Mechanical and Thermal Design of XMM

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The XMM spacecraft has a conventional structure and thermal design. Due to the long focal length of the telescopes (7.5 m), the mirrors are far removed from the instruments. On the ground and during the launch, the structure has to maintain the integrity of the whole spacecraft. The thermal control does not make use of onboard software. In orbit, the functions of the structure and the thermal control are mixed. Their global common requirement is to relate and align the set of mirrors at one end of the spacecraft with the set of instruments at the other.

Some parts of the instruments will be kept at cryogenic temperatures, but most of the spacecraft will be kept at about room temperature. It is the task of the thermal control to maintain these diverse requirements by passive and active means. Under inevitably varying thermal conditions, the structure has to stay very 'straight'.

Introduction

Once the scientific requirements (and goals) for a spacecraft are set, the system-level requirements follow. A global configuration is then selected that would, in principle, allow the realisation of the spacecraft within these constraints. So far, the constraints are mainly geometrical. The satellite should fit in a launcher, the (focal) distance between optics and detectors should be respected, mechanisms should be moving in the right direction, etc. At this early stage, the structural elements have no real size and the thermal-control elements have no real performance specifications. However, both for structural elements and for thermal-control elements, there is from the start a mass-allocation not to be exceeded. Geometrical constraints and functional requirements lead to an iterative design process that takes into account the realisation of such elements in real hardware. However, the design process gets more complex due to the fact that structural and thermal-control functions are completely coupled. In addition, the thermal control is strongly coupled to the power subsystem. This often makes it difficult to single out the constraints and requirements for the individual subsystems.

Structural design constraints and requirements

The spacecraft structure, like any other structure, is there primarily to guarantee the integrity of the spacecraft under any loading, such as during handling, testing and launch. In addition, it must allow the spacecraft to serve as an optical bench for a telescope and therefore the structure must provide the necessary thermo-elastic stability in orbit. In the case of XMM, this led immediately to the selection of ultra-high-modulus carbon-fibre composites (low thermal expansion) for the main structural elements. Another advantage of this material is its very high modulus of elasticity, which limits structural mass for a structure like this, which is (also) designed for stiffness.

These two favourable qualities of this carbon-fibre material, plus its low mass, have led to its widespread use on XMM, albeit for different reasons in different parts. For instance, for the telescope tube and the mirror support platform, a carbon-fibre composite was necessary for thermo-elastic reasons. A strongly directional lay-up made it possible to meet the requirements, whereas the mass could be kept low. On the other hand, for the central cone of the Service Module, the stiffness required was the main reason for using a carbon-fibre composite.

In complex items, such as the mirror support platform, the joints that are necessarily made out of metal degraded the intended high thermo-elastic stability to such a level that active thermal control was necessary. Here, a carbon-fibre composite had been selected for its high stiffness and strength. Other parts outside the optical path were made of aluminium for reasons of thermal conductivity (honeycomb for Service Module side panels), light-tightness and ease of production (telescope Sun shield, outgassing baffle).

In order to meet the system-level requirements, such as thermo-elastic stability or stiffness for minimum structural resonance frequencies, a system analysis (budget) was performed, from which subsystem apportionments could be made. This was, in particular, needed for those requirements where a number of parts or subsystems contribute. Margins were added to the subsystem apportionments in order to account for uncertainties and interferences of the interfaces.

Mechanical environment

The XMM structure is sized mainly against the launch environment. Only dedicated pick-up points are sized for ground handling and transportation loads.

The launch environment can be subdivided into the following elements:

a. launcher (quasi-static) acceleration loads – necessary to reach orbit
b. launcher dynamic loads – caused by solid-booster ignition, passage through zones of high winds and engine-thrust termination (both solid boosters and liquid stage)
c. launcher-separation shocks
d. acoustic pressure – mainly caused by engine noise reflecting from the ground.

As design parameters, (quasi-static) acceleration and dynamic loads are combined to form worst-case scenarios, and taken as static loads for sizing purposes. The dynamic component of the loading is amplified in the spacecraft and the result taken into account in the dimensioning. For XMM, the amplification in the lateral direction was particularly important. An interesting case has been the lift-off (booster ignition), where the maximum lateral acceleration is about 0.4g at the lower interface of the spacecraft and about 4.5 g at the top of the spacecraft.

The highest axial amplification occurs at the end-of-thrust phase of the booster. The lower interface of the spacecraft 'sees' 0.44g, whereas important masses such as the mirror modules and the focal plane are subjected to 1.1g. In this case, the quasi-static acceleration of 3.8g is more important.

For the Ariane-5 launcher, the shocks due to the separation of the payload shroud and the liquid upper stage from the rest of the launcher are more severe than the shocks due to the (classical) clamp-band separation. Ground tests have demonstrated that the higher level is not critical for the structure, and therefore it was not applied as a dimensioning criterion.

Acoustic pressure from Ariane-5 is high in the low-frequency range. This strongly loads the structures with low mass density (mass per unit area). The telescope Sun shield is a good example of such a case. For the main structure, this type of environment has not been critical.

The in-orbit environment was characterised by the low accelerations coming from the attitude control system. For the main structure, these accelerations are never critical, but the dynamic inputs from the reaction wheels may affect telescope performance. However, this jitter turned out not to be critical.

Structural qualification

The size of the spacecraft prevented a classical system-level approach in the structural qualification programme. A splitting into an upper and a lower module was a logical choice; it splits the telescope tube into two parts. The elements of each module were to be tested separately before integration. This was done by the element supplier to a level that integrity was sufficiently demonstrated. In this way, the risks of module-level testing would be minimised. Of course, mechanical and thermal analysis were performed beforehand, to show adequate de-coupling between modules and to confirm the validity of the modular approach.

The telescope tube was a special case in this sequence, since it contained the boundary between the two modules. In order to prove the integrity of the complete tube, it was loaded in its assembled state. An important aspect of the mechanical testing of these parts was the load level. This was selected to be well above the level to be expected in flight, because most of the parts were sized against stiffness requirements. This meant that in many areas the material thickness was larger than necessary to meet the strength requirements. This margin was exploited by increasing the load levels above the official initial flight loads. Later changes in expected flight loads, coming from module-level testing and updated launcher coupled-load analysis, could thus be absorbed without hardware changes.

Primary structural parts, such as the telescope tube, the tank support struts and the service module cone, were subjected to relatively simple static load tests prior to their delivery for integration into the spacecraft system. These were, of course, worst cases selected from a multitude of loading combinations. Items carrying a lot of equipment did not lend themselves to such simple tests. They were sufficiently over-designed to safely undergo and pass the module-level dynamic tests later in the programme. Such items were typically the focal-plane platform and Service Module side panels.

The telescope Sun shield, as a large and lightly-loaded structure, was a special case. It was felt that dynamic and acoustic loading of the shield was necessary at parts level, because of its complex nature and because of the need to verify its flawless deployment after loading.

Module-level dynamic testing was the next activity, in which shaker limitations were of interest. This was particularly the case for the lower module, due to its high mass (about 3100 kg). However, the modular testing did not prevent the application of loads on the internal interfaces between various equipment items. Of special interest here was the dynamic interaction between the large masses, such as the Mirror Modules, the Optical Monitor and the Service Module side panels full of equipment. Upper Module testing provided sufficient focal-plane loading (not previously tested) and allowed the verification of the cameras, the equipment and the interface with the telescope tube. Finally, the two modules were brought together for modal-survey and acoustic testing at system level.

The modal-survey test was extended with a 'boosted' test to verify the overall stiffness and strength of the telescope tube internal and external interfaces. Even after a loading up to about 1.6 times the flight load, the telescope tube did not show any anomalies.

Acoustic testing was performed to demonstrate overall structural integrity and alignment stability against this type of environment. The light labyrinth of the telescope Sun shield showed (repairable) damage. Additionally, the random vibration responses of equipment, resulting from the acoustic testing, were compared with the corresponding qualification levels. The result was an exceeding of the random qualification level for ten units, all on the side panels of the Service Module with relatively low-mass density. Nine units were successfully re-qualified. For the reaction wheels, a detailed analysis showed that the critical parts (bearings) had not been overloaded during the system-level acoustic test.

A new situation originated from the high shock loading defined for the launcher interface (see above). It was clear that a classical clamp-band release test (which was nevertheless performed) would not produce the required environment. Since no test hardware was available to do an adequate system-level shock test, it was already decided earlier in the programme to perform shock testing at equipment level. Previous system-level tests of Ariane for Cluster had produced equipment-level responses that would be relevant for XMM. The equipment-level responses were enveloped and integrated into the unit-level specifications. All equipment items that contain sensitive parts and those that are close to the launch interface were tested to this specification. A so-called 'ringing plate' test setup was used and no failures occurred.

Mission thermal constraints

The thermal control of XMM must fulfil two basic requirements: it must keep equipment and payload within the required temperature ranges, and it must provide a stable and uniform temperature of the telescope system when scientific observations are performed. The precise geometry and alignment of a telescope system imposes very strict and demanding temperature requirements, so that not only do temperature gradients have to be kept to a minimum, but also, and more importantly, variations of the gradients over time have to be minimised.

In particular, the mirror shells of the Mirror Modules have to be kept at an average temperature of 20°C, with spatial maximum temperature differences of ± 2°C in order to limit thermo-elastic deformations. The three Mirror Modules are mounted on the Mirror Support Platform, which also carries the Optical Monitor and the two star trackers. The optical boresights of all of these instruments have been carefully aligned on the ground and, in order to maintain that alignment, thermal distortions of the platform have to be minimised. Therefore, the platform is maintained almost isothermal, with deviations of less than ± 2°C. On the other hand, the Service Module equipment presents quite standard temperature ranges and attention is therefore mainly paid to simplicity and reliability.

Orbital thermal environment

The thermal design of XMM takes full advantage of the stable environment provided by its high-altitude, long-period orbit and by the limited variation of solar attitude angles that it will experience during observation phases (± 20° pitch combined with ± 20° roll). In fact, the Earth albedo and infrared heat fluxes are negligible along the largest part of its high-altitude orbit. Only at perigee passes, when the altitude reduces to 7000 km, will XMM’s thermal stability be slightly affected by the influence of the Earth.

The largest thermal perturbations occur during the eclipse seasons, when the satellite does not receive the Sun’s energy for a maximum period of 1.7 h (although, on average, the eclipses are much shorter). However, eclipses always occur below the minimum altitude that is required for observation (40 000 km), leaving time for the spacecraft to recover its temperature stability. Boost heating performed before and after the eclipses by means of heaters helps to reduce the time needed for recovery of the temperature drop caused by eclipses.

In order to cope with all orbital perturbations and with changes of satellite attitude, the telescope tube is completely insulated from the external environment and the heater power that is dissipated inside it can be almost continuously adjusted to compensate for changes.

Overall thermal-control approach

The XMM satellite relies on a combination of passive and active means of thermal control. The passive thermal control is mainly achieved by using classical highly-insulating multi-layer blankets. Typically, blankets are made internally of 20 double-sided aluminised layers separated by Dacron nets. The external layer of all blankets is made of carbon-loaded kapton, which gives the satellite its characteristic black appearance. This kind of kapton has been chosen because of its electrical conductivity, which avoids electrostatic-discharge problems. In addition, the thermo-optical properties of the black finish will not change during the satellite's ten-year lifetime, helping again to maintain temperature stability.

The thermal blankets of the telescope tube and of the hydrazine tanks have the additional task of acting as bumper shields against micro-meteoroid impacts. For this, they are kept at a distance of 2 cm from the structure by means of special spacers.

Telescope tube (Fig. 1)

The insulation performance that has been achieved by the XMM blankets is exceptionally good, especially for the large, undisturbed blankets that insulate the telescope tube. Together with the black lining of its internal surface, they keep the temperature gradient across the tube diameter small and stable. In fact, the measured temperature difference across the tube was only 3°C. The telescope tube is not equipped with heaters and its temperature control is purely passive.

Focal-plane assembly compartment (Fig. 2)

The focal-plane assembly compartment, located on top of the telescope tube and which contains the payload cameras, is controlled during operations in a totally passive way. This is made possible by the power dissipated by the instruments, which remains fairly constant during the mission observation periods. Consequently, the compartment's heat losses are trimmed such that the dissipated power (about 150 W) can keep the temperatures at the required level. Whenever an instrument chain is switched off, an appropriate ‘substitution’ heater line is switched on in order to replace the missing dissipated power and keep the heat power balance constant. In non-operative and emergency modes, mechanical thermostats will switch these heaters if the temperature falls close to the non-operation temperature limits of the equipment.

Figure 1. Insulated telescope tube

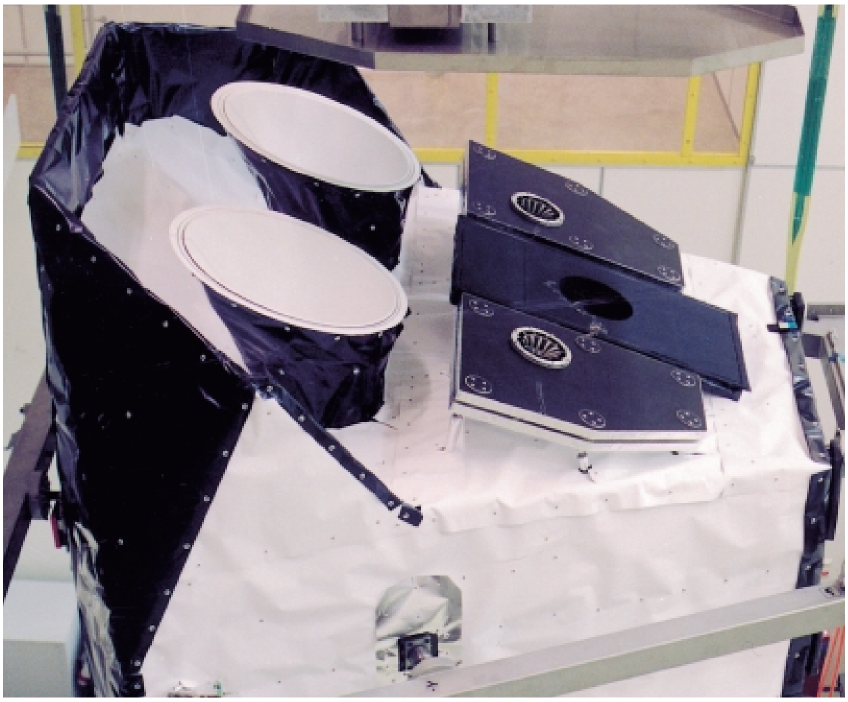

Figure 2. The focal-plane assembly compartment houses the payload cameras. Temperatures are passively controlled by the power dissipated by the instruments

The external shape of the focal-plane assembly compartment minimises the variation of Sun input, caused by changes in attitude of the satellite with respect to the Sun. In fact, the side surfaces and the top plane are canted 20° away from the Sun, so that they are always in shadow. The illuminated face is fully blanketed and acts as a Sun shade. The white-painted areas function as ‘foil radiators’ through which the heat can leave the compartment. Black and aluminium stripes are applied on their internal side, in order to calibrate their thermal impedance. The five camera radiators are connected by means of ‘cold fingers’ to the camera detectors to cool down detectors to cryogenic temperatures. Detectors can be heated by using local camera heaters.

Service Module (Fig. 3)

The Service Module, at the other end of the telescope tube, is also fully blanketed with the exception of panel radiators. On the Sun-side they are covered by mirror solar reflectors, while those on the anti-Sun side of the satellite are painted white. Where passive measures are not sufficient to meet the temperature requirements, heaters controlled by thermostats are implemented. No on-board software is used to activate and control heaters. Ground control can configure the heater lines to be powered, while mechanical thermostats perform the actual heater switching. In a typical mission observation phase, about 330 W are dissipated by the equipment and 80 W are provided by the heaters to maintain an internal average temperature of 15°C.

Mirror Modules and mirror support platform (Fig. 4)

The heaters used for fine temperature control of the Mirror Modules and the mirror support platform are powered by the ‘Mirror Thermal Control Unit’ (MTCU). The MTCU pulse-modulates the current of the heaters according to duty-cycle values stored in its memory. The ground station updates the duty-cycle values when necessary. This kind of control is possible due to the large thermal inertia of the mirrors,

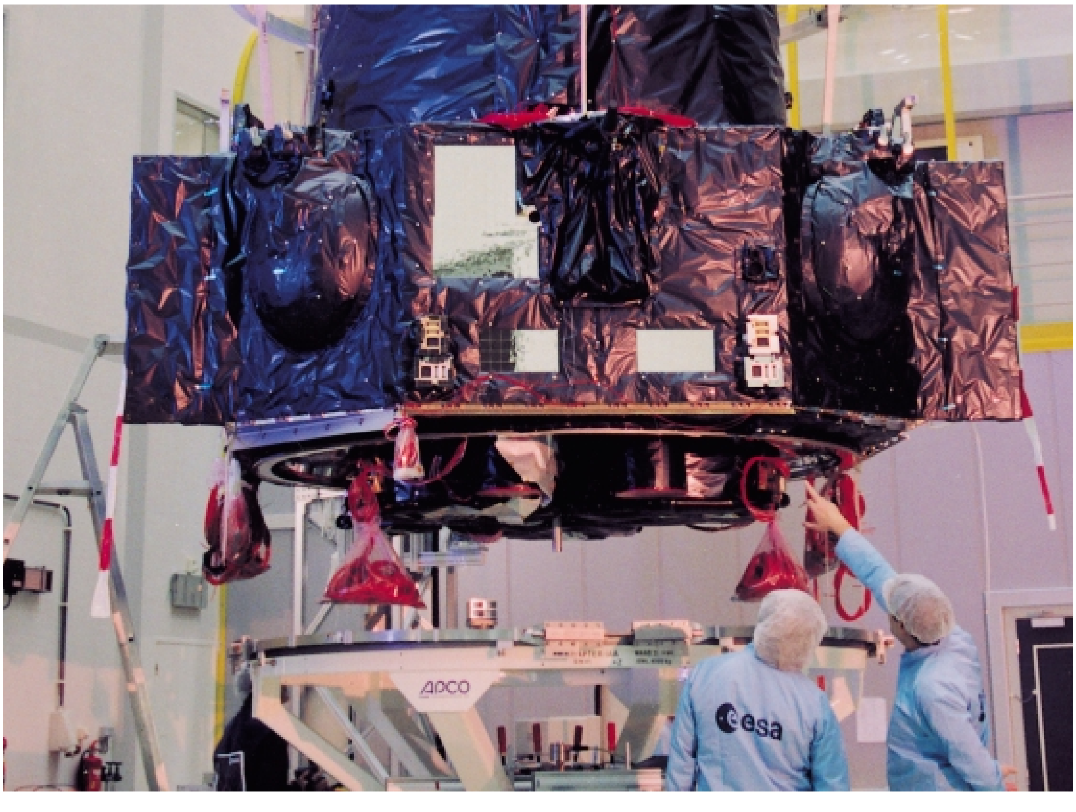

Figure 3. On the Service Module ground control configures heater lines, while mechanical thermostats perform heater switching

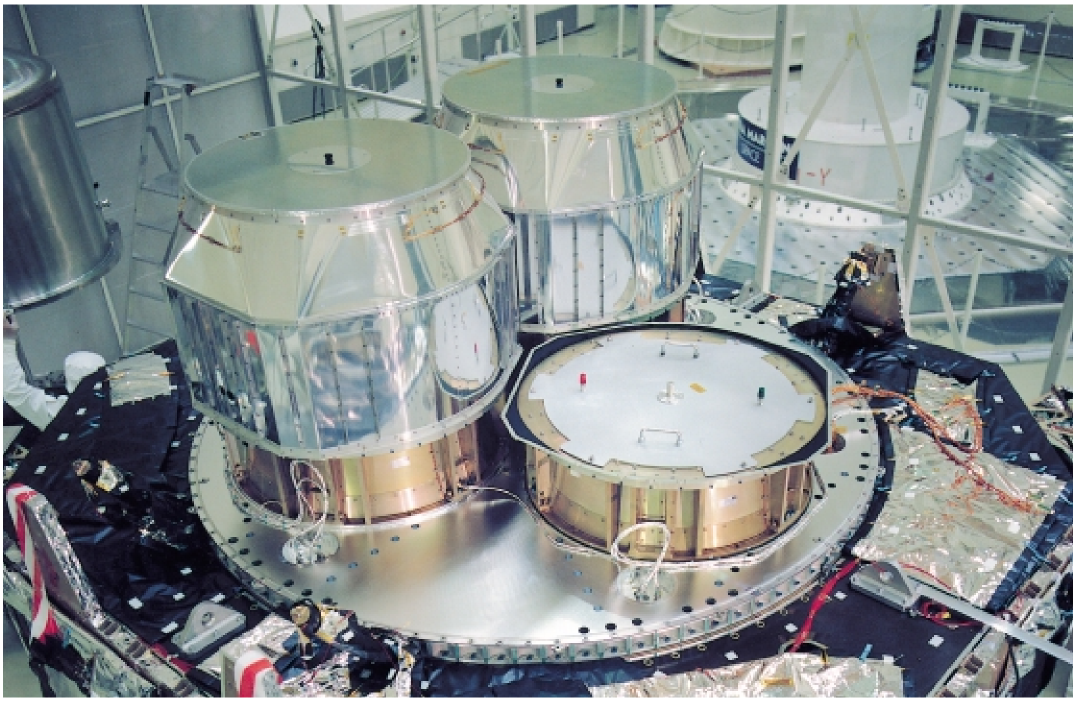

Figure 4. The heaters used for fine temperature control of the Mirror Modules and the mirror support platform are powered by the 'Mirror Thermal Control Unit'

the environmental stability of the orbit, and because all observations, for which strict temperature control is required, are always performed under ground control. A pulse-modulation cycle of 1 min allows adjustment of the heater power with a very fine resolution.

Each Mirror Module is thermally insulated from its surroundings and exchanges heat through its entry baffle to space and through its exit baffle to the telescope tube's interior. In order to compensate for the heat lost to space, each module is equipped with pulse-modulated heaters that can deliver up to 100 W. Also, the exit baffles are equipped with pulse-modulated heaters for the compensation of heat lost into the telescope tube. The exit baffle also has the task of thermally controlling the high-precision grating assemblies that need to be kept at 20°C with virtually no spatial temperature gradients. The heat radiated into the telescope-tube cavity keeps the tube at the right temperature level (between 15° and 20°C). The mirror support platform is completely covered by pulse-modulated heaters that can deliver up to 85 W of power. The various heater lines are individually set in order to avoid thermal distortion and to keep the boresight lines of the Mirror Modules, optical monitor and star trackers parallel with each other. The platform also ensures that the Mirror Modules are correctly aligned with the cameras.

Autonomy and failure management

The functioning of XMM's thermal-control subsystem has been designed such that it does not depend on any information from other subsystems. Each function can tolerate a single fault without the need for on-board failure management software, and any failure can be withstood for a maximum period of ground-station outage of 36 h. Each function can be performed by a nominal or by a redundant heater line powered by separate power-distribution units. The nominal and redundant lines of all essential heaters are powered throughout the mission, so that in the event of malfunctioning of the nominal line, the redundant one can automatically take over (triggered by thermostats or by the MTCU).

Verification of the thermal control

The thermal-control design was validated by means of a Sun-simulation thermal-balance test performed on the structural-thermal model of the satellite. The test was conducted in the Large Space Simulator (LSS) at ESTEC. Despite its large dimensions, the LSS facility could not accommodate the complete XMM satellite, which was therefore split into two modules that were tested separately. This modular approach was advantageous from a thermal point of view because it allowed testing of the lower module with the Mirror Module apertures correctly exposed to space (see also ESA Bulletin No. 94, May 1998). In addition, it was demonstrated by analysis that the interaction between the modules is small and well defined. The test allowed the validation of the thermal mathematical models used to design the thermal-control system and to identify its deficiencies. After trimming and final correction of the thermal design, a second thermal-balance test was performed during the thermal-vacuum system test on the flight model which ultimately confirmed the thermal design.