The Integration and Testing of XMM

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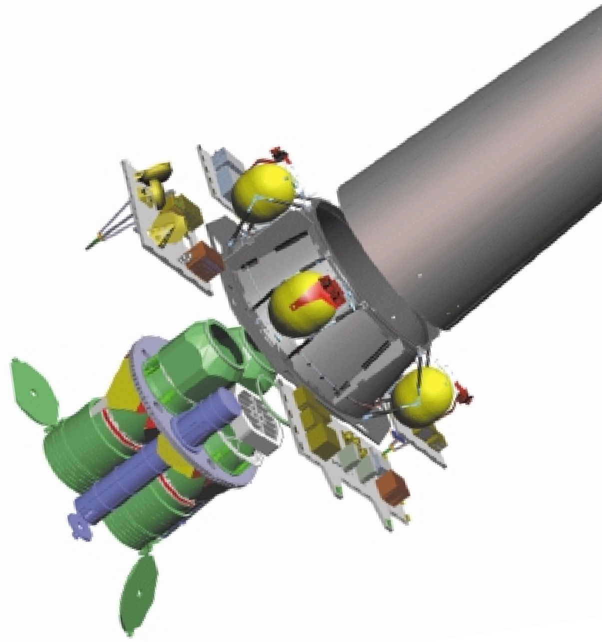
The XMM (X-ray Multi-Mirror) spacecraft, a spaceborne X-ray observatory to be launched by Ariane-5, stands 10 m high and measures over 4 m in diameter in launch configuration, for a launch mass of just under four tons. Such a tall spacecraft challenges the capabilities of existing European environmental testing facilities. Provisions were made in the design for a split according to geometry into an Upper Module and a Lower Module for environmental test purposes. Optical testing of the X-ray Mirror Modules – the core technological challenge – required the use of several existing and custom-built test facilities. In the face of strict schedule requirements, spacecraft-level test flows were organised around extensively parallel flows and all tests were scrutinised for their potential for early problem identification. This article briefly introduces the XMM configuration and schedule constraints, explains the spacecraft-level model philosophy, discusses the consequences for each category of test in terms of facility and test specimen configurations, and summarises the spacecraft test flows and the results achieved.

Configuration and schedule

The XMM satellite (Fig. 1) is configured in a modular manner, described in detail elsewhere in this issue. The Focal-Plane Assembly (FPA) can be fully integrated and tested independently from the Service Module (SVM). However, it is readily apparent that splitting the satellite into Service Module and Payload Module (PM) does not solve the problem of size limitations in environmental testing facilities, since the payload is distributed throughout the length of the spacecraft.

Furthermore, analysis determined that mechanical qualification of the SVM alone was unrealistic. The mechanical behaviour of the lower part of the spacecraft is largely determined by the presence of the three Mirror Modules (MMs), which together and with the two Reflection Grating Assemblies (RGAs) account for a mass of more than 1300 kg mounted into the Mirror Support Platform (MSP). Proper load introduction into the SVM from the MSP fully equipped with Mirror Modules is indispensable.



For environmental test purposes, the spacecraft is therefore split at roughly mid-height. This requires the introduction of an internal bolted interface between the Lower and Upper Telescope Tubes (LTT and UTT), but results in a configuration which lends itself to accommodation in the largest existing European test facilities, namely those at ESTEC.

The Lower Module (LM) consists of: SVM with MSP, Mirror Modules, RGA, Lower Telescope Tube and a closure plate. The Upper Module (UM) consists of FPA and Upper Telescope Tube.

The Lower Module and Upper Module dimensions are compatible with:
– the ESTEC Large Space Simulator solar beam size (6 m diameter) for thermal testing
– the ESTEC 280 kN electrodynamic shaker for vibration testing
– the ESTEC Mass Properties measurement machine with its latest L-4600 arm.

The fully assembled spacecraft is compatible with ESTEC's Large European Acoustic Test Facility (LEAF). Besides acoustic testing, the LEAF was also used to conduct a Modal

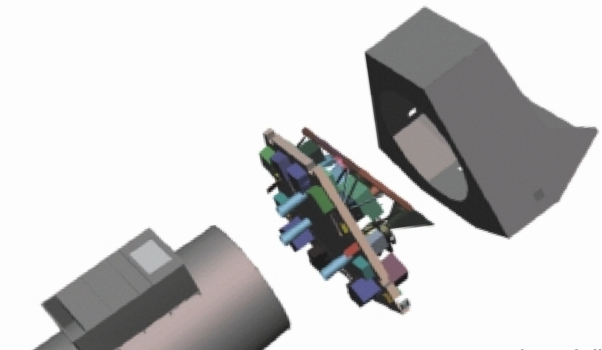


Figure 1. Exploded view of the XMM spacecraft. From top to bottom: FPA thermal tent, FPA with 3 EPIC cameras and 2 RGS cameras, Telescope Tube upper and lower parts, MSP with 3 Mirror Modules and Optical Monitor, SVM

Survey test on the fully assembled spacecraft. Also with XMM in fully assembled configuration in and close to the LEAF, fit-checks and a clamp-band release test were performed with the launch-vehicle adapter.

The spacecraft development schedule had to be compatible with delivery of the Flight Model experiments to the spacecraft in 1998 and with a budget-dictated duration imposing that launch take place no later than early-2000. Phase-B (preliminary design) was performed in 1995, Phase-C/D (detailed design, manufacturing and test) was initiated in March 1996. This translated into the obligation to perform the Structural and Thermal Model (STM) programme and Electrical Model (EM) programme in parallel, and to start the Proto-Flight Model (PFM) assembly before the end of the STM and EM programmes.

Spacecraft-level model philosophy

The Structural and Thermal Model was used to qualify by test the complete spacecraft primary structure and thermal design. The STM can be separated into Lower Module and Upper Module as described above, and the structural and thermal designs take into account the fact that the two are tested separately. The STM was also used to prove the LM-to-UM mating/de-mating procedures, verify the behaviour of the LM-to-UM interface, verify alignment and light-tightness design and test procedures, verify compatibility with the shock inputs, and exercise assembly and handling procedures and Mechanical Ground-Support Equipment.

The Electrical Model was used to verify the electrical design, internal interfaces, software, EMC/ESD, checkout procedures, and Electrical Ground-Support Equipment (EGSE). The EM units are flight-model representative in ‘form, fit and function’, but are not required to meet as stringent part-reliability standards as the flight units. The EM has no Telescope Tube and no Mirror Modules. The EM Focal-Plane Assembly and EM Service Module are each built around structures representative of the flight layout, so as to achieve good representation for EMC and harness layout.

As soon as their respective test programmes were completed, the STM and EM Service Modules were separated from the rest of their respective satellites and delivered for re-use to Integral, another ESA scientific satellite project that uses the same Service Module design.

The Proto-Flight Model is the actual satellite to be flown. The structural qualification had been acquired on the STM; the ‘Proto’ part of the name therefore concerns only limited electrical aspects and minor qualification gaps left by configuration changes. The PFM does not re-use any part of the STM nor EM models. However, because the flight Mirror Modules are extremely sensitive to contamination, testing of the PFM spacecraft was mostly carried out with the three STM Mirror Modules installed. This is possible because the STM Mirror Modules’ representativeness is excellent in all respects, except of course in terms of optical properties. The flight Mirror Modules were installed at the last mating of the two modules, after thermal and vibration tests and just before acoustic testing.

In addition, the RF Suitcase Model was provided to check RF compatibility between the spacecraft and the ground stations. The RF Suitcase re-uses parts of the EM (Central Data Management Unit and Transponder).

Test flows

All three test flows make use of the schedule optimisation made possible by the modular splitting of the spacecraft by conducting parallel testing whenever the two modules are not assembled together. For each of the three spacecraft models, integration of the Upper Module and Lower Module took place separately.

STM tests

Once the two modules of the Structural and Thermal Model (Fig. 2) were integrated, they were mated, aligned, submitted to light-tightness and alignment checks, de-mated, and shipped to ESTEC for environmental testing.

Each Module underwent, in turn, mass properties measurement, thermal-balance, and sine-vibration testing. The rest of the tests could be carried out on the complete spacecraft and therefore the Upper Module and Lower Module were mated and the assembled STM spacecraft underwent modal-survey testing, acoustic testing, clamp-band release (which also served as a spacecraft-level shock test), and a mechanisms functional test.

EM tests

Testing on the Electrical Model proceeded along with integration in the classical sequence, i.e. electrical integration tests (pin-to-pin, signal presence and shape) and Integrated System Tests (ISTs: all functionalities) were conducted after integration of each electronic unit and each major subsystem. After completion of the tests on both the Lower and Upper Modules, the two were linked by a harness representative of the harness running along the Telescope Tube in the PFM situation. Tests were conducted on the EM satellite to verify Electro-Magnetic Compatibility (EMC) behaviour, both radiated and conducted, and Electro-Static Discharge (ESD) behaviour, also both conducted and radiated. The software logic and code of all major subsystems were checked, exercised and debugged, including both open-loop and closed-loop testing of the Attitude and Orbit Control Subsystem (AOCS) and ISTs of the scientific experiments. The sophisticated Electrical Ground-Support Equipment was also put to the test, the architecture and interfaces between the core computer, the various items of front-end equipment, subsystem checkout computers and scientific instrument stations were exercised and their software debugged. After completion of the EM programme, those items not delivered to Integral as part of the EM Service Module were refurbished as Assembly, Integration and Verification (AIV) spares.

Figure 2. The XMM STM Lower Module (left) and Upper Module (right) at ESTEC

PFM tests

The Proto-Flight Model test flow generally followed the same principles as the STM and EM flows and combined them both. However, the PFM test flow was not a simple addition of the STM and EM test flows.

After completion of its integration along the mechanical and electrical integration procedures validated on STM and EM, the PFM Lower Module was tested for conducted and radiated EMC, then shipped to ESTEC where it first underwent sine vibration testing at acceptance levels in the axial (i.e. longitudinal) direction. Thermal tests (thermal balance, and thermal vacuum at acceptance temperature levels) in the ESTEC Large Space Simulator followed. The Lower Module was opened to permit the removal of several electronic units. They underwent minor modifications as a result of either component alerts or non-conformances, or hard-wired logic changes in the power subsystem decided upon after consideration of the lessons learnt from the recent in-orbit problems experienced by the joint ESA/NASA Solar and Heliospheric Observatory (SOHO). Other activities included the removal of one scientific experiment, the Optical Monitor telescope, to exchange the telescope optics for a higher-performance set; and to exchange, as scheduled, the STM Mirror Modules for the FM Mirror Modules. Exchange operations for the Optical Monitor and Mirror Modules took place in a Class-100 environment because of the sensitivity of the optics to contamination. After all flight units had been mechanically and electrically re-integrated, the Lower Module was mated to the Upper Module and the assembled spacecraft underwent acoustic testing.

The integration schedule for the PFM Upper Module was driven by the delivery schedules for the five focal-plane scientific cameras. The Upper Module went through conducted EMC and was shipped to ESTEC. For reasons of test-facility availability, it first went to thermal testing (thermal balance, and thermal vacuum at acceptance temperature levels) in the ESTEC Large Space Simulator. Mass properties, limited to weighing and determination of centre-of-gravity offset to the longitudinal axis, were measured. A sine vibration test in the lateral direction followed. Two electronic units were removed and were modified, for the same reasons as described for the Lower Module. Meanwhile, software debugging of the scientific cameras proceeded. The two modules were then mated, as described above.

Beyond the electrical integration tests and subsystem-specific Integrated System Tests, the PFM was submitted to functional testing between the major environmental tests and at major system milestones. To cut down on redundant testing, all flight procedures (both nominal and emergency) were distributed into six 'Spacecraft Functional and Performance Test' (SFPT) series that were used instead of specific functional tests. The potential risk was that tests before and after an environmental test or integration step were not always one-to-one identical, potentially making test-result comparison more difficult. All six SFPT series were run, and this drawback has not materialised; the few test deviations have been correctly diagnosed. The advantages of this approach are a significant time saving and the possibility to stagger the very labour-intensive preparation and verification of flight procedure software in an efficient manner. One of the SFPT series was run during thermal-balance/thermal-vacuum testing in addition to subsystem-specific ISTs.

Communication interfaces with the ground segment, located in this case at ESA's European Space Operations Centre (ESOC) in Darmstadt, Germany, were verified by use of the RF Suitcase Model, without having had to wait for completion of the PFM spacecraft. Communications were also checked at intervals by allowing the ground segment to listen-in on the PFM electrical testing being performed at ESTEC. These Listen-In Tests were followed by System Verification Tests (SVTs), i.e. full-fledged end-to-end (spacecraft-to-Mission Operations Centre) tests to exercise all telemetry and telecommand and all flight procedures.

Thermal testing

In total, four environmental spacecraft-level thermal tests were performed, all in the Large Space Simulator (LSS) at ESTEC, the largest solar-simulator facility in Europe: thermal-balance tests on the STM Upper and Lower Modules, and thermal-balance/thermal-vacuum tests on the PFM Upper and Lower Modules.

The purpose of the thermal-balance tests was to validate the thermal mathematical models and to verify the ability of the Thermal Control Subsystem to keep payloads and spacecraft equipment within specified temperature limits under simulated extreme expected orbital conditions. The Upper Module was mounted upright (as it will stand on top of the Ariane-5 launcher) inside the chamber. The Lower Module was 'upside-down', with the 2700 kg mass of the Service Module and Mirror Modules on top of the lower half of an extremely lightweight telescope tube. This unusual set-up (Fig. 3) offered the possibility of simulating very realistically the thermal environment of the bottom part of the spacecraft where the Mirror Module apertures had an unobstructed view to cold space. The correct simulation of the heat fluxes lost into space was of paramount importance for the verification of the temperatures and gradients of the Mirror Modules and the Mirror Support Platform. This would not have been possible if a more conventional mounting of the spacecraft by means of its launch-vehicle interface flange had been selected.

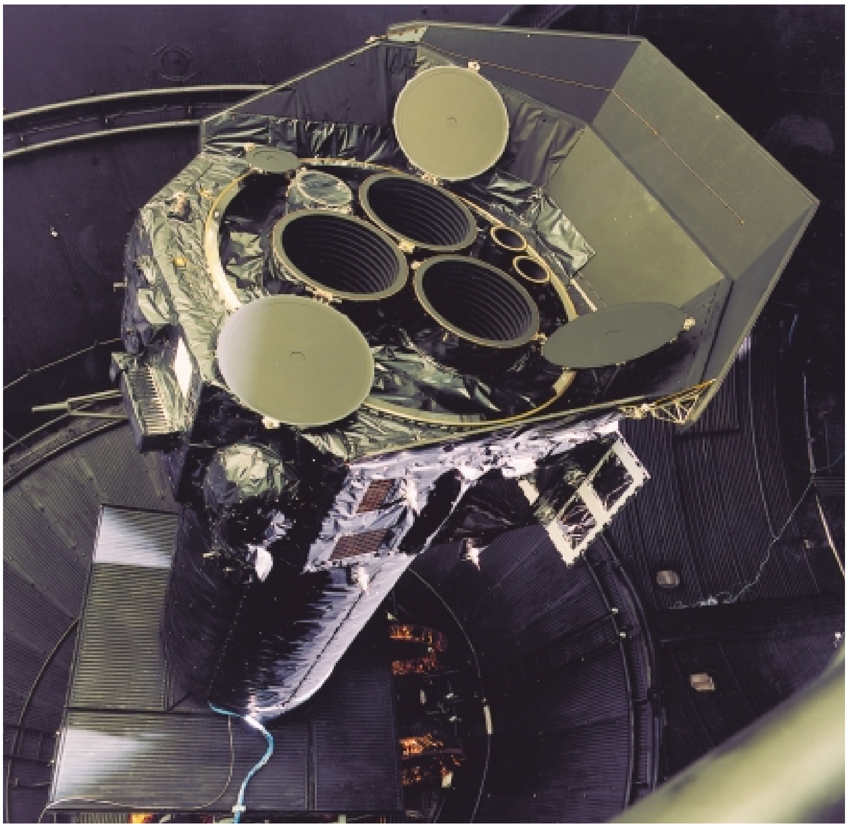


Figure 3. The XMM PFM Lower Module in the Large Space Simulator at ESTEC (January 1999). The Telescope Sun Shield is deployed. The three Mirror Module doors and the Optical Monitor door are open

Due to the architecture of XMM, it was simple to simulate the thermal interface provided by the missing spacecraft module. Because of the low thermal conductance of the long thin-walled Telescope Tube entirely made of carbon-fibre composite, the two modules cannot exchange heat by conduction. The flux exchanged by radiation was simulated by controlling the temperature of a plate inside the test adapter. The two modules were mounted by means of the same test adapter on the LSS gimbal stand, which provided the possibility of changing the spacecraft's attitude with respect to the solar beam direction as required by the simulation of the various orbital phases.

Because of the stringent cleanliness requirements imposed by the optics of the telescope system, a pure nitrogen purge line was located inside the test adapter and used for directly venting the interior of the telescope tube during the re-pressurisation phases. The cryo-panels inside the facility were used to trap contaminants. The STM thermal-balance test also had to verify the effectiveness of the cleanliness measures and procedures adopted in providing the cleanliness level required for the thermal-vacuum testing of the PFM spacecraft, which was then performed with the same set-up, configuration and adapter.

The objective of the PFM thermal-vacuum tests was to verify that the fully integrated spacecraft performed correctly in all operational modes at the expected extreme temperatures induced by the orbital conditions. In addition, some thermal-balance test phases were inserted into the thermal-vacuum programme in order to verify the Thermal Control Subsystem performance after minor modifications had been introduced between the STM design and the final FM design. For cleanliness reasons (even though eventually the cleanliness levels achieved were very good and well within contamination budget), the tests were carried out with the STM Mirror Modules installed in the PFM spacecraft Lower Module, instead of the Flight Model Mirror Modules. In addition to revealing the need for minor trimming of radiators and minor repairs to defective heater lines, the thermal tests have been fully successful in verifying the thermal-control performance and the thermal predictions.

Structural testing

Static strength tests

Strength verification of the primary structure was achieved by statically loading each of the major constituents (SVM central cone, SVM upper and lower platforms, upper and lower Telescope Tube) separately at their own level by their respective manufacturers, i.e. before system-level structural testing. These tests were performed at qualification levels on the STM elements, and at acceptance levels on the PFM elements.

Vibration tests

One test objective was to validate the structural mathematical models used to predict the spacecraft's behaviour during test and in flight as calculated by the Launch vehicle Dynamic Coupled Analysis. Another test objective was to provide proof-of-strength for those parts that did not see a strength verification beforehand, namely: Focal Plane Platform, Service Module equipment panels and their interfaces to the equipment, Focal Plane Assembly secondary structure, Service Module shear walls, Service Module secondary structures such as thruster brackets and Telescope Sun Shield (TSS).

In each of the three orthogonal axes, each STM module was sine-vibration tested following the classical sequence: low-level, intermediate level to define notch profiles, qualification level followed by low-level again in order to check that modal characteristics had not been affected by the tests.

Shaker input levels for the STM Upper Module could not be taken directly from the Ariane-5 User's Manual because of the transfer characteristics of the Lower Module. A system-level response analysis was run to determine these transfer characteristics and the resulting inputs from the Lower Module into the Upper Module at the interface between the Lower Telescope Tube and the Upper Telescope Tube. These levels were used as inputs for the Upper Module testing.

For the STM Lower Module testing, the input levels to be found in the Ariane-5 User's Manual were taken. Despite the absence of the Upper Module, the Lower Module has many modes corresponding to the complete system dynamics, so that a system-level notch profile could be established. This notch profile was acceptable also to the launch authorities.

The testing of both STM modules has demonstrated that the desired response levels have been reached at the resonances as foreseen.

For PFM acceptance testing, the levels were determined by first dividing the levels actually achieved during qualification on the STM by a factor of 1.25. Manual and automatic notch levels were then corrected down in two narrow frequency bands to account for possible shaker control overshoot, thereby making sure sensitive flight hardware was not endangered. The levels were then checked against the results of the Launch Vehicle Dynamic Coupled Analysis and it was verified that acceptance levels showed positive margins throughout the frequency spectrum. This conservative approach both ensured safety of the flight hardware and conserved significant margins to the flight environment, at the time known only as measured values on the first two Ariane-5 flights. Later, the results of measurements aboard the third Ariane-5 flight confirmed the suitability of this approach.

The PFM Lower Module (with about 80% of the total mass, the heavier of the two) was sine-vibration tested with input only in the longitudinal direction (Fig. 4). This saved significant test time and cost. This approach was possible because the successful experience acquired during STM qualification had drawn attention to the fact that cross-coupling alone was sufficient to induce the responses that would have been sought in a test with lateral input. Also, correlations of STM test results with mathematical test predictions were very good and provided confidence in the modelling. The modifications from STM to PFM were few and minor, except for one change of location for one of the two batteries; even this change was not significant at spacecraft level and the panel affected was tested separately to validate the change locally.

The PFM Upper Module was sine-vibration tested only with input in the lateral (z-axis) direction. The rationale was similar to that applied for the Lower Module, with the difference that the results of the Launch vehicle Coupled Dynamic Analysis show less substantial margins in lateral accelerations than in axial. It was therefore decided to test in the more critical lateral direction.

Modal survey

The modal-survey testing was performed on the STM spacecraft by a team from DLR-Göttingen (D). It has shown that the overall lateral mode corresponds very well with computer predictions (11.7 Hz measured, against 11.8 Hz calculated) and has confirmed the recurrence, on the complete spacecraft, of local Service Module modes as found in the Lower Module test. The objective of identifying below 100 Hz all modes with effective mass above 5% of the total mass has been met. This test has been rounded off with a so-called 'boosted' run in which high lateral inputs were given to the Focal Plane Platform such that response levels reached flight levels times a qualification factor. This dwell test at 11.7 Hz demonstrated the load capacity of the fully built-up central core in both lateral directions, as well as the stability of the first lateral resonance under increased loading. This also confirmed qualification of the Lower-to-Upper Module bolted interface.

The excellent results obtained from the STM Modal Survey, together with the fact that the changes from STM to PFM were minor and with the availability of sine-vibration results for both the PFM Lower and Upper Modules, led to a decision not to perform such a modal survey on the PFM spacecraft. The workmanship of the Lower-to-Upper Module interface was checked by inspection (the bolted flange is of a simple design) and by the acoustic test performed on the complete spacecraft.

Figure 4. The XMM PFM Lower Module during axial sine-vibration testing on the ESTEC 280 kN shaker (December 1998)

Acoustic testing

Acoustic testing particularly involved the structures with low mass per surface area such as the Telescope Sun Shield, Service Module upper and lower platforms, Telescope Tube and Focal-Plane Assembly secondary structures.

For STM qualification, dummies represented the solar arrays. Flight solar panels were submitted to separate acoustic tests. The Telescope Sun Shield had gone through an acoustic verification at unit level.

Responses at the level of the Service Module units were recorded for comparison with the unit-level specifications.

The Ariane-5 specified launch environment (plus 4 dB qualification margin for the STM test) determines the qualification and acceptance test levels. Additional STM qualification runs were performed to solve facility control questions, to assess margins available and to take into consideration the acoustic environment measured on the first two Ariane-5 launches. The maxima measured in each octave on the two flights were taken as flight environment plus margins for uncertainty and for qualification. This approach was thus conservative, but realistic in view of flight experience. Compared to the Ariane-5 User's Manual, it led to an increase of several dBs in the low frequency bands, but also to a substantial decrease in the high-frequency bands, where the original User's Manual specification was unnecessarily constraining. The launch-vehicle authority also welcomed this approach, since it adequately covered all concerns about uncertainties above the User's Manual specification in the low frequency bands.

This STM spacecraft-level acoustic-test series was successful in demonstrating qualification of the structure and also in identifying those units for which more unit-level qualification data had to be acquired, which was subsequently done.

For PFM spacecraft acceptance, the acoustic test was performed on the complete PFM spacecraft, including FM solar arrays and Telescope Sun Shield, with the same realistic spectrum, but of course without the addition of the 4 dB qualification margin.

Adapter fit-check and clamp-band release
An Arianespace team performed this test, with the complete STM spacecraft clamped to its launch-vehicle adapter. After a fit-check with the adapter, it involved the pyrotechnic release of the 2624 mm-diameter clamp band. One objective was to prove correct fit to the adapter including accessories (e.g. clamp band, clamp-band extractors and catchers, umbilical connectors, purge ports, release springs, separation switches). Another objective was to demonstrate the feasibility of mating the Telescope Sun Shield to the spacecraft after clamp-band installation and to show proper clamp-band release without interference with any part of the spacecraft, including the Sun Shield. A third objective was to measure the shock levels induced by the clamp-band pyrotechnic release on both sides of the separation plane and further at selected equipment levels. Subsequently, a release of the Telescope Sun Shield was performed to verify proper functioning of its deployment mechanism, even after clamp-band release shock and under adverse thermal gradients. This series of STM qualification tests was completely successful and the results gave rise to no particular concerns.

Shock testing had been performed at unit level, on EQM of FM units as determined on a case-by-case basis, on all those units of the Lower Module for which susceptibility to shock could not be excluded simply by design. Upper Module units are located too far from the launch-vehicle interface to be of any concern.

For PFM spacecraft acceptance, another fit-check with the flight adapter was performed. A pyrotechnic clamp-band release on the PFM was not performed, since all of the useful information that it could provide had been successfully gathered during the STM test*.

Physical checks
Mass properties
The mass, the Centre of Gravity (CoG) and Moments of Inertia (MoI) of both the Lower and Upper Modules (separately) were measured on the STM spacecraft along all three axes. These measurements agreed very well with the predictions.

For PFM acceptance, the mass, CoG location in the horizontal plane and MoI around the longitudinal axis of both Lower and Upper Modules (separately) were measured. This was just to double-check that no gross error had slipped into the calculations and to correct the inevitable small errors due to, for example, test harnesses or minor equipment exchanges. This kept the test configuration simple. Values around the other two axes, while much more cumbersome and costly to measure, need not be known with high accuracy. The STM testing had sufficiently validated the prediction of their value.

Alignment and light-tightness
At regular intervals between STM satellite tests, checks have verified that the spacecraft was able to maintain full integrity, alignment and light tightness – which are crucial to the scientific mission – throughout the gruelling qualification environment (Fig. 5). Custom-designed equipment was built to meet the size, configuration and accuracy requirements of XMM, for both the alignment and the light-tightness measurements.

Between major environmental steps, alignment and light-tightness were checked on the PFM spacecraft in accordance with the procedures verified during STM qualification. Because of the excellent performance of the structure, the checks were somewhat less extensive than on the STM. The major alignment activity consisted of positioning the five scientific cameras located at the telescope focal plane, while taking into account the measured characteristics of the Mirror Modules and

* To account for uncertainties concerning the frequency spectrum and level of shocks imparted by Ariane-5 during the flight, a thorough complementary unit-level shock analysis and test programme was conducted on EQM units in parallel with the launch campaign, as a double-check.

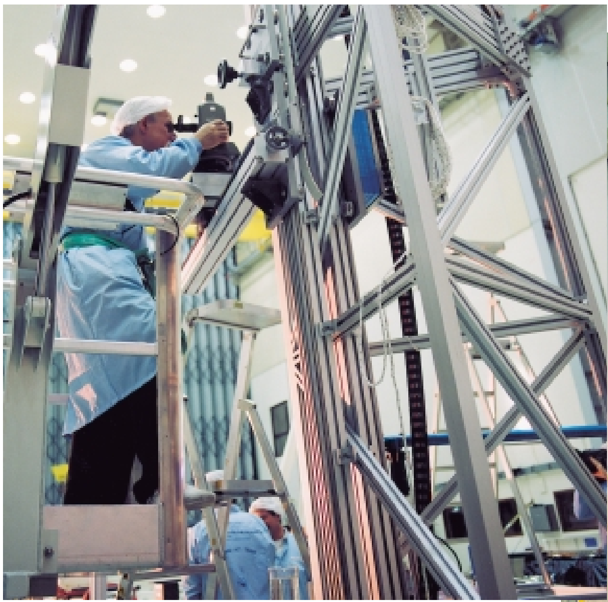


Figure 5. The STM XMM spacecraft assembled on the alignment rotary table. The alignment stand is on the right

Reflection Grating Assemblies. This was done at the time of the mating of the two satellite modules to form the assembled spacecraft, with the actual flight-model Mirror Modules installed.

The accuracies required are only millimetric, but the large size of the spacecraft and the criticality of the positioning – and its stability – for the scientific mission make the time-consuming and delicate alignment activities critical for PFM acceptance. Light-tightness of the telescope is similarly critical, since even minute amounts of stray light would blind the exquisitely sensitive CCD detectors of the experiment cameras, which are able to count X-ray photons one by one and are not completely insensitive to visible light.

EMC testing

All units were fully EMC tested, radiative and conductive, for emissions and for susceptibility. XMM is not a particularly difficult satellite EMC-wise, as it does not carry very powerful sources. The results from unit-level tests had shown considerably wider margins than the required 6 dB between worst-case emissions and susceptibility. However, because of spacecraft size, just as for environmental testing, full-fledged EMC testing in an anechoic chamber would have been next to impossible for the complete satellite, at least if cleanliness requirements were to be observed. It would still have been very cumbersome even if performed on the two separate modules. Nevertheless, self-compatibility and compliance with the launch-vehicle radiative environment had to be demonstrated.

The active electronics are located on the Focal-Plane Assembly and Service Module. The Telescope Tube along which the harness is strapped holds the FPA and SVM about 7 m apart. In electromagnetic terms, the active electronics represent EMC sources, while the interconnecting harness acts like an antenna. Additionally, the parallel routing of different signal cabling could be susceptible to cross-talk. On the other hand, radiated coupling between the Focal-Plane Assembly and the Service Module is minimal.

On the EM satellite, the Lower and Upper Modules were connected by a harness. Conducted emissions and susceptibility were checked. Electrostatic discharges were tested, first conducted (which uncovered malfunctions on two units, later corrected) and then radiated. Radiated emissions and radiated susceptibility were then measured.

All of these tests, even the radiated ones, were performed in a clean room and not in an anechoic chamber. This was only possible because the environment had been measured and verified to be quiet and because the test was performed during the evenings, with little activity around. Despite the very low limit imposed by the launch-vehicle compatibility requirements in the critical 420–480 MHz band, the influence of ambient noise was demonstrated to be small enough to obtain clear and positive results. This is indeed true provided the measurements are performed in a sufficiently narrow bandwidth, i.e. 100 kHz as required by the Ariane-5 User's Manual. Compliance is also made easier by the fact that during launch few units are on, namely the batteries, main supply bus and regulation equipment and telecommand receivers. Susceptibility testing also took into account the relatively high field strength measured at the launch base and originating from various sources other than the launch vehicle itself.

For the PFM testing, the Electrical Model approach was reproduced and even simplified somewhat. For schedule and configurations reasons, it was impractical to perform the tests on the assembled satellite because it would have meant putting off the EMC tests until the end of the programme. For the purposes of acceptance, and in view of the good results obtained on the EM plus good knowledge of all equipment from unit-level tests, PFM tests were carried out separately on the two modules. In addition, to take into account the requirement to verify radiated emissions towards the launch vehicle, the PFM Lower Module radiated EMC test was carried out on the Lower Module equipped with the Telescope Tube harness and the two FPA units that will be powered during launch preparations. These are the FPA Remote Terminal Unit (RTU) for data handling, and the FPA Power Distribution Unit (PDU) for power. Similarity to the behaviour observed on the EM was confirmed for both modules. The measured radiated emissions comply with the launch-vehicle requirements. Performing the measurements in the usual clean room at quiet times again provided usable results at a comparatively low cost.

ESD testing would have been risky on the flight model; it could have caused inadvertent failures or reductions of lifetime. Therefore ESD testing was not performed on the PFM.

Mirror module testing

The core of the XMM X-ray focussing optics is made up of three highly nested Wolter-1 grazing-incidence X-ray telescopes. They provide a large photon collecting area: each 1420 cm^2 at 1.5 keV and 600 cm^2 at 8 keV. Their spatial resolution is better than 16 arcsec. To obtain such an area and resolution while still keeping the mass reasonable, it was necessary to develop the technology for manufacturing thin mirror shells, assembling them into telescopes, called Mirror Modules (Fig. 6) in this context, without loss of performance, testing them thoroughly, and assembling them into a spacecraft while keeping contamination low so as to avoid performance degradation.

It was soon realised that a large amount of Mirror Module testing had to be performed. The 'Panter' X-ray facility at the Max Planck Institute (MPE) in Neuried, Germany, was available to XMM. However, several aspects pleaded for the creation of a new test facility. In addition to the sheer amount of testing of the Mirror Modules that was needed, the Panter facility was to be used for testing the scientific cameras of XMM. The fact that the Mirror Modules tested at Panter had to be in the horizontal position was not insignificant for such thin mirror shells, so parasitic gravity effects could not be excluded. Most important

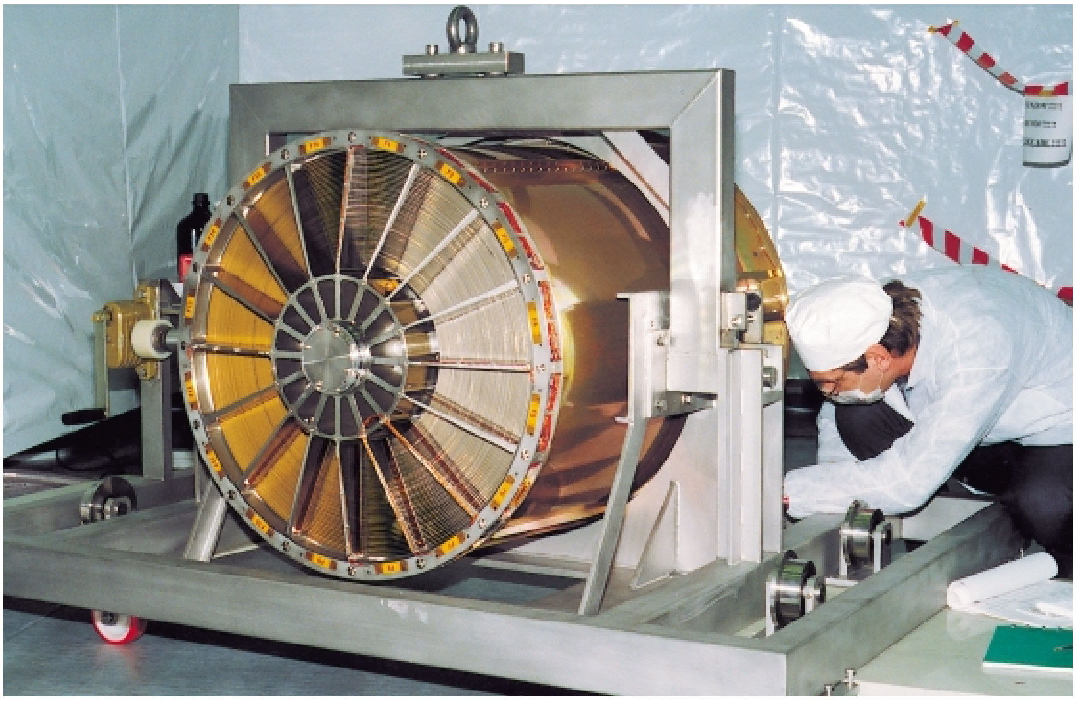


Figure 6. An XMM Mirror Module

Figure 7. The XMM PFM spacecraft assembled and attached to the container chassis before closure of the container lid

for the measurement of optical performance, a third of the mirror shell surface could not physically be properly illuminated because of the slight divergence of the X-ray beam. The XMM Project Office therefore decided in 1994 to complement the Panter facility by building a custom-designed, vertical facility equipped with an 800-mm EUV collimator and two thin X-ray beams, specially adapted to the dimensions of the XMM Mirror Modules. This facility, called 'Focal-X', is located at Centre Spatial de Liège (CSL), in Belgium.

Nine Mirror Modules have been tested at the Panter facility and at CSL since the completion of Focal-X in 1996: one Qualification, three Structural and Thermal, and five Flight models. Each Mirror Module underwent a sequence of optical tests (EUV full illumination image quality, X-ray local measurements of reflectivity and scattering). Specific tests in Focal-X investigated stray-light characteristics for sources close (up to 7 deg) to the field of view. To validate the stray-light modelling of the telescope, stray-light characteristics at higher angles were measured on two Mirror Modules (one of them equipped with its Reflection Grating Assembly) in a custom-built test set-up at a Daimler-Benz Aerospace facility in Ottobrunn, Germany. At CSL, the sequence continued with sine and random vibration tests on the CSL shaker, thermal-vacuum tests in another CSL vacuum chamber, and final optical tests according to a sequence similar to the first one. For the STM Mirror Modules, the optical tests were of course omitted, but the environmental tests cleared them for further use in the spacecraft-level test programme as described above. They also trained staff, procedures and equipment in advance of the delicate testing of the Flight Models. After the second Flight Model, the test sequence was optimised to take advantage of the learning curve achieved. The optical checks in-between vibration and thermal tests were omitted, some image quality checks were speeded up, the number of time-consuming X-ray reflectivity check points was decreased, and the number of thermal cycles was reduced from 6 to 3. On the other hand, extra test sequences were added to verify the behaviour and performance of the Mirror Modules equipped with their X-ray baffles and, for two of them, with their Reflection Grating Assembly. All Mirror Modules passed the tests and demonstrated consistently better-than-specified performance. The testing also provided the mass properties and alignment values (focal length, orientation of optical axis) needed for the PFM spacecraft alignment activities. Since XMM carries three Mirror Modules, two FM Mirror Modules are full-performance flight spares.

Onwards to launch

The spacecraft launch-preparation campaign is a continuation of the integration and test activities. In this respect, operations such as the assembly of appendages, battery charging,

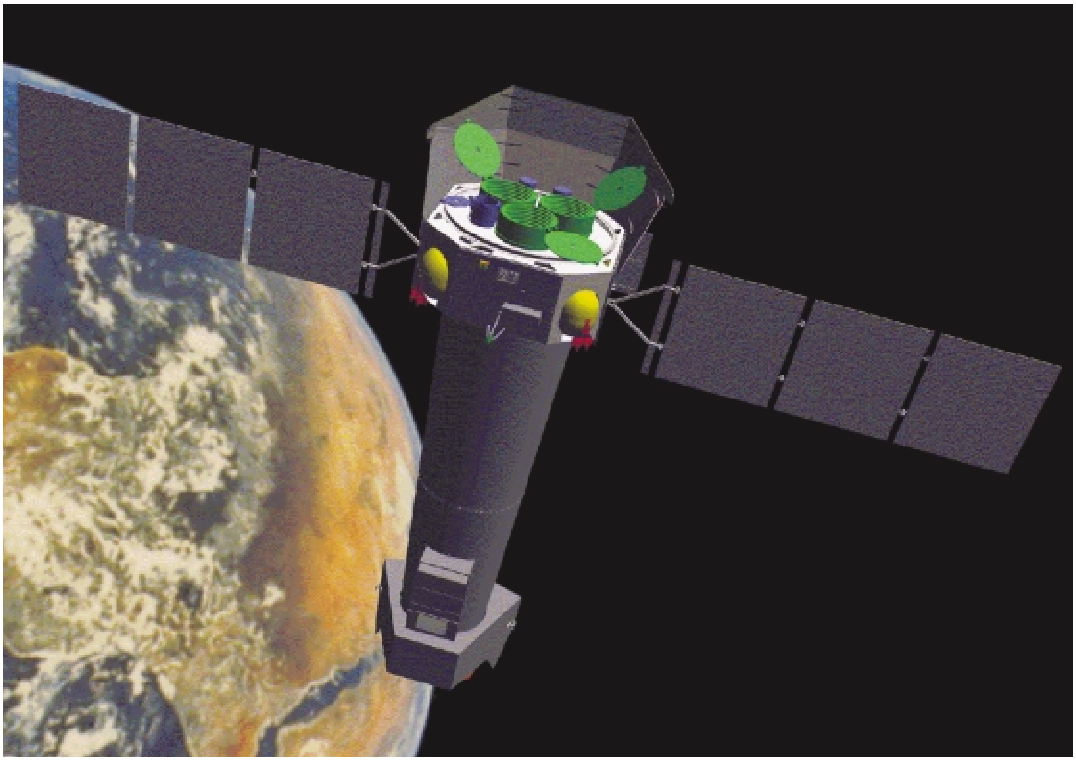


Figure 8. XMM in flight configuration (artist's impression)

virtually all electrical checkout, alignment stability check, light-tightness check, and camera door checks have been performed just as they were performed during PFM acceptance. The complete end-to-end telecommand and telemetry chain from the Control Centre at ESOC to the spacecraft has been exercised during a System Validation Test, similar to those performed when the spacecraft was still at ESTEC. However, a number of operations have novel aspects:

– The complete spacecraft was transported in one piece (Lower and Upper Module assembled; Fig. 7) to the launch site in one very large container, whereas all previous transportations were in three parts, each in their own container. The spacecraft and its ancillary equipment were transported by sea on a ship that also carried Ariane launch-vehicle stages, parts and equipment from Europe to French Guiana.
– The Reaction Control System tanks are for the first time fuelled with real hydrazine, rather than the water that was used once on the STM spacecraft and twice on the PFM spacecraft to fill the tanks before the vibration and acoustic tests.
– The second flight battery has been installed (one was already installed in the spacecraft before shipment).
– The Telescope Sun Shield has been installed on the spacecraft *after* mating of the spacecraft to the launch vehicle, to allow access to the adapter and clamp band.

The eleven-week launch-preparation campaign is scheduled to lead to the spacecraft's launch in December 1999 and commissioning in early 2000 (Fig. 8).

Conclusion

Large spacecraft such as XMM stretch or surpass the capabilities of existing environmental test facilities in Europe. The XMM test programme has combined testing on the complete spacecraft wherever possible with modular testing where unavoidable. It has made optimal use of existing test facilities for both environmental and electrical testing. While full-illumination, collimated, end-to-end optical tests on the complete satellite at X-ray energies in representative flight conditions was not possible, a combination of optical and alignment tests at Mirror Module level, scientific-camera level and spacecraft level has come as close as possible to an end-to-end verification. This has permitted satisfactory qualification and acceptance and has been possible thanks to the favourable split into modules taken into account from the beginning of the XMM design process.

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