# The Pointing and Alignment of XMM

**A. Elfving & G. Bagnasco**
XMM Project, ESA Directorate for Scientific Programmes,
ESTEC, Noordwijk, The Netherlands

**The pointing and alignment performance of the XMM spacecraft will have a very strong influence on the quality of the scientific results obtainable. The pre-launch unit and subsystem tests and subsequent analyses have shown that the scientific requirements will indeed be met with comfortable margins and the performance goals will be met for more than 90% of all anticipated observations.**

### XMM's optical system

The exploded view of the XMM spacecraft shown in Figure 1 identifies the main elements of the optical system*. Three Mirror Modules (MM-1, 2 and 3), equipped with two Reflecting Grating Assemblies (RGA-1 and 2), and the self-contained Optical Monitor (OM) are mounted at the heart of the spacecraft. The optical system is completed by five Charge Coupled Device (CCD) detector cameras, of which three (EPCH and EMCH-2 and 3) are placed at the 'primary focus' of the respective Mirror Modules. The remaining two cameras (RFC-1 and 2) are suitably positioned at a 'secondary focus' on the imaginary 'Rowland circle', where the spectrum created by the two grating assemblies can be collected.

* More detailed descriptions of the Scientific Instruments and the Mirror Modules on-board XMM can be found on pages 21 and 30 of this Bulletin.

### Requirements and goals

*Pointing*

The pointing requirements originate from the scientists and have been thoroughly defined and negotiated between the Project and the instrument Principal Investigators early in XMM's design phase (Phase-B). Since a stringent pointing requirement is a direct cost driver, it was decided to split the scientists' demands into:

– requirements, which make the mission worthwhile, and

– goals, which would enable each instrument to achieve its ultimate performance.

The requirements must still be fulfilled by the spacecraft under all worst-case conditions, for example at end-of-life and immediately after an eclipse or a slew manoeuvre. The goals, on the other hand, may only be fulfilled under certain conditions but then for the majority of the observation time, e.g. a bright guide star.

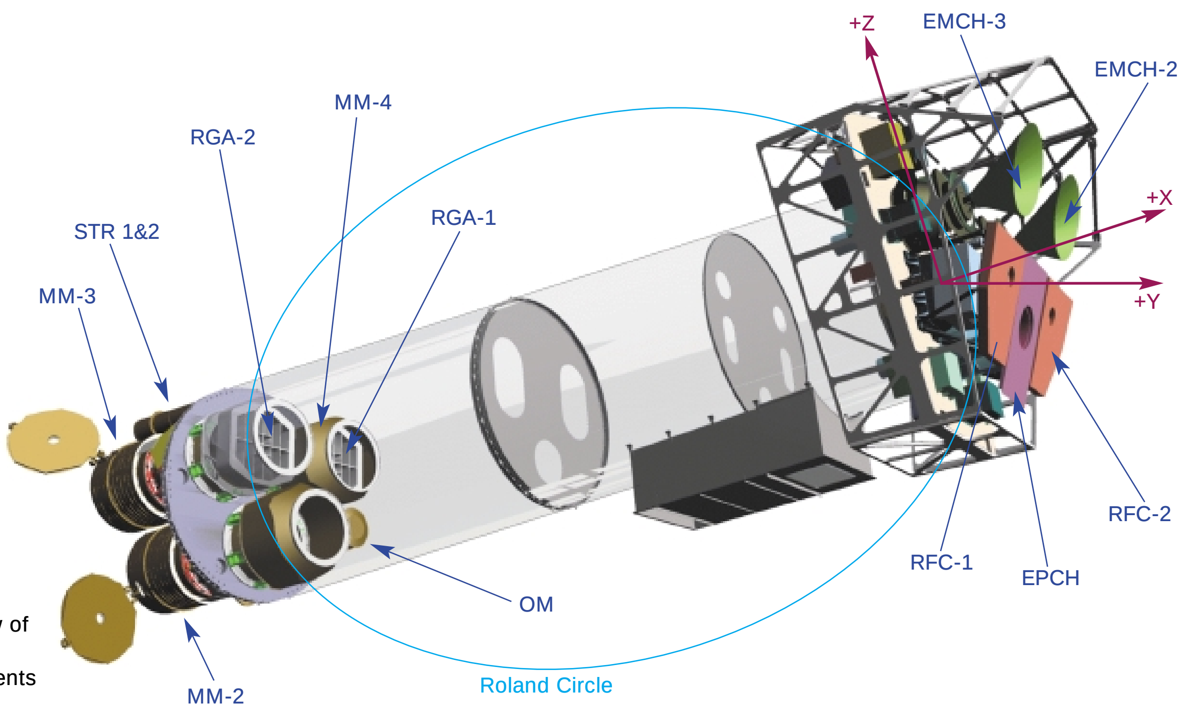


Figure 1. Exploded view of the XMM spacecraft, showing the main elements of the optical system

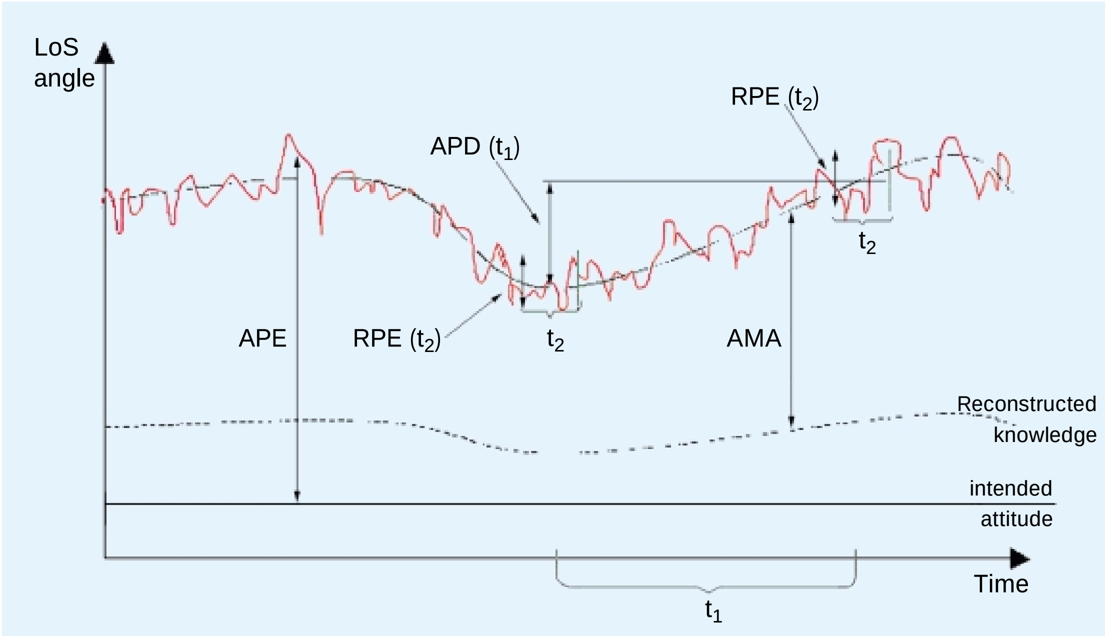


Figure 2. Pointing definitions for XMM's instruments

There are typically four requirements that are of particular interest to the scientists (Fig. 2):

*The Absolute Pointing Error (APE),* defined as the angular separation between the actual direction and the intended telescope line-of-sight. The APE must be such that the image of the observed target will fall onto the instrument detector. Since all of the instrument detectors on XMM are relatively large, being at least ~6 arcmin, in practice this requirement is not very stringent.

*The Absolute Measurement Accuracy (AMA),* defined as the angular separation between the actual direction and the reconstructed (a posteriori) direction of the telescope. The RGS instrument, and to some extent also the EPIC instrument, uses the location of a photon event on the CCD relative to the observed target as an indication of the energy of the photon. The AMA is therefore a very important performance parameter to allow the investigator to accurately reconstruct the energy spectrum of an X-ray source.

*Table 1. Instrument pointing requirements and goals*

| *Instrument* | *EPIC* | *RGS* | *OM* |
|---|---|---|---|
| APE | | | |
| Req. | 60 | 60 | 60 |
| Goal | - | - | - |
| AMA | | | |
| Req. | 10 | 10 | 10 |
| Goal | 1 | 4 | - |
| APD | | | |
| Req. | 45 | 45 | 45 |
| Goal | - | 2 | - |
| RPE | | | |
| Req. | 5 | 5 | 5 |
| Goal | 1 (5 sec) | 2 (30 sec) | 0.25 (10 sec) |

*The Absolute Pointing Drift over 16 hours (APD),* defined as the change in the angular separation between the actual direction and the intended direction of the telescope over the observation time. The APD is an indication of how well data from individual exposures can be superimposed without further processing in order to establish an integrated image. For XMM, images are superimposed a posteriori, on-board for the OM instrument and on the ground for RGS and EPIC, and thus the APD requirement is not too stringent.

*The Relative Pointing Error over 2 minutes (RPE),* defined as the angular separation between the actual direction of an axis and a reference axis, over the instrument exposure time. The allowed magnitude of RPE is usually defined as less than half of the instrument angular resolution, in order to ensure that the exposure is not 'blurred' by the instrument/spacecraft motion. The RPE requirement for the OM is very stringent, since this instrument has very high resolution in the visible/UV spectrum, ~1 arcsec.

The applicable pointing requirements and goals for each instrument's line of sight in arcseconds at 95% confidence level are shown in Table 1.

*Alignment*

In the case of alignment as well, thorough negotiation with the scientists has led to the definition of the relevant payload requirements, driven by the characteristics of the XMM optical system.

The alignment requirements for each EPIC 'primary focus' camera are expressed in terms of its maximum allowed translation and rotation with respect to the Mirror Module focus position and bore-sight. Because of the long Mirror Module focal length (7.5 m), its focal depth, which is a measure of the sensitivity of the optics to de-focussing, is of the order of several millimetres. Such insensitivity, combined with CCD detector dimensions of the order of several centimetres, led to maximum allowed translation and rotation requirements of the order of some millimetres and arcminutes, respectively.

Somewhat more complex has been the definition of the alignment requirements in the case of the 'secondary focus' RGS CCD cameras combined with the grating assemblies, mounted on the Mirror Modules. In order to minimise optical aberrations for this 'three-body' optical configuration, it is required that the three units involved - MM, RGA and RFC - lie on an imaginary 6.7 m-diameter 'Rowland circle'. Consequently, a careful apportionment of the alignment requirements had to be established early in the programme.

Another important consequence of the 7.5 m distance between the X-ray mirrors and the CCD cameras is that related to the stability requirements imposed on the structure in-between, which in the case of RGS camera, for example, must be <0.1 mm over 16 hours and <0.2 mm over 3 months.

## Analysis and Verification

*Pointing and alignment budget*

Having defined the requirements and goals applicable to each instrument, an exhaustive pointing and alignment budget was established. The initial use of this budget was to make error allocations to the relevant subsystems, i.e. structure, thermal, AOCS, instruments, AIV alignment and ground processing. It became apparent that there are two dominating error contributors to the challenging measurement accuracy (AMA) goals:

– the thermo-elastic stability between the star trackers and the Mirror Modules and between the latter and the focal-plane cameras, and
– the star position-determination accuracy of the star tracker, i.e. the bias error.

To achieve the short-term pointing stability (RPE) goals, it is essential to reduce the following two effects as much as possible:
– the measurement noise of the star tracker
– the micro-vibrations originating from subtle imbalances or imperfections within the reaction wheels.

After a first round of error-budget iterations, the requirement and goal type of specifications were again carried forward into the subsystem and unit specifications, to obtain the best price/performance procurement.

*Pointing verification*

The pointing verification process has been based on a combination of analysis, simulations and direct testing of the actual performances of the most critical contributors, namely:

– bias and noise performance measurements of the star tracker
– micro-vibration measurements of the reaction wheels
– thermal gradient test of the mirror support platform and of the telescope tube
– telescope-tube characterisation by deflection measurements under an imposed temperature gradient.

As an example, Table 2 shows the specifications and actual performance of the star tracker.

*Calibration campaign and alignment verification*

An end-to-end test of the complete XMM spacecraft in order to check the X-ray performances and the correct alignment of all the elements is not possible due to its sheer dimensions. For this reason, already before the start of Phase-B, the alignment-related Assembly, Integration and Verification (AIV) strategy was developed along two main directions, with the aim of avoiding 'late surprises' during the spacecraft alignment. It was decided to:

– carry out an extensive characterisation of the Mirror Modules, both in stand-alone configuration and in integrated configuration together with the grating assembly. Such a calibration campaign allowed the verification at an early stage in the programme that the main parameters of the optical system were within the allocated alignment budget, i.e. the focal length and the 'Rowland circle' diameter

*Table 2. Star-tracker specifications and performances*

| *Error type* | *Requirement end-of-life* | *Measured begin.-of-life* | *Estimated end-of-life* |
|---|---|---|---|
| Bias (2 σ, in arcsec) | 3.5 | 1.5 | 1.5 |
| Noise (1 σ, in arcsec): | | | |
| Magnitude 8.5 | 2.5 | 1.5 | 1.6 |
| Magnitude 6.5 | 2.5 | 0.3 | 0.3 |

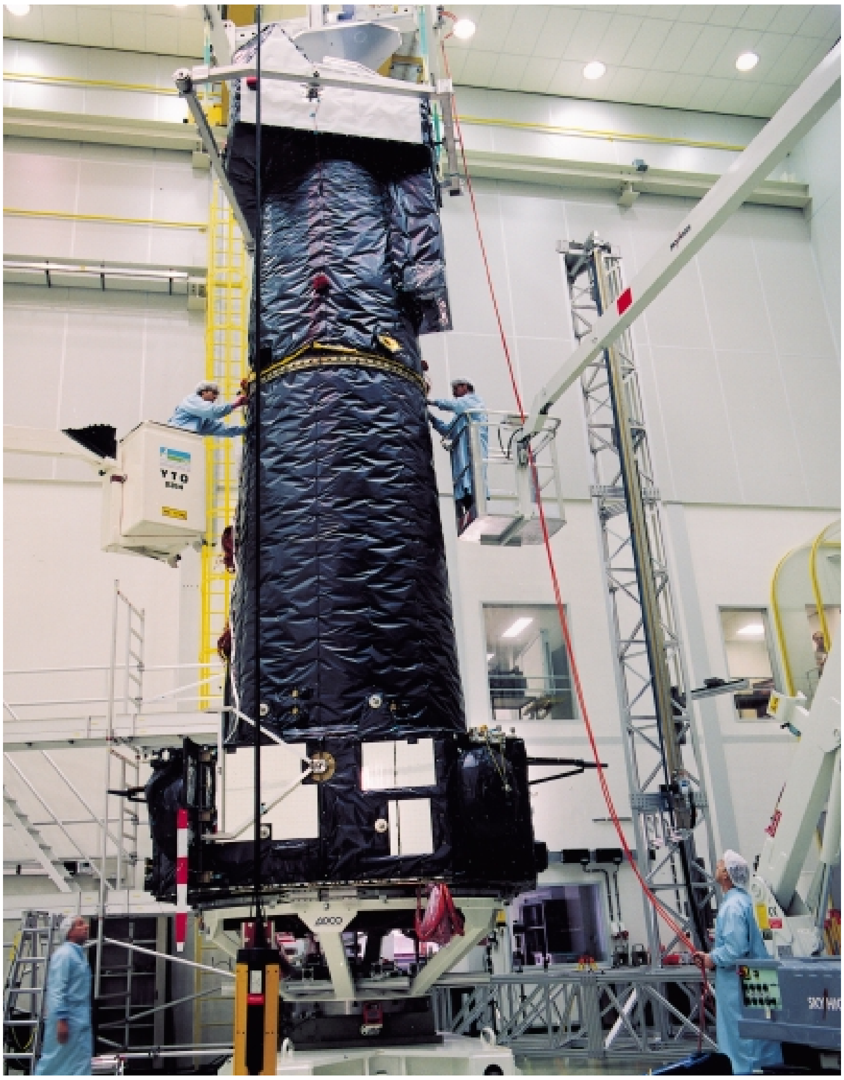

Figure 3. The alignment set-up used to check the axial positioning of all units at spacecraft level

– establish detailed and consistent alignment procedures starting from unit level (CCD cameras, grating assemblies and Mirror Module), to module level (MM with grating assemblies), up to spacecraft level. This in turn led to the implementation of specific features in the designs of all of the constituents of the optical system, the spacecraft and the Optical Ground Support Equipment to allow simple and precise checking of alignment. As an example, the early design of the structure already identified the necessity of through holes in the Service Module, in order to allow mirror-cube viewing from the alignment stand during spacecraft integration. Design provisions for alignment corrections were also implemented, e.g. shims and eccentric mounting plugs.

*Table 3*

| *Errors in arcsec* | *Requirement goal* | *Predicted worst case* | *Predicted ~90% of obs.* |
|---|---|---|---|
| AMA | 10 | 5 | |
| for RGS | 4 | | 3.1 |
| RPE | 5 | 1 | |
| for OM | 0.25 | | 0.33 |

The Mirror Module tests, conducted at the Panter X-ray facility in Munich, Germany, and in the UV facility at the Centre Spatial Liège in Belgium, demonstrated that we were indeed on course to meet the requirements.

In a similar fashion, all other spacecraft constituents like the telescope tube and the mirror and instrument platforms were characterised in order to refine and confirm the predicted alignment budget.

A detailed set of alignment procedures at spacecraft-integration level were developed, debugged and verified already during the spacecraft structural-thermal model test campaign. The mature status of these procedures ensured that the tight integration schedule for the flight-model spacecraft could be maintained.

Figure 3 (right) shows the alignment set-up used during final checking at spacecraft level of the relative axial positioning of all of the units.

The final payload-alignment activities at spacecraft level were carried out in July 1999 at ESTEC, within the scheduled time and to the satisfaction of all parties involved: the scientific experimenters, the Prime Contractor and ESA.

## Predicted In-obit Performance

All the results of the unit and subsystem tests, analysis and simulations, together with the results of the spacecraft thermal-balance test and alignment activities, have finally been assembled into the pointing and alignment predictions. These predictions show very promising performances for the telescope. All ‘requirements’ are met with comfortable margins, and ‘goals’ will be met for up to ~90% of all observations. As an example, the Table 3 shows the predictions for the measurement accuracy for the RGS instrument and the short-term pointing stability for the OM instrument:

## Acknowledgement

The authors wish to acknowledge the team effort by all personnel in the groups involved, i.e. the Dornier team, the teams at Centre Spatial de Liège, and at the MPE-Panter facility in Garching and the ESTEC metrology group. They are to be congratulated on their success in the timely and accurate design, implementation and determination of the optical performance of the XMM telescope.