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Optical design of the Optical Monitoring Camera (OMC) of INTEGRAL

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Abstract. The Optical Monitoring Camera (OMC) will observe the optical emission from the main targets of the gamma-ray instruments onboard the ESA mission INTEGRAL. The OMC is based on a refractive optics with an aperture of 50 mm focused onto a large format CCD (1024 × 2048 pixels), and a field of view of 5° × 5°. This paper describes the design of the optical system and the optical baffles of the OMC.

Key words. instrumentation: photometers – space vehicles: instruments – techniques: photometric

1. Introduction

The ESA scientific mission INTEGRAL (The International Gamma-Ray Astrophysics Laboratory) is dedicated to the fine spectroscopy and fine imaging of celestial gamma-ray sources in the energy range 15 keV to 10 MeV with concurrent monitoring in the X-ray (3–35 keV) and optical (*V*-band) energy range. The INTEGRAL spacecraft was launched in 2002 by a PROTON rocket from Baïkonur into a 72-hour orbit with an inclination of 52.5 degrees, a perigee of 9000 km and an apogee of 154 000 km. The INTEGRAL spacecraft is designed for a nominal 2 years mission, extendable to 5 years. The Optical Monitoring Camera is a 20 kg class instrument mounted on the top of the INTEGRAL payload module. A 6-lens telephoto optical system is imaging stellar objects on a CCD detector mounted in a Focal Plane Assembly (FPA). An optical baffle affords the necessary reduction of straylight. A once-only deployable cover protects the optics from contamination during ground operations and early operations in orbit. This paper describes the design of the optical system and its baffle.

2. Optical system design

The optical system has specifications of a 154 mm focal length, a 5° × 5° square FOV (field of view) and a 50 mm diameter entrance pupil. The optical design is driven by two main parameters: high optical performance and specific environmental conditions dictated by the orbit and the INTEGRAL spacecraft. These parameters are summarised in Table 1. The optical performance must be met within the operational conditions range while the non-operational environment defines the extreme conditions for survival of the instrument. The high radiation dose requirement was defined by the possibility in a first time to use an Ariane V launcher and an orbit into the radiation's belts (i.e. perigee at 7000 km and apogee at 114 000 km). The rocket and the dedicated orbit were decided when the instrument was already designed. The nominal operational temperature and the very wide temperature ranges result from the thermal design of the instrument. Moreover, the thermal requirements at the interfaces dictate the lens barrel material (titanium alloy), although it is not the best choice in terms of thermo-optical performance with an athermalized focus (focal plane assembly mainly in INVAR material).

The high radiation dose requirement imposed the use of radiation-hard lenses and limited seriously the number of available glasses and the design possibility. The optical design and theoretical performance are fully described in E. Mazy et al. (1998a,b, 1999). The F/3 optical design consists of six radiation-hard lenses housed, by doublet, in a titanium barrel (see Fig. 1). The titanium and the glass fit correctly in terms of thermal expansion and allow to sustain the large non-operational thermal range. The filter assembly holds two coloured filters (Schott BG39 and GG495) defining the useful spectral range (*V* band centered at 550 nm). An additional BK7G18 glass window protects the filters from radiation. The filter assembly is dismountable for testing purposes. The optical design was particularly intended to suppress ghost

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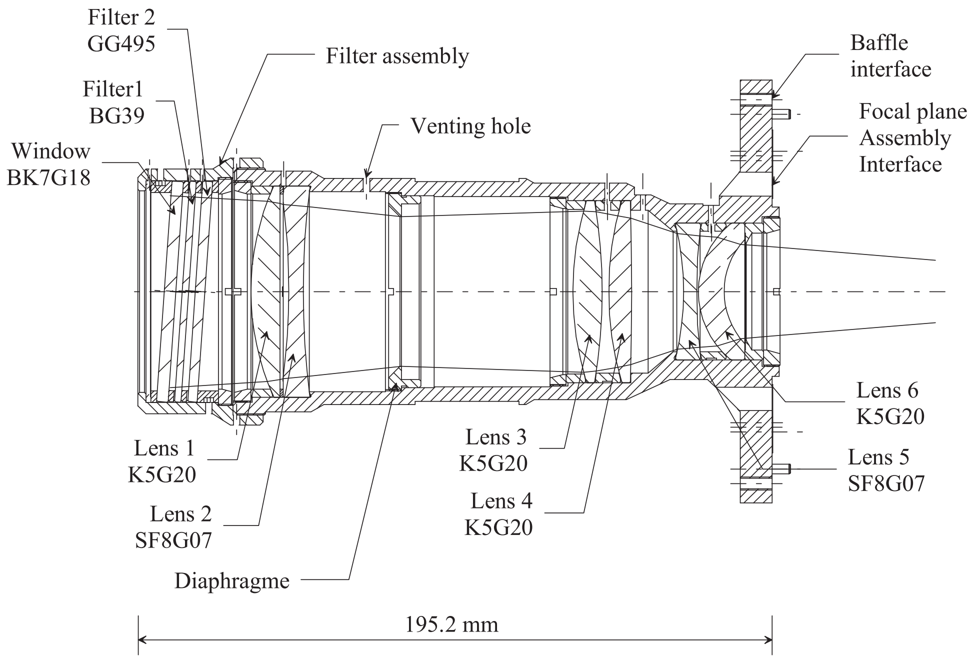

Fig. 1. Mechanical design of OMC optical system.

Table 1. Optical requirements and environmental conditions.

Encircled energy	>70% in a pixel ($13 \times 13\ \mu m^2$)
Modulation Transfer Function (MTF)	>70% at Nyquist Frequency (38.5 c/mm)
Backfocus	≈50 mm
Transmission (at 550 nm)	>70% at the beginning of life
	>60% at the end of life (5 years mission)
Spectral range	Johnson *V* band centred at 550 nm
Lens barrel material	Titanium alloy (Ti-6Al-4V)
Backfocus (part of Focal Plane Assembly) material	INVAR
Radiation dose	42 krad over 5 years (worst case)
Nominal conditions	0 C (in vacuum)
Thermal range (operational conditions)	−20 C to +20 C
Thermal range (non-operational conditions)	−80 C to +45 C
Vibrations (non-operational conditions)	Random: 27 g RMS in the range 20–2000 Hz

images: lens curvatures were set to enlarge as more as possible unavoidable ghost images onto the detector. In addition, a space qualified multilayer antireflection coating ($R < 1\%$) was applied on all optical surfaces to reach the optical transmission requirement and to decrease ghost image level. The external surface of the BK7G18 glass window in the filter assembly is kept free of coating for radiation and cleanliness purposes. In the same way, the filter assembly optical items are tilted to reject focalized ghost images out of the detector. Lens barrel black chromium coating also contributes to the straylight rejection. A retainer was modified on the flight model to limit an unexpected straylight diffusion onto the detector verified on the qualification model environmental tests. Table 2 summarizes the theoretical optical performance taken into account manufacturing tolerances. At the edge of the required thermal range, the MTF is out of the specification mainly due to lens barrel material imposed by the thermal design.

The optical system was tested at CSL (Centre Spatial de Liège, Belgium) at subsystem level and at instrument level. At subsystem level, the lens barrel passed the environmental tests successfully, excepted lens microsettings that did not degrade the WFE (WaveFront Error) more than 36 nm peak-to-valley. That is insignificant in terms of optical performance and demonstrates that no optical item had moved or broken during the test which would have degraded the optical performance. At instrument level, the expected optical performance was measured at CSL in real conditions in nominal case, cold case, and hot case (in vacuum with the environment respectively at −120 C, −150 C and −100 C). The optical measurements consisted in a 24.4 c/mm (2/3 Nyquist frequency) bar test measurement and a subpixel LSF (Line Spread function) measurement. Figure 2 shows the experimental MTF at various off-axis distances respectively in cold case, nominal case and hot case. Taking into account all the off-axis directions

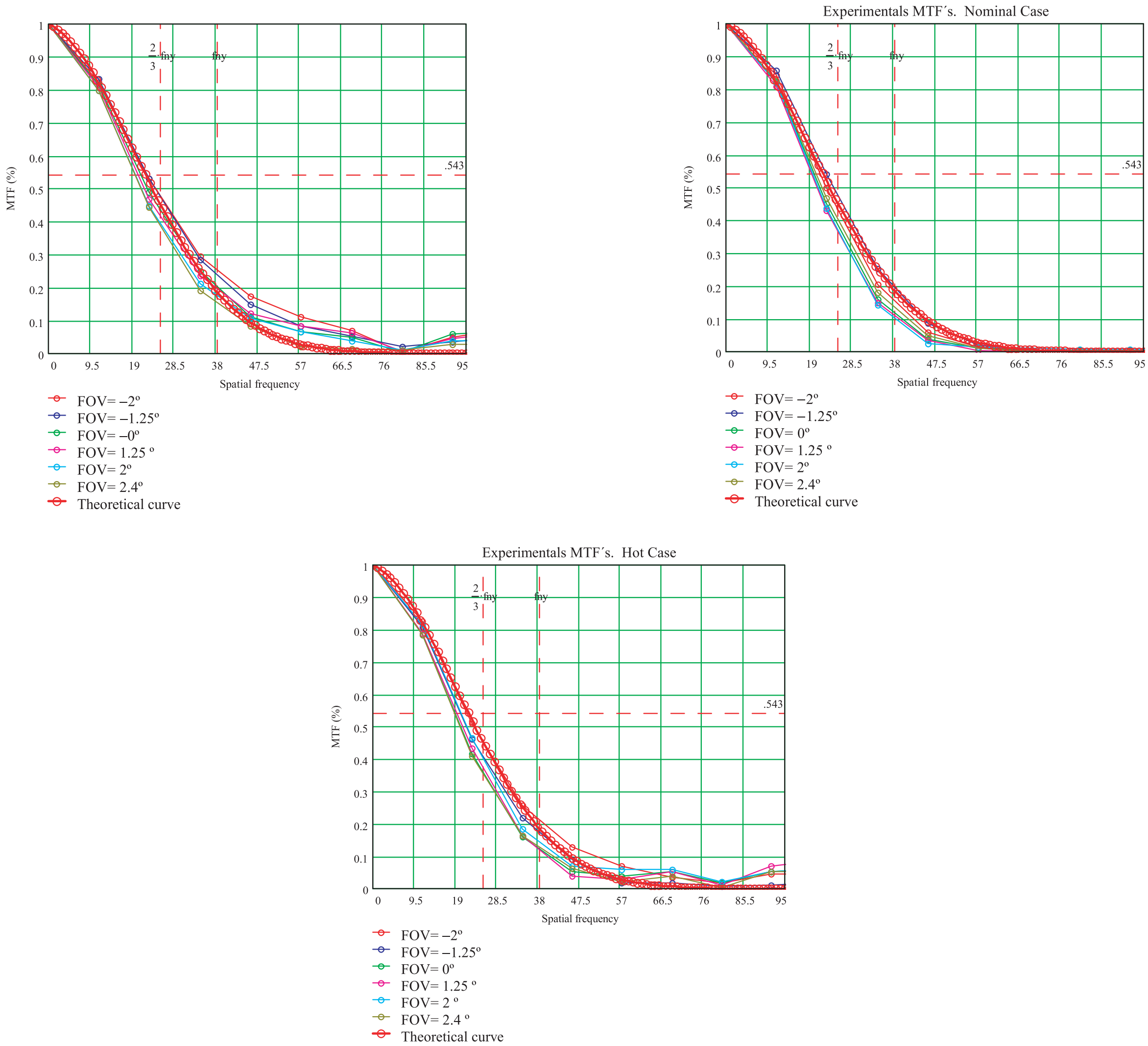

Fig. 2. Experimental MTF results in cold, nominal and hot cases, for different off-axis distances.

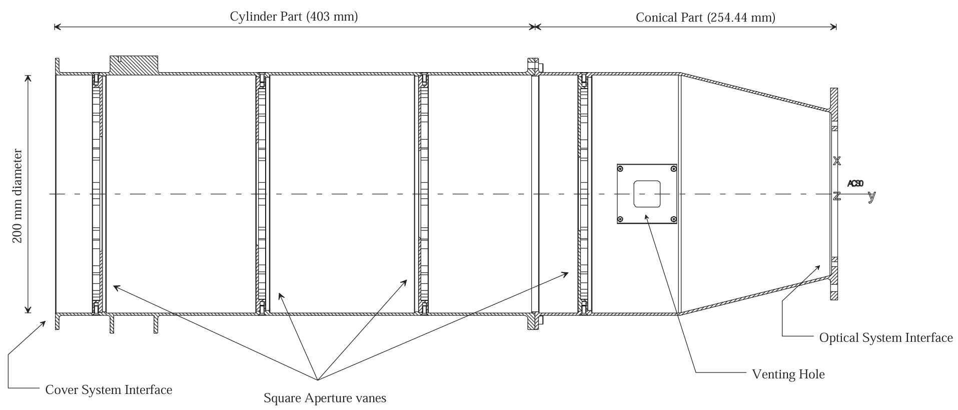

Fig. 3. Overview of the OMC forebaffle.

and the complete thermal range, the mean PSF had a dimension of 26.8 arcsec FWHM (Full Width Half Maximum). The measured performance is fully consistent with the theoretical analysis. Commissioning of OMC instrument after the launch has shown a measured PSF of 24.5 arcsec FWHM (Full Width Half Maximum), very close to the on ground measurement.

3. Baffle design

The main baffle was designed to achieve the high rejection factor required for observation of stars up to visual magnitude of 19.0. An overview of the baffle is shown in Fig. 3. The main baffle consists of a cylinder and a cone, both made of aluminum

Table 2. Theoretical performance in the optical system nominal thermal range. We list the MTF at Nyquist frequency and the diameter the encircling 70% of the energy.

FOV	MTF at Nyquist	70% Encircled energy (μm)	MTF at Nyquist	70% Encircled energy (μm)	MTF at Nyquist	70% Encircled energy (μm)
	$T = -20$ C		$T = 0$ C (nominal)		$T = +20$ C	
0°	72	10.1	80	6.7	58	13.1
1°	71	10.3	80	6.7	59	13.0
2°	69	10.7	81	6.4	60	12.6
2°.62	67	11.0	80	6.3	61	12.2

and with a mean thickness of 2 mm. On these tubes interfaces are added for the optical system, for the cover system, for the alignment cube, for the mounting legs, for the lifting tool, for the MLI grounding and for the electrical connectors. Inside this tube, 4 square aperture vanes are inserted for straylight purposes. The cover system door aperture defines the fifth vane at the baffle entrance. A venting hole is also included in the design to allow depressurization without parasitic light. The entire baffle is black anodized to improve the rejection efficiency.

Straylight rejection onto the detector operates at various levels into the OMC instrument. Inside the 20 arcdeg square UFOV (Unobstructed Field Of View), straylight is produced by internal reflection into the lenses (ghost images) and into the lens barrel. Outside the UFOV, straylight is produced by multiple diffuse reflection through the baffle and the lens barrel. This straylight source is more restricting due to the large number of bright sources in these viewing angles. The overall baffling of the instrument also provides high rejection against other important straylight sources such as the Sun light and spacecraft elements: direct reflections on the payload and diffraction on the forebaffle edge can also produce straylight in the OMC baffle. Although the instrument is located at a top position on the platform, two elements of the payload can be considered as candidates for straylight sources as shown in Fig. 4: the +X panel of the PLM (PayLoad Module) structure and the SAS. All these elements are thermally protected with Kapton MultiLayers Insulation (MLI), as illustrated in Fig. 4.

All the elements of the instrument have been designed to help attenuate straylight:

– the forebaffle is designed for Sunlight and Payload Module straylight sources;
– the main baffle designed for reduction of straylight sources outside the UFOV;
– the lens barrel and the focal plane assembly are designed for the attenuation of straylight sources inside the unobstructed field of view.

An ASAP (registered mark) ray-tracing model of the instrument had been developed at CSL taking into account all surfaces optically active for the straylight analysis. All internal surfaces of the instrument with their associated coatings or diffuse properties were included in the model. Black coating samples were measured to set the BRDF (Bi-directional Reflectance Distribution Function) properties of surfaces. Primarily the model evaluated the impact of stellar bright

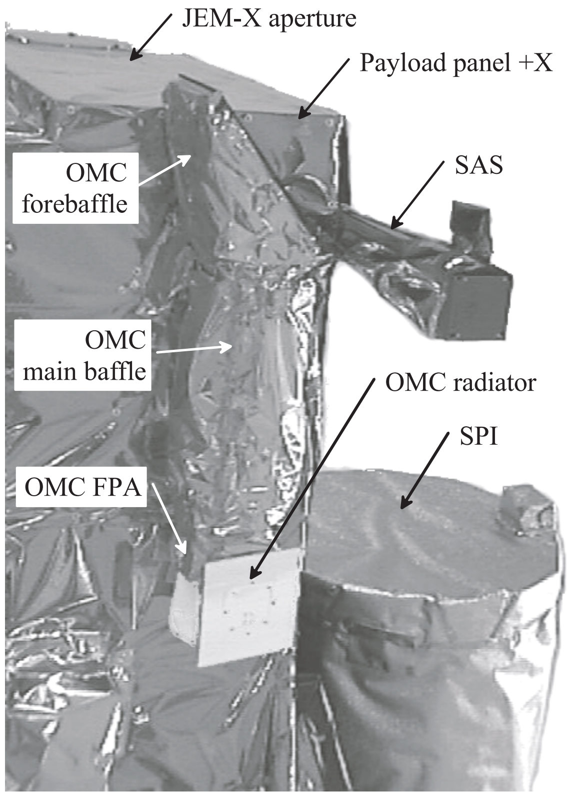

Fig. 4. Overview of the OMC instrument wrapped in its thermal blanket.

sources by using point sources in the sky. Figure 5 shows the results of the simulation giving the straylight flux reaching the detector area, that was confirmed to be uniformly spatially distributed on all the pixels, in comparison with a $mV = 19$ point source in the FOV and focalized on a single $13 \times 13\ \mu m^2$ pixel. The worst case occurs for a bright source focalizing just outside the detector, onto the radiation shield: straylight is then reflected by the radiation shield with grazing incidence angle. Black coating performance is limited in such configuration. To study the impact of the Sunlight reflected by the payload, a rough model of the spacecraft had been developed. The straylight produced by the spacecraft elements was evaluated with the complete model of the instrument combined with the payload model. Table 3 summarizes the straylight flux on the CCD, compared to the faintest object flux in the FOV (10^{-19} W/pixel) that needs to be detected by the OMC. In each case, conservative assumptions were used. The baffle design and

Table 3. OMC baffling straylight performance summary.

Sources	**Straylight flux**
Point source inside the FOV	$<10^{-28}$ W/pixel
Point source inside the UFOV	$<10^{-19}$ W/pixel for a $mv = -4$ point source
Point source outside the UFOV	$<10^{-29}$ W/pixel for a $mv = -4$ point source
PLM panel reflected Sun light	$<10^{-25}$ W/pixel
SAS support reflected Sun light	$<10^{-25}$ W/pixel
Sun light diffracted by the forebaffle	$<10^{-23}$ W/pixel

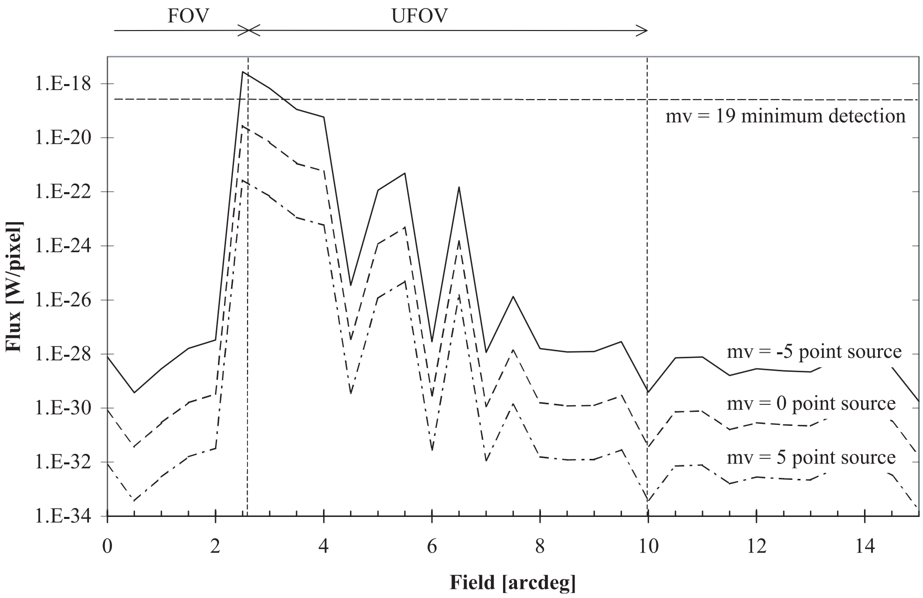

Fig. 5. Straylight from external stellar objects.

manufacturing is a major element in the straylight rejection and OMC capabilities. Straylight measurement at instrument level was performed in vacuum conditions at CSL and at INTA and was in good agreement with simulated curves. Measurements gave a rejection factor of 10^{-6} just outside the FOV and 10−10 for larger off-axis distances.

4. Conclusions

The OMC optical system and its baffle were designed in order to fulfill high scientific requirements in a hard space environment. A complete set of environmental tests was performed at sub-system level and at instrument level to predict the instrument behaviour in flight conditions. Ground measurements gave a mean PSF size of 26.8 arcsec FWHM over all the FOV and for a quite wide thermal range. That was confirmed during the instrument commissioning, and after launch a 24.5 arcsec FWHM PSF was measured. High care was taken for the straylight design and the flight model was modified with the qualification test heritage, giving full confidence in the flight hardware. First flight acquisitions during the commissioning phase show a limiting measurable magnitude of $mV = 18.2$. The straylight reaching the detector is negligible (below the measurement level).

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