Optical Design of the INTEGRAL Optical Monitoring Camera

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ABSTRACT

The Optical Monitor Camera (OMC) is a part of the scientific payload being developed for the INTEGRAL mission, scheduled to be launched in 2001. The OMC is an imager that will monitor star variations in the V-band in a 5 x 5° field of view. An optical system based on 6 lenses has been developed in order to meet the optical requirements in specific environmental conditions. The concept of the optical system and the optical performances are discussed in this paper.

The optical design was mainly driven by the high radiation levels and the very wide temperature range of the instrument. The system has been optimized with specific constrains: limited radiation resistant glasses availability and lens barrel material.

The filter section is designed in order to improve the optical performances and to withstand the high radiation environment. Great care is taken for the tolerance analysis that is a key factor for the manufacturing process. Specific stray light analyses including ghost effects are included in the optical design.

Keywords: Optical design, radiation resistant glasses

1. INSTRUMENT DESCRIPTION

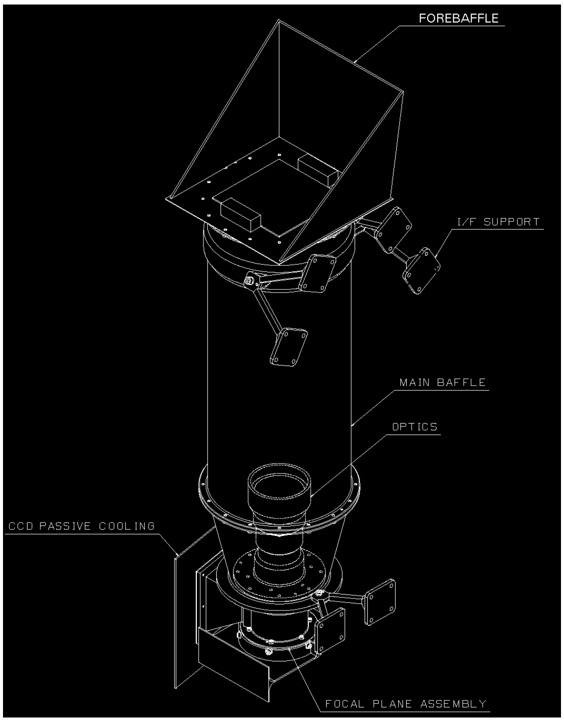

Figure 1: The OMC instrument

The Optical Monitoring Camera (OMC) is a part of the INTEGRAL payload, an ESA scientific mission (INTErnational Gamma-Ray Astrophysics Laboratory) dedicated to the fine spectroscopy and fine imaging of celestial gamma-ray sources. It covers the energy range of 15 keV to 10 MeV with concurrent monitoring in the X-ray (3-35 keV) and optical (V-band) energy range. The satellite is scheduled to be launched in 2001 with a PROTON although all environmental specifications have also to be fulfilled for the alternative ARIANE 5 option.

The Optical Monitoring Camera (OMC) is being built by a consortium of Spanish (INTA), Belgian (CSL), Irish (UCD/DIAS) and British (MSSL) institutes [1]. The OMC instrument consists of a CCD camera unit connected to a single electronic unit. It is a 20 kg class instrument mounted on the top of the INTEGRAL payload module. The camera unit is based on a large format CCD (2048x1024 pixels) working in frame transfer mode (1024x1024 pixel image area) that avoids the use of a mechanical shutter. The CCD is cooled by means of a passive radiator down to operational temperatures lower than -80°C for noise reduction purposes. An optical baffle affords the necessary reduction of scattered sunlight required for faint source detection up to mv = 19. A once-only deployable cover is used to protect the optics and the baffle from contamination during ground testing and early operations in orbit. The figure 1 shows a schematic view of the OMC instrument.

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Aperture size :	50 mm diameter
Field of View (FOV) :	5 x 5 arcdeg square
Pixel size :	13 x 13 µm_ 17.6 x 17.6 arcsec_
Spectral range :	V-band centred at 550 nm
Sensitivity :	19.7 visual magnitude

Table 1: OMC requirements

The main optical requirements of the instrument are listed in table 1. The FOV is defined by the payload pointing mode. It is a compromise between the source confusion and the FOV of other instruments on the payload, particularly the X monitoring instruments. The V-band selection is achieved with a specific filter included in the optical system. The very high sensitivity will be reached with adequate diaphragms and dedicated baffles.

2. OPTICAL DESIGN AND PERFORMANCES

1. Requirements

The optical design is driven by two main parameters: high optical performances and specific environmental conditions. These parameters are summarized in table 2. The optical performances must be met in the operational conditions while the non-operational environment defines the extreme conditions that shall be withstood without damage. The nominal operational temperature and the very wide temperature ranges result from the thermal design of the instrument. These thermal constrains have a direct impact on the alignment plan and the thermo-optical design. Moreover the thermal requirements at the interfaces dictate the lens barrel material. That reduces drastically the opto-mechanical design freedom. Moreover the OMC location on the top of the payload induces high vibration levels which drive the mechanical design.

Encircled energy:	70% in the pixel (13x13 µm_)
Modulation Transfer Function (MTF):	> 70% at the Nyquist Frequency (38.5 c/mm)
Backfocus:	≈ 50 mm
Transmission (@550 nm):	> 70% at the beginning of life > 60% at the end of life
Lens barrel material:	Titanium alloy (Ti-6Al-4V)
Radiation dose:	42 krad over 5 year sin case of Ariane V launcher
Nominal conditions :	0°C (vacuum)
Thermal range (operational conditions):	-20°C to +30°C
Thermal range (non-operational conditions):	-80 to +45°C
Vibrations (non-operational conditions):	Random: 27 g_{RMS} in the range 20 – 2000 Hz

Table 2: Optical requirements and environmental conditions

2. Optical design

Due to the possibilities of a launch with a Proton and an Ariane V, the optical design has to take into account the worst case conditions. In the case of an Ariane V launcher, the orbit crosses the radiation belts and the payload will encounter 42 krad of additional dose during the 5 years lifetime mission. The high radiation levels impose to select whenever it is possible radiation resistant glass materials to reduce to the minimum the impact of the radiations on the lenses degradation. The main effect of the radiations in glasses is a loss of transmission that will affect directly the overall photometric budget of the instrument.

Because of the aperture size and the availability of radiation resistance glasses, the optical system is based on an optimized 6-lens design [2] as shown in the figure 2.

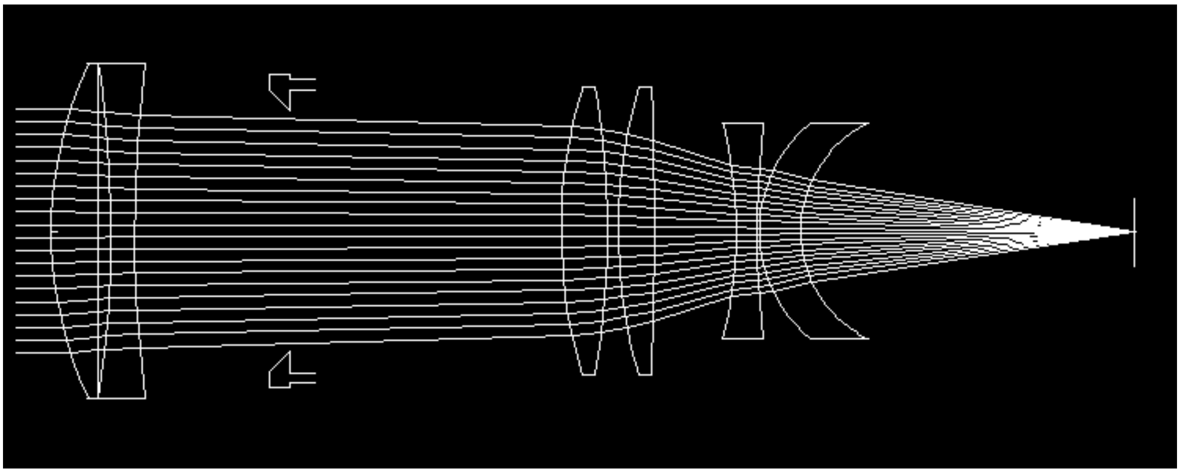


Figure 2: Optical system profile

The lens materials and the optical tolerances are listed in the table 3.

Element n°	Lens Material	Surface n°	Glass	Fringes (@542 nm TBC)	Thickness [mm]	Wedge	Tilt	Decenter [mm]
1	K5G20	1	Grade 3	10	0.1	1’		0.021
		2		10	0.05		1.5’	
2	SF8G07	3	Grade 3	6	0.1	0.5’		0.022
		4		10	0.1		1’	
Stop		5						
3	K5G20	6	Grade 3	10	0.1	1’		0.021
		7		6	0.04		1’	
4	K5G20	8	Grade 3	10	0.04	1’		0.021
		9		10	0.03		Reference	
5	SF8G07	10	Grade 3	6	0.1		0.5’	0.03
		11		10	0.1	1.5’		
6	K5G20	12	Grade 3	6	0.03		5’	0.04
		13		6		2’		
Detector		14					2’	0.1

Table 3: Optical tolerances of the optical system (without filters)

3. Thermo-optical performances

The theoretical optical performances in nominal conditions, including worst case degradation with tolerances, are listed in the table 4.

	% MTF at 38.5 c/mm		70% Encircled Energy diameter [µm]
Field of view	Radial	Sagittal	
0°	80	80	6.7
1°	80	80	6.7
2°	81	80	6.4
2.265°	81	80	6.3
3.55°	81	80	6.4

Table 4: Optical performances with tolerances in nominal conditions (0°C, vacuum)

Although the design fulfils the optical performances in nominal conditions, the optical system will not fully meet all the optical requirements in the specified thermal range. It is mainly due to the combination of the lens barrel in Titanium and the FPA in Invar. Mechanical and thermal constrains at the focal plane assembly interface dictate the selection of these materials. The FPA is made of Invar to ensure a stable detector location and to limit the heat flux towards the cold parts surrounding the CCD.

The centring and accurate alignment of the FPA with respect to the optics are obtained with tight tolerance locating pins at the interface. From the thermal point of view, it is necessary to limit the heat conductance between the lenses and the very cold FPA. Therefore, Titanium is a good candidate. Moreover, it also provides athermalisation of the optical system with an expansion coefficient similar to the glasses. With this solution, the lens mount can withstand the very large non-operational thermal range without producing stresses or misalignments. Unfortunately, with an Invar FPA, the backfocus doesn't undergo the equivalent scaling obtained in the optical system. A small thermal defocus appears and degrades the thermo-optical performances.

The table 5 shows the estimated performances, assuming isothermal variations in vacuum.

Field	System at –20°C			System at –10°C			System at +10°C			System at +20°C		
	% MTF at 38.5 c/mm		70% Encircled Energy diameter [µm]	% MTF at 38.5 c/mm		70% Encircled Energy diameter [µm]	% MTF at 38.5 c/mm		70% Encircled Energy diameter [µm]	% MTF at 38.5 c/mm		70% Encircled Energy diameter [µm]
	rad	tan		rad	tan		rad	tan		rad	tan	
0°	72	72	10.1	80	80	6.7	72	72	9.6	58	58	13.1
1°	71	71	10.3	79	79	6.6	73	73	9.4	59	59	13.0
2°	69	70	10.7	79	79	7.3	75	73	8.9	62	60	12.6
2.62°	67	70	11.0	78	79	7.6	76	74	8.5	64	61	12.2
3.55°	64	69	11.4	76	78	8.2	78	74	7.8	67	61	11.7

Table 5: Optical performances for different temperatures

With isothermal variations in vacuum, the system doesn't fulfil completely the MTF requirement at extreme operational temperatures, particularly at high temperatures. The encircled energy requirement is nearly achieved in all cases.

This optical configuration is particularly sensitive to radial thermal gradients. With a +2.5°C radial gradient (from centre to edge of the lenses), the performances remain only compliant at 0°C. To limit as much as possible these degradations, flexible heaters with thermostat will be used on the lens barrel external surface. This active thermal control will keep temperatures in the operational range and will reduce the internal thermal gradients. The axial thermal gradient will be limited to –10°C (from lens 1 to lens 6) with a small influence on the optical performances.

4. Filter assembly design

The Johnson V-filter has been designed with 2 filter glasses (Schott BG39 and GG495). It is one of the most critical items in the optical system since on one hand there are no specific filter materials optimized to withstand high radiation levels without damage. On the other hand the filter has to be located in a collimated beam, in front of the optical system, to limit the aberrations and the stray images. In this forehead position, the filter is directly submitted to the radiations through the baffle aperture and indirectly through the baffle thin walls (2 mm thickness of aluminium). Without any protection and by taking into account the payload shadowing and the OMC design, the filter should encounter, at the end of mission lifetime, a dose of 2.10^5 rad for the BG39 glass and $1.7\ 10^4$ rad for the GG495 glass.

The effect of radiation dose in the filter materials is difficult to estimate since no data is available. A study has been performed by the glass manufacturer on 2 very similar materials: BG38 and GG475 (nearly same bandpass and heat treatments). Using these data, the transmission losses can be respectively evaluated to –1.1 % for the BG39 and –3.9 % for the GG495. To limit the damage induced by the radiation dose on the filter, a radiation resistant glass plate is added before the filter plate. A trade-off between the total transmission, the mass and the transmission losses due to the radiation dose concluded to add a 3.5 mm Schott BK7G18 glass plate: the transmission losses decrease to –0.2 % and –1.1 % respectively for the BG38 and the GG475 filter glass.

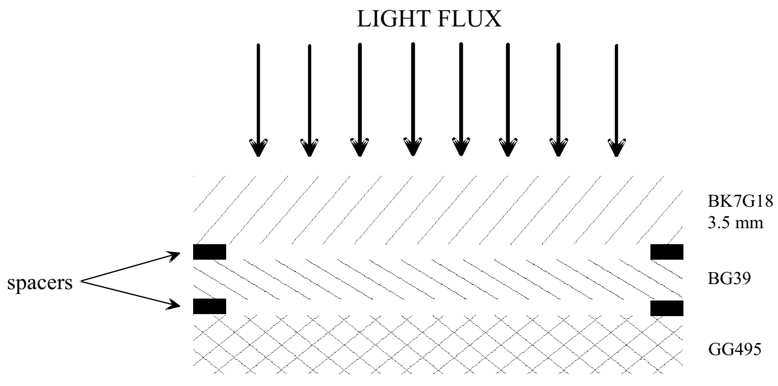


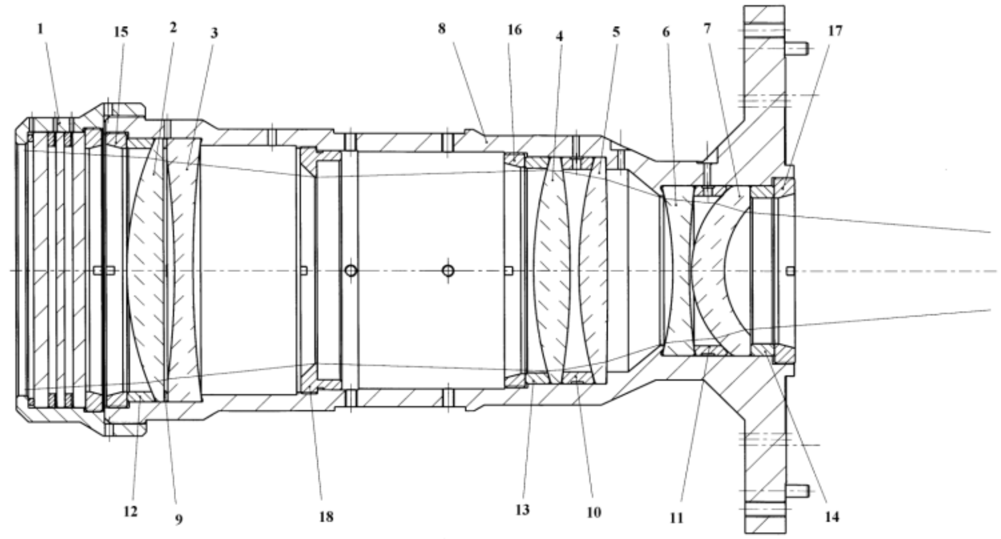
Figure 3: Filter stack design

The figure 3 illustrates the final design of the filter assembly. All the optical surfaces are coated with a space qualified anti-reflective (AR) coating (R ≤ 0.5% at 470 ≤ λ ≤ 650 nm) to improve the transmission. The surface towards the cold space of the protective BK7G18 glass plate is left free of coating to avoid coating degradation with the high radiation level. The transmittance at 550 nm of the complete optical configuration (filters+lenses) is near 72 % at the beginning of life (BOL). The degradation during the lifetime of the mission, assuming an Ariane V launcher, is detailed in the table 6. At the end of life (EOL), the total transmission is limited to 68 %. There remains a 8 % margin at EOL, that has to take into account the AR coating degradation which is not well characterized.

	Shield	Filter 1	Filter 2	Lens 1	Lens 2	Lens 3	Lens 4	Lens 5	Lens 6	Total
BOL transmission	95 %	84.2 %	99.6 %	98.4 %	98 %	98.4 %	98.6 %	98.2 %	98.5 %	72 %
EOL transmission	95 %	84 %	98.4 %	97.5 %	97.6 %	97.5 %	97.9 %	97.8 %	97.7 %	68 %

Table 6: BOL and EOL transmission budgets

3. OPTO-MECHANICAL DESIGN



1: filter assembly
2: lens 1
3: lens 2
4: lens 3
5: lens 4
6: lens 5
7: lens 6
8: lens barrel
9: distance ring
10: distance ring
11: distance ring
12: pressure ring
13: pressure ring
14: pressure ring
15: retaining ring
16: retaining ring
17: retaining ring
18: aperture stop

Figure 4: Mechanical design of the optical system

Tight tolerances necessary for the positioning of optical surfaces were defined by the optical design. To meet accurate tolerances (table 3), the lenses are maintained directly in their seats with pressure or retainer rings. The contact areas are tangential to reduce the stresses on the lens surfaces [3]. The filters don't require such accurate mounting, therefore an elastomere ring is used to reduce the stress. The figure 4 shows the mechanical design and the lenses configuration.

Due to the thermal requirements at the interface, the lens barrel material is set to Titanium alloy (Ti-6Al-4V) although this one associated with an Invar FPA degrades the thermo-optical performances. The filter assembly is screwed on the main lens barrel. Venting holes and thermostat interface are foreseen to allow the use in vacuum and the temperature control. The lens barrel flange interfaces with the baffle and the focal plane assembly on the same side on two concentric contact areas. The torques applied on retainers have been computed to fulfil the vibrations requirements without misalignments. The two first lenses (i.e. lens 1 and 2 in figure 4) are particularly subject to high acceleration due to their location and their mass. The optical system vibration behavior has been qualified at such level in the CSL shaker facility.

4. STRAY-LIGHT ANALYSIS

The OMC instrument must have the ability to detect faint sources (up to mv = 19.7). This requires very stringent light shade conditions [4]. All the sub-systems are studied to provide efficient stray-light attenuations. In the case of the optics, internal reflections are avoided with AR coatings on optical surfaces and deep blue anodizing on the lens barrel. Although this latter coating is not the most suited for stray-light reduction, it is used for technological and cleanliness purposes. This coating doesn't add any extra thickness to the lens seats and hasn't to be taken into account for the alignment budget. Moreover it passivates and hardens the surface allowing a decrease of the friction between the lens barrel and the retainers, limiting by this way the applied torque necessary to fulfil the vibration specifications.

As no tight tolerance is needed for the aperture stop, it is coated with black chromium, which adds a larger extra-thickness. The black coating on this element is more crucial, the aperture stop being illuminated with nearly normal incidence. In this case, an efficient diffusive absorbing coating is primordial.

Ghosting is an additional source of spurious signal. When bright sources are imaged through the optical system, part of the focused energy can be internally reflected by the optics and collimated back to the detector. In the OMC instrument, care was taken to reduce these blemishes over all the FOV during the optical design. The main source of ghosting is the filter stack located in the collimated beam. It gives perfectly focussed ghost images, which are superimposed with the real image. The flux in the ghost images can be computed with standard optical softwares. This important part of the stray-light is affecting directly the optical design, and was included in the study at the earliest stage of the design. The other ghost interactions give spots with energy 9 orders of magnitude lower, spreading on a blur diameter larger than 3 mm.

5. CONCLUSIONS

The optical system of the Optical Monitoring Camera has been optimized to fulfil most of the requirements although the lens barrel and FPA materials are not the most appropriate association from the optical point of view. The combination of Titanium with Invar limits the thermal range and the thermal gradient where the optical requirements are fulfilled. The isothermal variations are limited to [-20°C; +20°C]. Larger range could be obtained by limiting the optical quality criterion to the 70 % encircled energy diameter. Moreover the system is very sensible to radial gradient which will be reduced with the active thermal control. The filter assembly has been designed to limit the optical degradation and the transmission losses due to the radiation doses. Specific lens material and optical design are selected to withstand these doses.

The mechanical design takes into account the optical tolerances and the mechanical stresses in the lenses. Care was taken to reduce stray-light and ghost images with absorbing coatings and anti-reflective coating on the optical surfaces.

6. ACKNOWLEDGMENTS

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7. REFERENCES

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