The Scientific Instruments On-board XMM – Technical Highlights

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The payload carried by the X-Ray Multi-Mirror Mission (XMM), the second Cornerstone of the ESA Horizon 2000 Science Programme, consists of three scientific instruments: the Reflection Grating Spectrometer (RGS), the European Photon Imaging Camera (EPIC), and the Optical Monitor (OM). This article provides a general overview of the main characteristics of all three instruments.

Introduction

At the end of 1999, when the XMM satellite is put into its 48-h highly elliptical orbit by an Ariane-5 vehicle from the European launch base in Kourou, French Guiana, X-ray astronomers from all over the World will have the opportunity to exploit the most powerful X-ray observatory ever built.

For the first time, they will have the unique possibility to perform simultaneously:

– high-throughput non-dispersive spectroscopic imaging, with the EPIC instrument
– high-resolution dispersive spectroscopy, with the RGS instrument, and
– optical/ultraviolet imaging with the OM instrument.

An exploded view of the XMM payload, with the main elements labelled, is shown in Figure 1.

Three Mirror Modules, co-aligned with the OM telescope, and equipped with two RGS grating assemblies, lie at the heart of the XMM telescope. Each Mirror Module, with a focal length of 7.5 m, will provide an unprecedented collecting area, thanks to its 58 nested Wolter-I-type shells*, designed to operate in the soft X-ray energy band between 0.1 and 10 keV (1-100 Å).

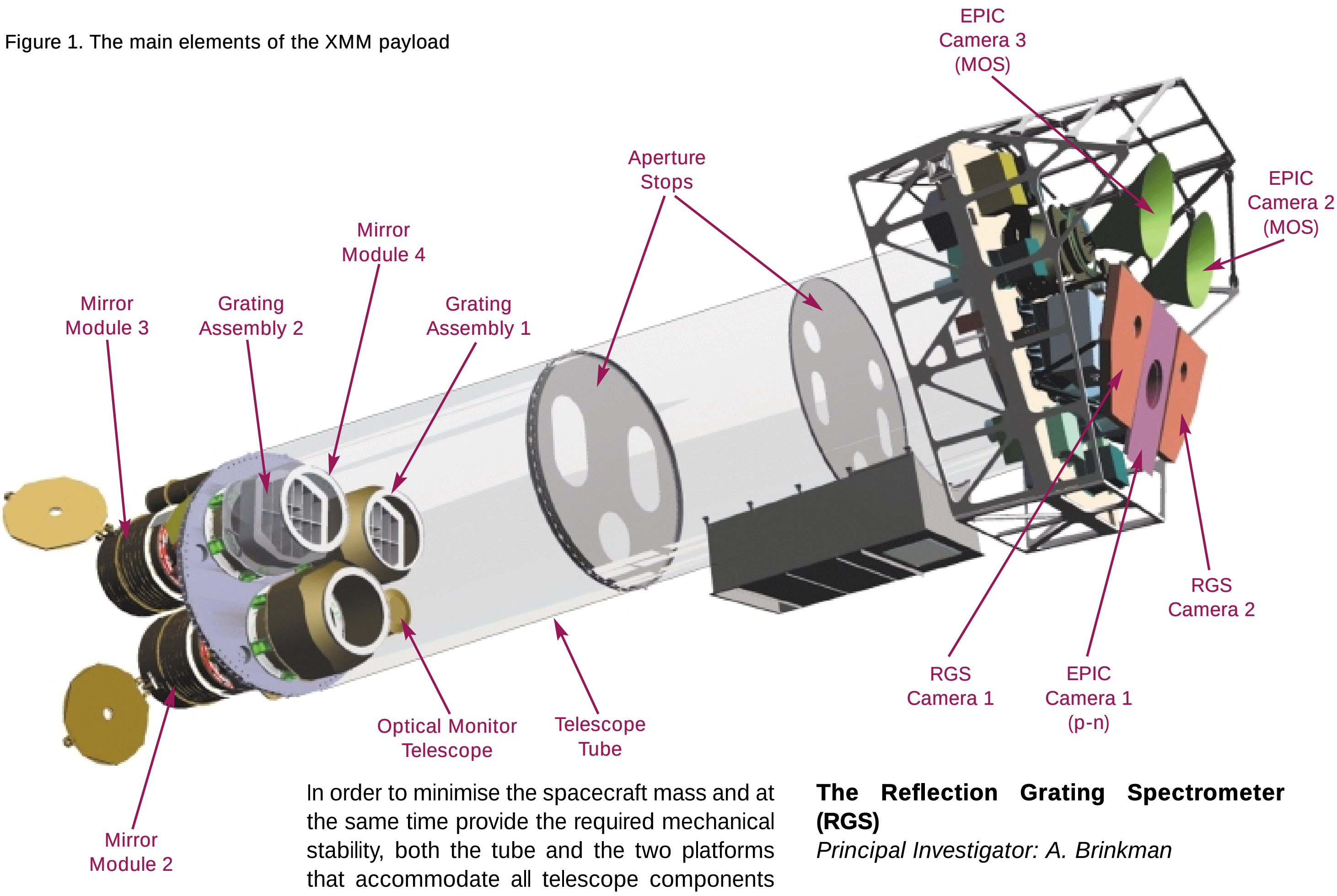
The XMM telescope is completed by three EPIC cameras, placed in the foci of the three Mirror Modules, and by two RGS cameras, suitably positioned to collect the spectrum created by the two grating assemblies. A Telescope Tube, which is equipped with two aperture stops for stray-light suppression and with an outgassing baffle for cleanliness and decompression purposes, separates the Cameras from the Mirror Modules.

* For a detailed description of the Mirror Modules, see the companion article in this Bulletin titled ‘XMM’s X-ray Telescopes’ on page 30.

Table 1. Main characteristics of the XMM instruments

Instrument	Main Purpose	Energy Range/ Bandwidth	Spectral Resolution (E /ΔE)	Spatial Resolution (arcsec)	Sensitivity	Total Mass/Power
EPIC	High-throughput non-dispersive imaging/ spectroscopy	0.1 - 15 keV 1 - 120 Å	5 - 60	14 (Half Energy Width)	10^{-14} erg/cm^2 sec	235 kg 240 W
OM	Optical/UV imaging	160 - 600 nm	50 -100 (with grisms)	1	< 24 magnitude	82 kg 60 W
RGS	High-resolution dispersive spectroscopy	0.35 - 2.5 keV 5 - 35 Å	200 - 800 (400/800 at 15 Å in 1st/2nd order)	N.A.	3 x 10^{-13} erg / cm^2 s	248 kg 140 W

Figure 1. The main elements of the XMM payload



In order to minimise the spacecraft mass and at the same time provide the required mechanical stability, both the tube and the two platforms that accommodate all telescope components are made of Carbon Fibre Reinforced Plastic (CFRP), with an aluminium honeycomb core.

Each instrument on board XMM has been designed and built by a multi-national consortium of institutes and industries, directly funded through the resources of the countries involved and under the leadership of a Principal Investigator (PI). Figure 2 (opposite) provides an overview of the industrial participants and the three instrument consortia. The main scientific performances and technical characteristics of the EPIC, OM and RGS instruments are listed in Table 1.

The Reflection Grating Spectrometer (RGS)

Principal Investigator: A. Brinkman

Instrument concept

The conceptual idea behind the RGS instrument is depicted schematically in Figure 3. The incoming X-ray radiation, collected and focused by the Mirror Module, is partly intercepted by a set of reflection gratings which, like a prism, disperse the various wavelengths at different angles so that a spectrum can be collected and analysed by a strip of Charge Coupled Device (CCD) detectors. The X-ray radiation that passes undispersed through the set of gratings is focused onto the EPIC cameras for imaging purposes.

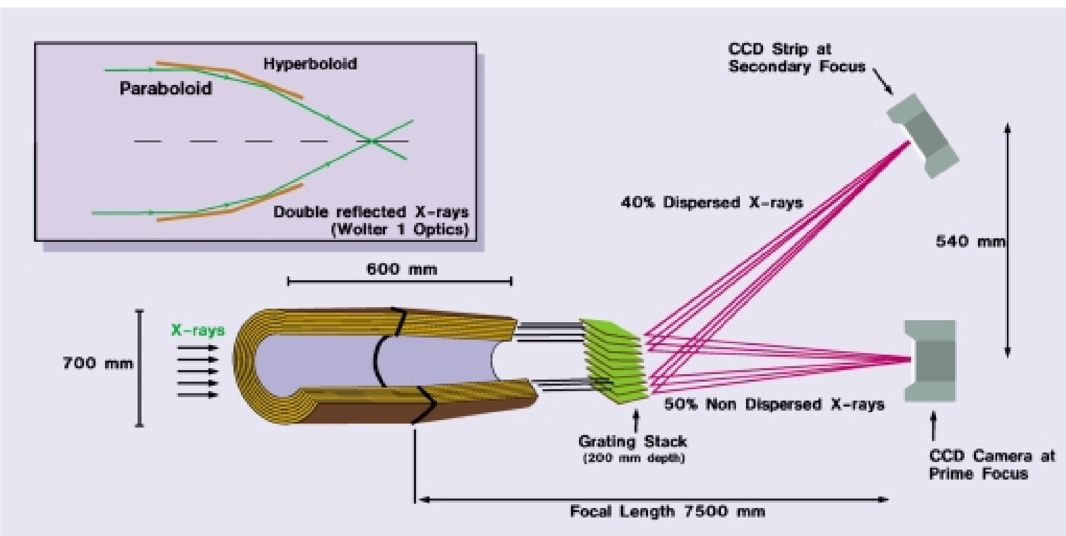


Figure 3. Schematic of the concept underlying the RGS instrument

Figure 2. The industrial structure (above) and participants in the three Instrument Consortia

Institute	Instrument	Country
Mullard Space Science Laboratory	OM (PI)/RGS	UK
University of Leicester	EPIC (PI)	
School of Physics, Birmingham	EPIC	
University of California, Santa Barbara	OM	USA
Los Alamos and Sandia National Labs.	OM	
Columbia University, New York	RGS	
University of California, Lawrence Livermore National Lab.	RGS	
Centre Spatial de Liège	OM	B
Space Research Organisation of the Netherlands, Utrecht	RGS (PI)	NL
Service d'Astrophysique, Saclay	EPIC	F
Centre d'Etude Spatiale des Rayonnements	EPIC	
Institut d'Astrophysique Spatial, Orsay	EPIC	
Paul Scherrer Institute, Villigen	RGS	CH
Istituto di Fisica Cosmica, Milan	EPIC	I
Istituto di Tecnologie e Studio delle Radiazioni Extraterrestri, Bologna	EPIC	
Istituto di Astronomia, Palermo	EPIC	
Max-Planck-Institut für Extraterrestriche Physik, Garching	EPIC	D
Institut für Astronomie und Astrophysik, Tübingen	EPIC	

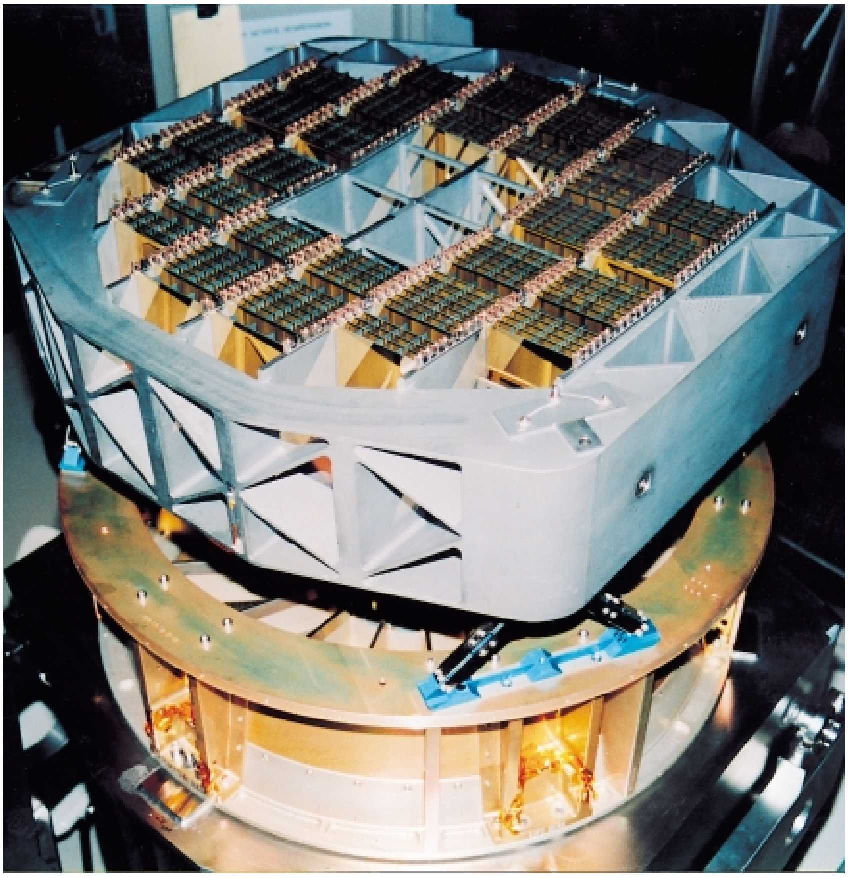


Figure 4. The grating array of the RGS instrument

Instrument description
Many of the design parameters – such as the number, size, type of gratings and CCD, and their relative positions – have gone through a long and complex optimisation process aimed at maximising the three main RGS scientific drivers: bandwidth, spectral resolution and sensitivity. This process has led to an instrument configuration featuring two identical independent instrument chains, each consisting of five units:
– a grating array
– a CCD camera
– one analogue electronics unit
– two digital electronics units, which are cold-redundant.

Some of their characteristics are described below.

The grating array, shown in Figure 4, is made up of a stiff lightweight monolithic beryllium structure, which houses 182 reflection gratings. In order to achieve its X-ray dispersing capabilities, each reflection grating features more than 600 groves/mm ruled on a 200 micron-thick gold layer, deposited on top of a 20 cm x 10 cm silicon-carbide substrate. Linear and angular positioning accuracies between gratings of the order of a few microns and a few arcseconds have been achieved by means of sophisticated manufacturing techniques, like precision diamond grinding and interferometric alignment. Finally, precise and stable mounting of the grating array onto the Mirror Module is achieved by means of three V-shaped titanium flexures.

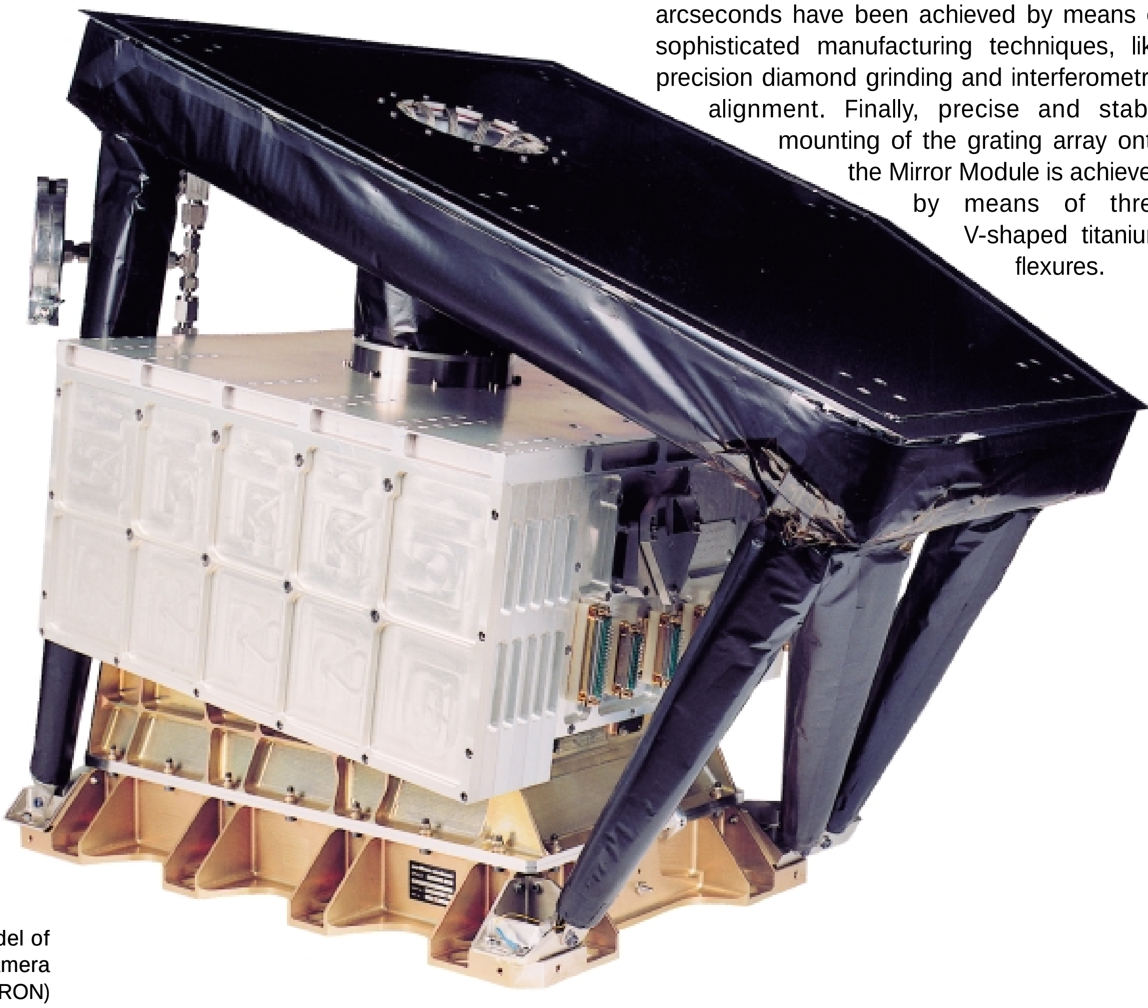


Figure 5. The flight model of the RGS Camera (courtesy of SRON)

The need to maximise the instrument's sensitivity and at the same time optimise its optical characteristics has driven the RGS camera design and dictated the choice in terms of the number, type and working temperature of the CCD detectors that lie at its heart. Figure 5 shows the flight model of the RGS camera.

Passive cooling to about -80°C for optimal CCD performance is achieved by connecting the CCD bench inside the camera, via an aluminium cold finger, to a flat two-stage radiator viewing cold space. Six glass-fibre struts provide a robust support and at the same time minimise the conductive heat inputs on the radiator itself. Further thermal insulation of the cold CCDs from the warm external environment is accomplished by two separate heat shields, which by means of a sophisticated 'labyrinth' structure, achieve stable CCD positioning, satisfactory thermal de-coupling and substantial radiation shielding.

The choice of 'back-illuminated' CCD technology enables a high quantum efficiency to be achieved throughout the 5 - 35 Å instrument bandwidth. Each CCD has 768 x 1024 pixels, 27 x 27 microns in size. A strip of nine of these devices have been chosen so that the 253 mm-long spectrum created by the grating array can fit onto the detector focal plane, shown in Figure 6. Both the CCD strip and the centre of the grating array are positioned on an imaginary circle about 7 m in diameter, to minimise the aberrations of the optical system.

Among other tasks, the 'front-end' electronics inside the camera performs the CCD read-out, its conditioning and the signal amplification by distributing a suitable clock sequence and setting the correct bias voltages and gains for the preamplifiers.

The remainder of the electronics is distributed inside the analogue and the digital units. The former processes the pre-amplified signals coming from the nine CCDs, converts them into digital signals using a 12-bit Analogue-to-Digital Converter (ADC) and passes them, together with the set of housekeeping parameters, to the digital electronics. This unit is substantially in charge of the overall control of the instrument by, for example, choosing the appropriate operating mode for the instrument and configuring it accordingly, as well as formatting the data into suitable telemetry packets following data reduction. It also handles the incoming telecommands and provides appropriate power to the instrument.

The European Photon Imaging Camera (EPIC)

Principal Investigator: M. Turner

Instrument concept

The EPIC instrument is made up of three independent instrument chains, each one consisting of a camera unit with a Charge Coupled Device (CCD) detector assembly, an analogue electronic unit for camera control and signal conditioning, a digital signal-processing unit, and a data-handling unit, responsible for overall instrument control, data formatting, and interfacing to the spacecraft.

The three CCD cameras, positioned in the primary foci of the Mirror Modules, can be configured in a wide range of observation modes, which affect their sensitivity, and their spatial, spectral and time resolution. In this way, a large variety of time-correlated imaging and spectral measurements of one or more celestial objects can be gathered in a single observation.

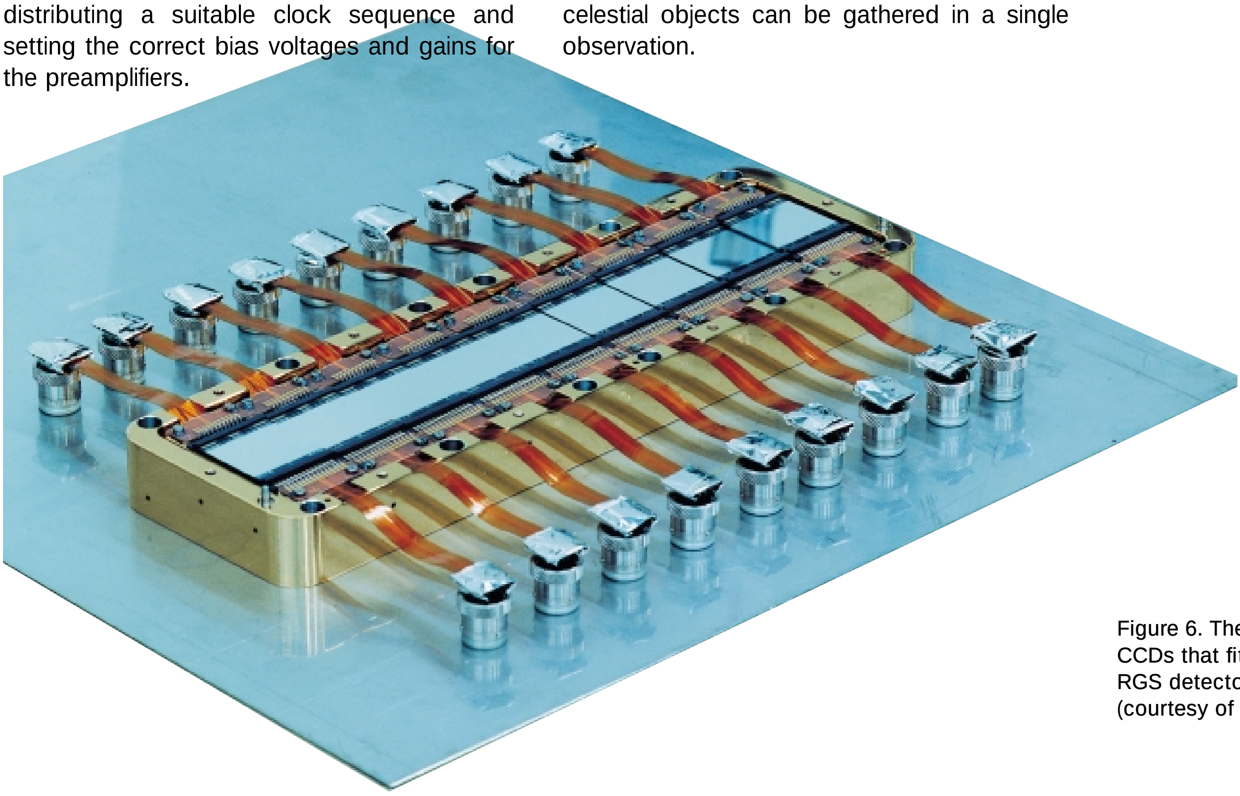


Figure 6. The strip of nine CCDs that fits within the RGS detector's focal plane (courtesy of SRON)

A Radiation Monitor completes the EPIC instrument set-up. It will continuously monitor the particle radiation environment to which XMM will be exposed, thereby providing us with valuable supporting data on the actual performances of the sensors and electronics.

Instrument description
Two cameras consist of an arrangement of seven metal-oxide (MOS) CCD arrays covering the 30 arcmin field of view of each Mirror Module. Each CCD is mounted on a ceramic carrier, which in turn is integrated on an Invar support structure for the complete focal-plane assembly.

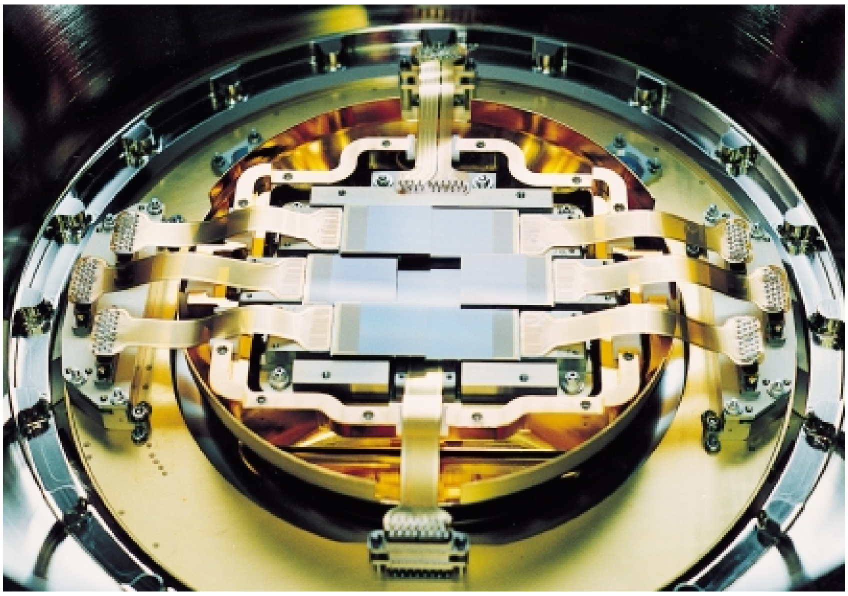


Figure 7. One of the two EPIC instrument MOS CCD assemblies during integration

Figure 7 shows a MOS CCD assembly during integration at Leicester University (UK). Each MOS CCD features an imaging area of 600 x 600 pixels, 40 microns in size, capable of detecting X-rays in an energy band ranging from 0.1 to 15 keV, with a maximum timing resolution of 1 ms. In a typical observation mode, the full focal plane, consisting of seven CCDs, is read out in 2.7 s.

The third CCD camera, shown in Figure 8, differs from the first two MOS cameras mainly in terms of the semiconductor technology used, and the CCD size, number and layout.

Figure 9 shows an integrated p-n focal-plane layout. Twelve back-illuminated CCDs are all generated on a single 10 cm-diameter wafer. Each of them is organised as a 64 x 200 matrix of 150 micron-sized pixels. The use of p-n technology has resulted in a higher quantum efficiency than comparable instruments, particularly for energies around or below 0.5 keV and above 6 keV. Typical full-frame readout times of 48 ms can be achieved, with a maximum timing resolution of 40 microsec.

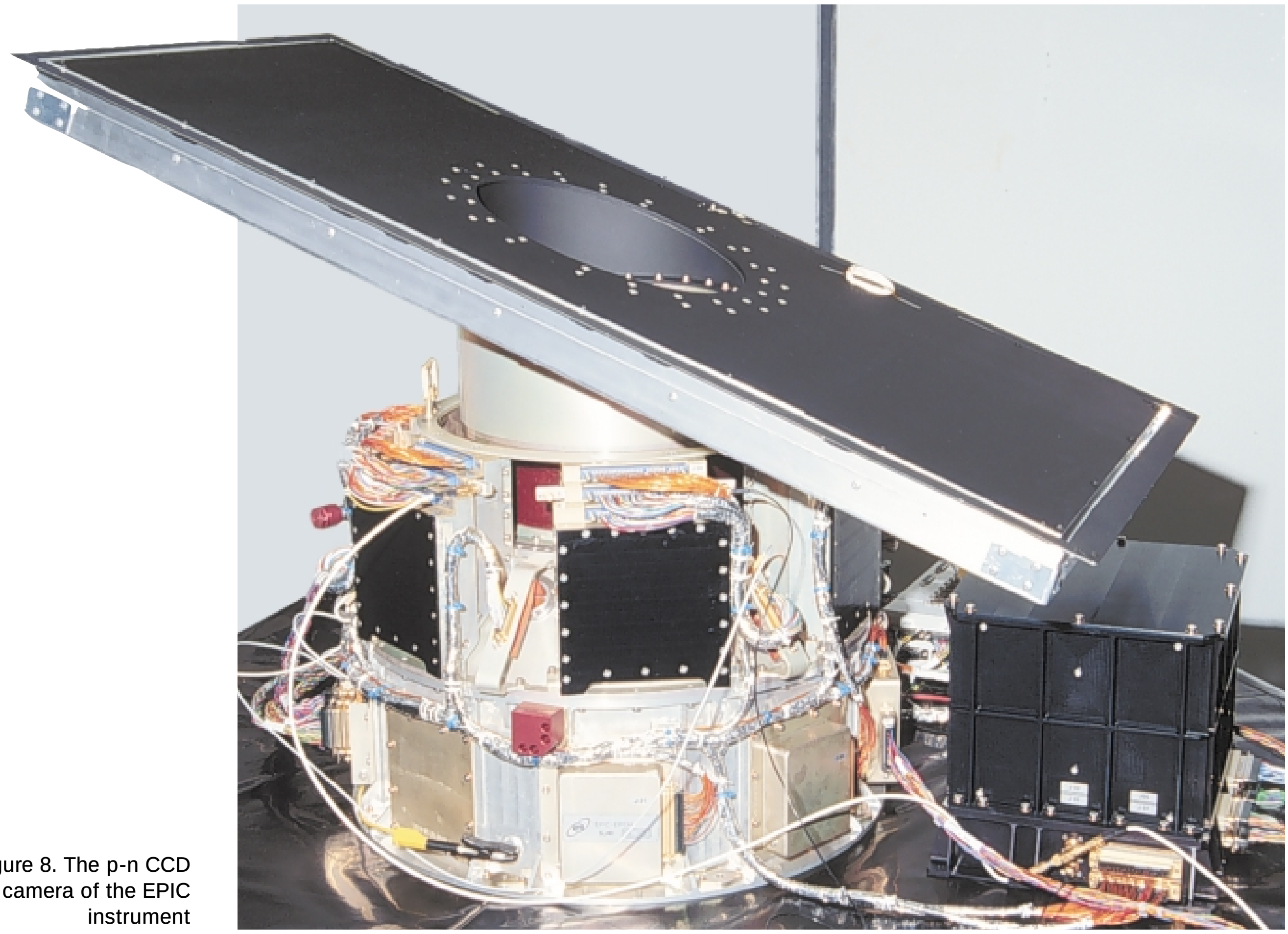


Figure 8. The p-n CCD camera of the EPIC instrument

Electrically, the CCDs are divided into four quadrants of three CCDs each, which can be controlled and read out separately by four electronic sections that provide for direct driving and buffering of all CCD signals.

Both the MOS and p-n focal-plane assemblies are enclosed in a vacuum-tight camera housing, which provides suitable shielding from the particle radiation environment.

In order to maximise instrument sensitivity, the three CCD detector assemblies are passively cooled to -100°C by means of a cold finger thermally coupled to a radiator system facing cold space. Figure 10 shows a top view of the Focal Plane Assembly in which the two MOS camera conical (white) radiators and the flat p-n camera rectangular radiator (black) between the two RGS camera radiators, can be identified.

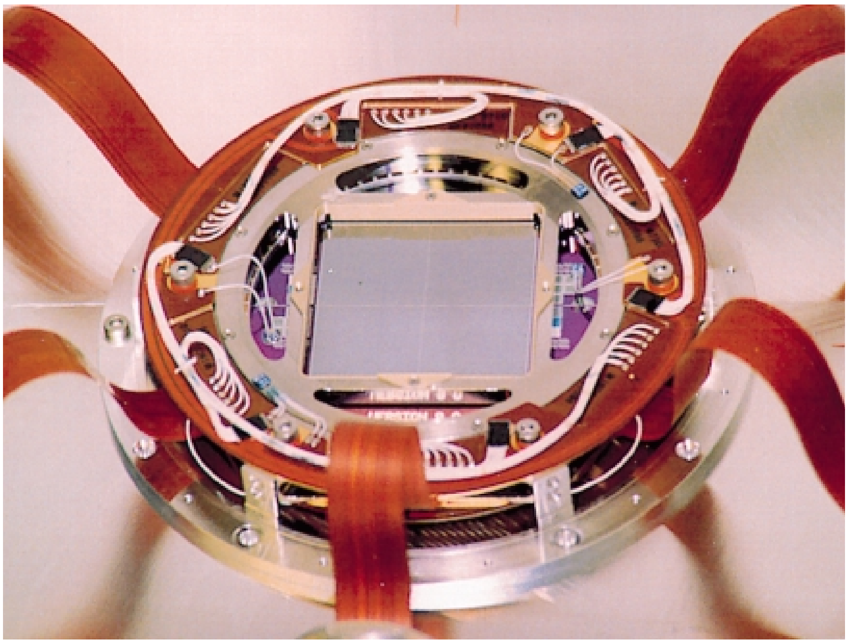


Figure 9. An integrated EPIC p-n CCD focal-plane layout

Figure 10. XMM's Upper Module during final MLI installation, showing the Focal-Plane Assembly

Another common feature of the MOS and p-n cameras is a filter-wheel mechanism with four aluminised Mylar filters of different thicknesses, which can be suitably selected depending on the intensity of the source.

The MOS Analogue Electronics Unit accommodates all programmable CCD sequencers, clock drivers, and bias voltage generators. The CCD output signals are fed to analogue signal chains with multiplexers and eight ADCs with 12-bit resolution, allowing a single CCD to be read out via two nodes in certain operational modes, together with the other CCDs. The thermal control for the camera and filter-wheel electronics is also housed in this box.

The eight CCD raw data streams are passed on to a digital signal-processing unit, which serves for high-speed data pre-processing and reduction. Eight Event Detection Units with pattern libraries and offset maps provide for the discrimination of X-ray events from gamma rays, particle events, and background noise.

The Event Analyser and the Control Electronics Units carry the equivalent functions of these two MOS units in the p-n chain. The Event Analyser is responsible for generating all CCD clock signals, reading the analogue signals of the 12 CCDs, digitising the data and making the basic noise and offset subtraction and event discrimination.

The Control Electronics accommodates various control and interface functions which are needed within the p-n camera system, such as camera-temperature and filter-wheel control. The bias voltages of the CCDs are also controlled and a large set of CCD parameters is made available for incorporation into the instrument's housekeeping telemetry.

The formatted output data from the MOS and p-n chains are passed on to the respective data-handling units. They represent a general-purpose 16-bit microprocessor architecture, with high-speed interfaces for handling the science data. All science and housekeeping data are formatted into telemetry packets according to ESA standards. The unit also decodes, checks and executes all tele-command packets.

The data-handling units select and control the various operating modes of the cameras: Full-Frame mode allows the readout of all CCDs; Window mode reads out only a selected area of the CCDs; Fast/Timing mode is selected for high time resolution, while Burst mode is selected for high-speed readout. Additionally, various Diagnostic modes can be commanded in order to support instrument calibration or to check CCD performance parameters before commencing an observation.

The Radiation Monitor detector is mounted on the outside of the XMM satellite and features three redundant silicon detectors. Two are sensitive to high-energy particles, such as electrons above 200 keV and protons above 10 MeV, while the third can detect low-energy electrons above 30 keV. Count rates and spectra of the particle radiation are accumulated in an electronics unit, which formats the raw data in either a Fast mode, with a time resolution of 4.0 sec, or in a Slow mode with an accumulation period of 512 sec.

The Optical Monitor (OM)

Principal Investigator: K. Mason

Instrument concept

The Optical Monitor is a modified Ritchey-Chrétien optical/ultraviolet telescope with a 30 cm diameter primary mirror, co-aligned with the three X-ray Mirror Modules, so that simultaneous observations in the X-ray and in the optical/UV regime can be carried out. The OM is a powerful instrument that will be capable of detecting sources with a sensitivity limit of magnitude 24 in its 17 arcmin field of view. It can provide images in the wave band from 160 to 600 nm with a resolution of about 1 arcsec, spectra of X-ray sources by means of low-resolution grisms (optical devices that combine the characteristics of a grating and a prism), and high-time-resolution photometry.

Instrument description

Three units compose the OM instrument: the telescope unit and two cold redundant digital electronic units. Figure 11 identifies the main constituents of the telescope, which can be summarised as follows:

- A long baffle with internal radial vanes for minimising stray-light from off-axis sources.
- A door fitted on the baffle to protect the optics from contamination whilst on the ground and during launch.
- The telescope module, made up of a 30 cm-diameter primary mirror and a 7 cm-diameter secondary mirror.
- The blue module which houses a beam deflector, and the two redundant detectors equipped with their respective filter wheels.
- The detector processing electronics.
- The telescope power supply.

The incoming light is focussed by the telescope module onto a 45 deg flat mirror mechanism, which can deflect the beam onto either of the

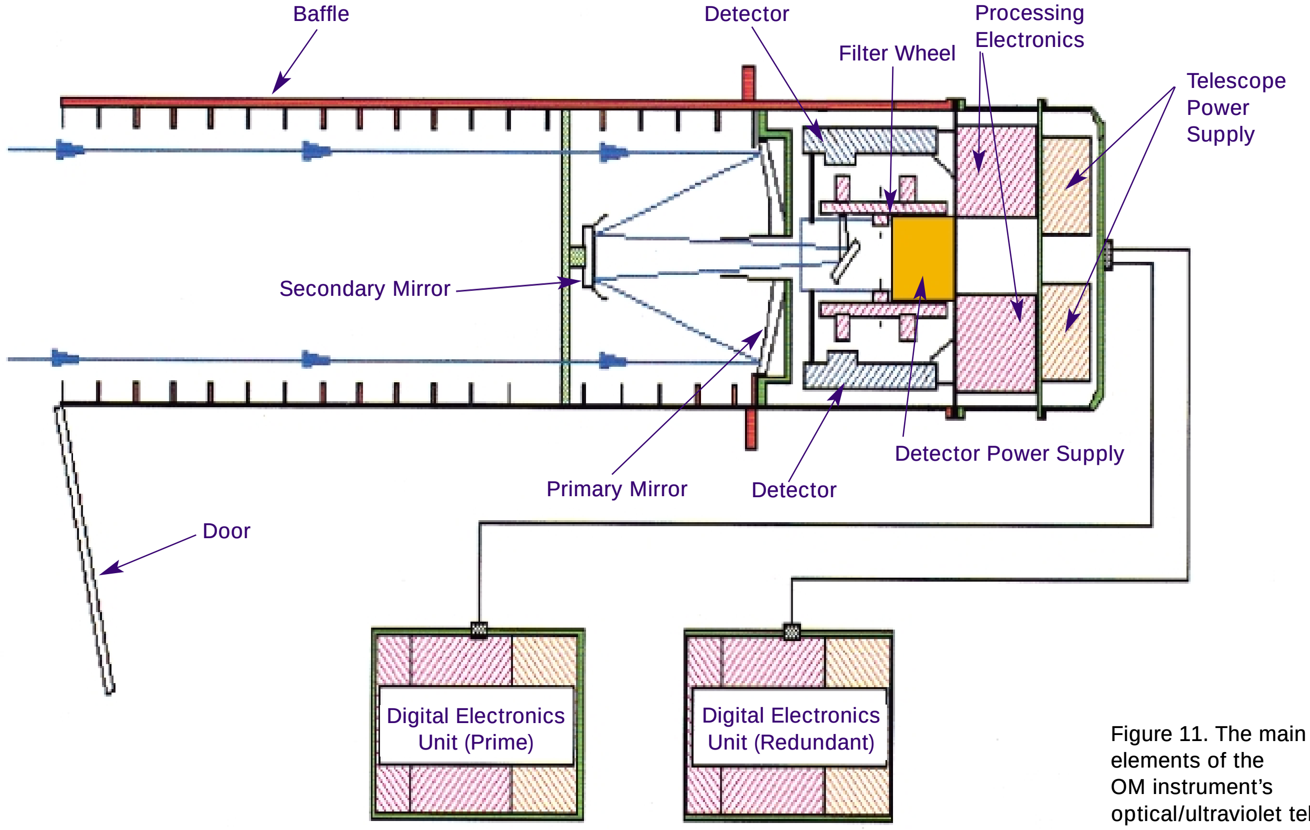


Figure 11. The main elements of the OM instrument's optical/ultraviolet telescope

two detectors by a 180 deg rotation around its longitudinal axis. Two filter wheels with seven filters, two grisms, a magnifier and a blocked position are positioned in front of the detector entrance aperture. Each detector assembly consists of an image intensifier with a photo-cathode, a micro-channel plate, a tapered fibre optics and a CCD.

The detector electronics reads out the CCD every 10 msec and centroids the photo-electron cloud with a resolution of 1/8th of a CCD pixel. This allows reconstruction of the angular position of the photons within a 0.5 arcsec circle over a 2048 x 2048 grid.

In order to maintain the detector temperature at around 30°C and to provide cooling to the rest of the electronics at the back of the telescope, four heat pipes transfer the heat to the front baffle, which acts as a radiator. The optics are maintained at 20°C by means of control heaters.

Each digital electronic unit consists of three parts: a digital-processing, an instrument-control and a power supply. The first one performs science data processing, including image accumulation over typically 1000 sec. Four digital signal-processing microprocessors and 11 Mbyte of memory are used to perform this function. It is also possible to store all of the time-stamped events for a small area of the detector in order to study the time-variability of sources.

In order to maintain the 1arcsec resolution over the complete exposure, the digital-processing electronics performs tracking every 10-20 sec on the acquired image and corrects the position of the detected photons accordingly.

Before being passed to the spacecraft's On-Board Data-Handling System, data are sent to the processor inside the instrument controller for proper packet reformatting. The instrument controller also provides the basic instrument control function, telecommand processing, housekeeping monitoring and code up-linking. Finally, the power-supply provides conditioned power for both the digital-processing electronics and the instrument controller.

Conclusion

XMM, with its simultaneous observation capabilities provided by dispersive high-resolution X-ray spectrometers (RGS) and by high-throughput non-dispersive X-ray imagers (EPIC) in combination with optical/ultraviolet images (OM), will guarantee a substantial leap forward in the X-ray astronomy of the next millennium.

Acknowledgement

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