CAPTEC for their total, around-the-clock dedication to getting every aspect of the AOCS tested; R. Harris, D. Jukes and M. Backler of Matra Marconi Space (UK) for having conceived and flawlessly implemented a complex AOCS within an unprecedented short time; P. Henry, P. Chapman and M. Neal of Matra Marconi Space for their unselfish contributions in a difficult labour situation; B. Scheurenberg of Dornier for his eagerness to get a good propulsion system delivered on time; A. Schnorhk of ESTEC for his expertise and experience in every aspect of the propulsion system; J. Wohlfart of Dornier and C. Carnevale of Fiat Avio for getting the propulsion system through the CSG safety acceptance and safely fuelled; A. Ferretti of Fiat Avio for his well thought out propulsion system design and technical supervision of its suppliers.