

International Conference on Space Optics—ICSO 2018

Chania, Greece

9–12 October 2018

Edited by Zoran Sodnik, Nikos Karafolas, and Bruno Cugny



Full-SiC derotator optics for METimage: preliminary design and verification approach

E. Renotte

C. Bastin

F. Bernard

A. Bernat

et al.



icso proceedings



Full-SiC Derotator Optics for METimage: Preliminary Design and Verification Approach.

E. Renotte ^a, C. Bastin ^a, F. Bernard ^a, A. Bernat ^a, JM. Boitrel ^d, M. Bougoin ^d, C. Flebus ^a, E. Gillain ^a, P. Gloesener ^a, A. Jago ^b, G. Laffitte ^d, F. Lemagne ^a, D. Logut ^c, F. Mallet ^d, A. Mazzoli ^e, F. Michel ^a, M. Pfafe ^b, M. Pinel ^a, J-M. Schumacher ^a, F. Wolfs ^a.

^a AMOS s.a., Liège, Belgium ; ^b Airbus Defence and Space GmbH, Immenstaad, Germany ; ^c Airbus Defence and Space SAS, Toulouse, France ; ^d Mersen Boostec SAS, Bazet, France ; ^e Centre Spatial de Liège, Liège, Belgium

ABSTRACT

METimage is an advanced multispectral radiometer for weather and climate forecasting developed by Airbus Defence & Space under the auspices of the German Space Administration (DLR) for the EUMETSAT Polar System –Second Generation (EPS-SG). The instrument is equipped with a continuously rotating scan mirror with a 1.7s period followed by a static telescope. The scan mirror permits an extended Earth view of 108° per revolution and regular views to on-board calibration sources. A derotator assembly, which is half-speed synchronised with the scanner, is inserted in the optical beam after the telescope to compensate the image rotation in the focal plane. The derotator optical arrangement is a five-mirror concept that minimises the polarisation sensitivity. The derotator design is constrained by optical performance, mass and compactness, which led to the selection of a full silicon carbide (SiC) concept. This paper describes the preliminary design and verification approach of the derotator optics.

Keywords: Earth observation, MetOp-SG, METimage, optical derotator, silicon carbide

1. INTRODUCTION

The EUMETSAT Polar System – Second Generation (EPS-SG) shall provide global observations from which information on variables of the atmosphere and the ocean and land surfaces can be derived. The observation data shall cover a broad spectral range (from UV to MW), are related to different spatial coverage (global and regional) and are characterised by a variety of different time scales, in order to continue and enhance the services offered by the EPS system. The EPS-SG mission encompasses various observation missions and consists of space and ground-based elements.

The Meteorological Operational Satellite – Second Generation (MetOp-SG) is the space segment of the EPS-SG mission. It is composed of two separate satellites, each carrying a different payload instruments complement (Fig. 1).

These satellites are operating in a low-earth, near-polar, sun-synchronous orbit with a midmorning mean local solar time descending node. They are 3-axis stabilised and Nadir-pointing with a yaw steering mode.

METimage is embarked on MetOp-SG satellite A. METimage [2,3] is implemented as passive imaging spectro-radiometer, capable of measuring thermal radiance emitted by the Earth and solar backscattered radiation in 20 spectral bands from 443 nm to 13.345 μm . The instrument achieves global coverage with 500 m square pixels by continuous scanning orthogonal to the flight direction. It employs in-field separation of the spectral channels. Due to the scan motion, the image moves sequentially over the detector channels. By proper timing of the sampling, a certain pixel in the image is measured sequentially by different spectral channels. The definition of the spectral range for the spectral bands is performed by filters in front of the detectors. The instrument is implemented as in-beam scanner with static telescope and synchronous field de-rotation. Calibration is performed during each scan with different calibration sources without interrupting the scientific observation. The observation principle is depicted in Fig 2.

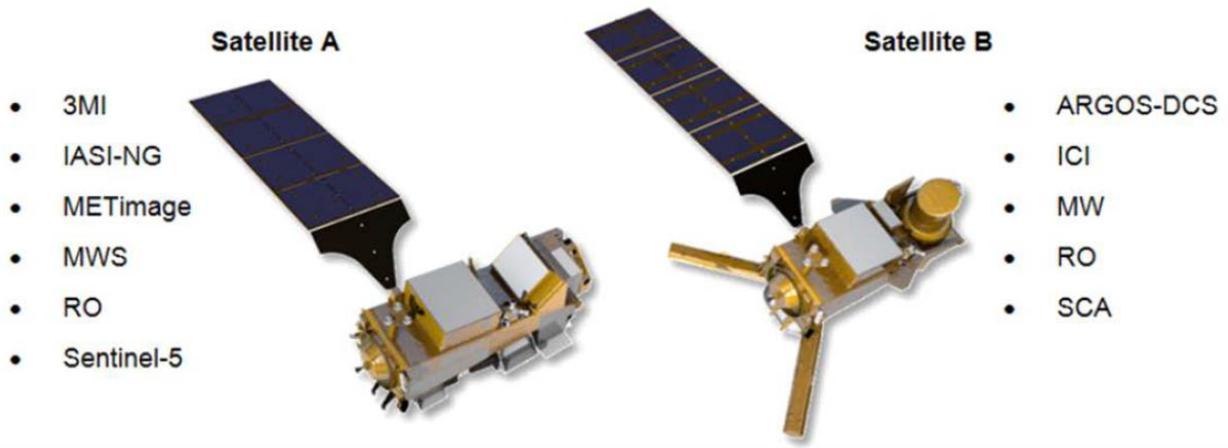


Figure 1. MetOp-SG, the two-satellite space segment of EUMETSAT's EPS-SG mission.

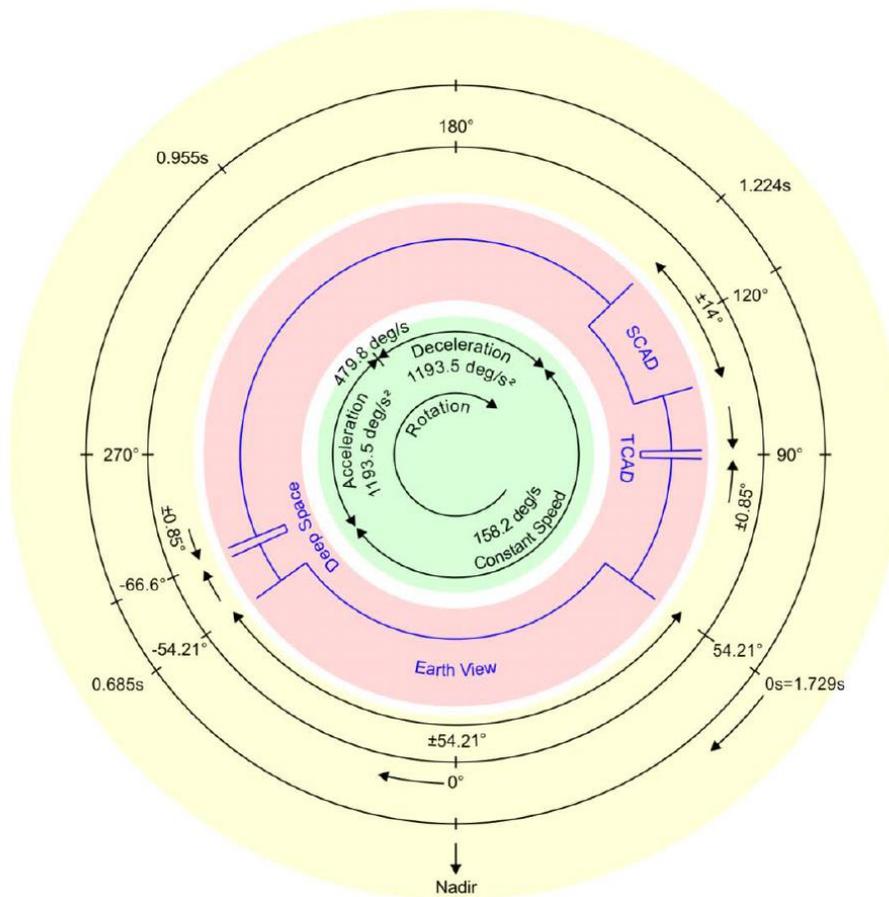


Figure 2. METImage observation principle.

At the entrance of the optical instrument a continuously rotating scan mirror is redirecting the light to the telescope, where the light either is coming from the Earth view or from the calibration sources. A de-rotator assembly, which is synchronised with the scanner and rotates at exactly half of the scan speed, follows the telescope and ensures a regular imaging geometry by correcting the image rotation in the focal plane. Two beam splitters split the observational wavelength range into three

bands, each supported by a separate detector. The VNIR FPA is located in the telescope's focal plane. The 6 spectral bands are realised by filters. While the instrument and the visible focal plane operate at ambient temperature, the infrared optics and focal planes operate within a cryostat at 60K. Field masks within the optical paths of the infrared bands ensure proper spatial co-registration between the bands. The relay optics, needed to reduce the spot size at the infrared detectors, are implemented by lens optics. The infrared focal planes (SMWIR and LWIR bands) are actively cooled by a pulse tube cooler.

2. DESIGN DESCRIPTION

2.1 Derotator Overview

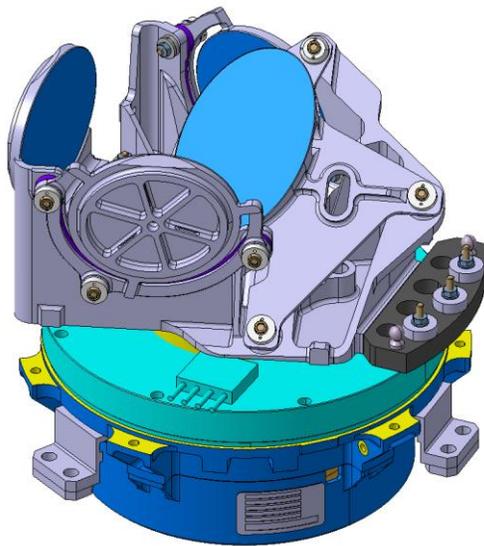


Figure 3. METImage Derotator Assembly (including mechanism, courtesy of Airbus Defence & Space).

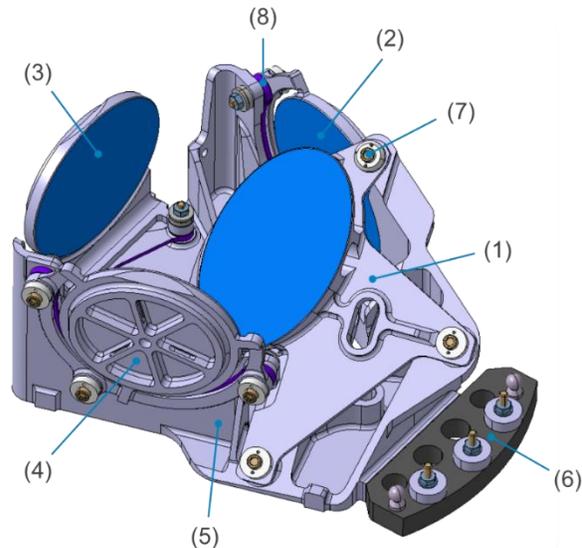


Figure 4. Derotator Optical Assembly.

The optical system consists of five flat mirrors (referred to as M1, M2, M3, M4 and M5), which form an optical derotator as originally presented in the US Patent 4,929,040 [1]. The derotator optics is mounted on a rotating mechanism (Fig. 3) provided by Airbus Defence & Space. During operation, the image of the object through the derotator rotates twice with the rotation of the derotator optics. The Derotator mechanism being half-speed synchronized with the scanner compensates the image rotation in the focal plane.

The orientation of the five mirrors with respect to each other is optimized to minimize polarization sensitivity. The five mirrors are made of BOOSTEC® SiC material (SiC) and mounted on a baseplate from the same material. The baseplate is bonded to an Invar ring that mounts to the rotor of the mechanism.

The Derotator Optics is shown in Fig. 4. Its mass is 2.14kg (calculated) with a maximum dimension of 254mm. It consists of:

- One structural baseplate (5) made of SiC material bonded to the interface ring of the Derotator mechanism (not shown in Fig. 4). A counterweight (6) is added to the baseplate for mass balancing,
- One M1-M5 duplex flat mirror (1) made of SiC material,
- M2 (2), M3 (3) and M4 (4) flat mirrors made of SiC material.

2.2 Baseplate

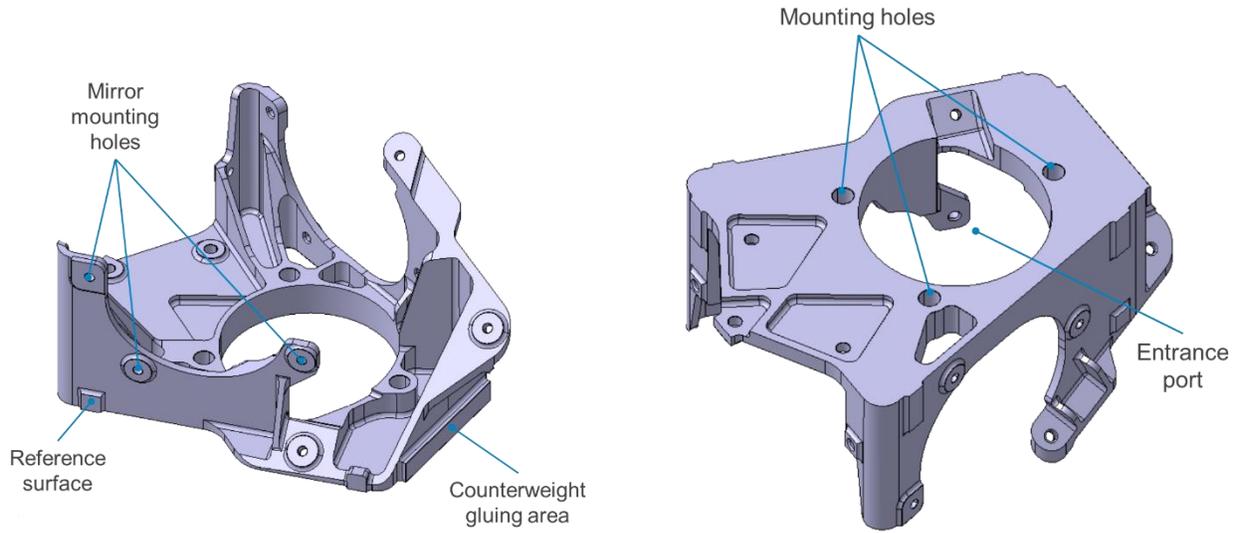
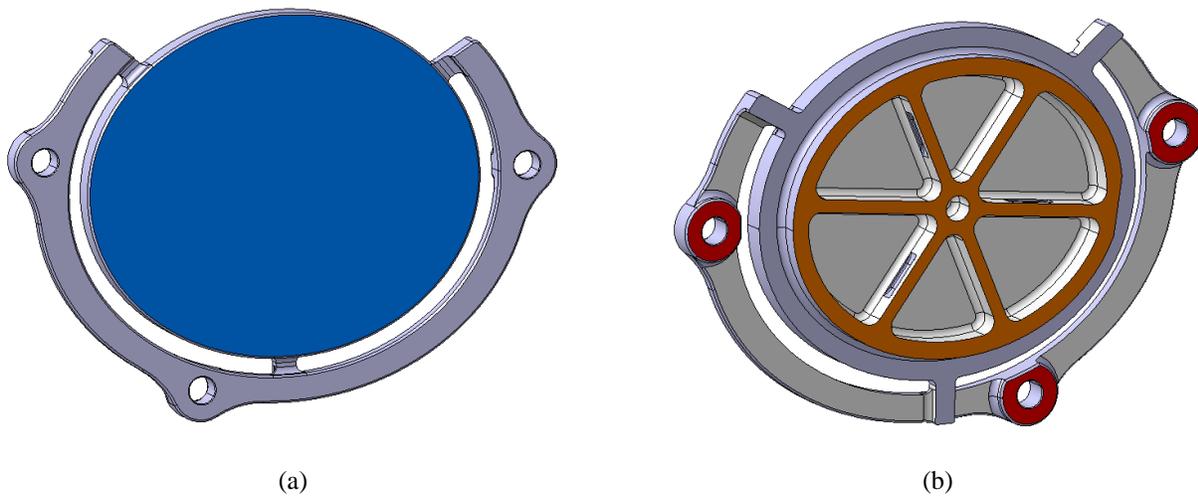


Figure 5. Derotator Baseplate.

The Baseplate is a monolithic piece of SiC (0.8kg) that provides four patterns of mounting holes for the individual mirrors, a circular entrance port on the mechanism side, and a pattern of three holes for interfacing the mechanism rotor on its bottom face (Fig. 5). A counterweight is added to the baseplate for mass balancing of the derotator around the rotation axis. The counterweight additional supports removable alignment references like e.g. CMM reference balls.

2.3 Mirrors and Coating



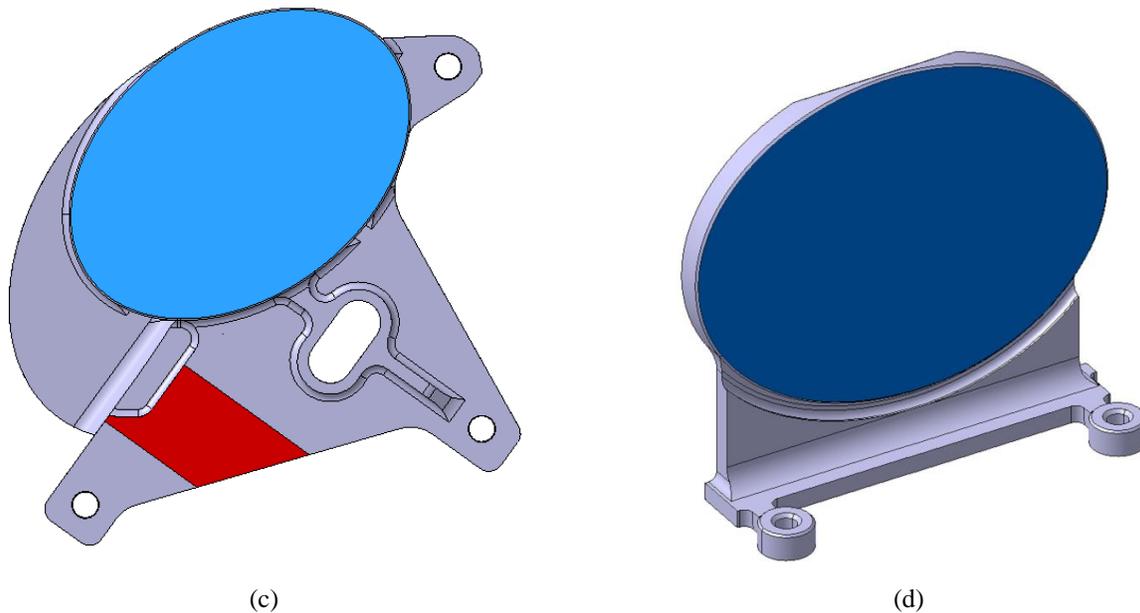


Figure 6. Mirror details: (a) M2 front face, (b) M2 back face, (c) M1/M5 duplex mirror, (d) M3.

Details of the mirror constructions are presented in Fig. 6. M2 and M4 mount to the baseplate walls using a horseshoe shaped ring. Because of room restrictions, M3 rather uses a bracket to mount onto the baseplate bottom. M1 and M5 are arranged back to back, with a small prism angle, in a monolithic SiC piece. M1/M5 duplex mirror is mounted on a tilted plane.

The optical surfaces of the mirrors are treated with Chemical Vapour Deposition (CVD) silicon carbide cladding. Per process, the CVD SiC is free of voids and can be optically polished. After polishing, a specific protected Silver coating is applied on the mirror surfaces to improve the reflectivity and limit the polarization sensitivities.

Each mirror is fastened to the baseplate with three bolts. Except for M1/M5, shims are inserted between the mirror and the baseplate. The shims are adjusted for correcting planarity defects and aligning the mirrors (see below).

3. OPTICAL PERFORMANCE

The derotator optical performance requirements can be split in 3 categories

- Line-Of-Sight (LoS) performance (pointing, co-registration/distortion and pupil position), which are mainly linked to rigid body motion of individual mirrors
- Optical image quality (Wave Front Error), which is mainly linked to surface errors of individual mirrors
- Optical transmission and polarization, which are linked to the coating performance

LoS and image quality performance requirements are broken down by error source, and by mirror, as shown in next figure.

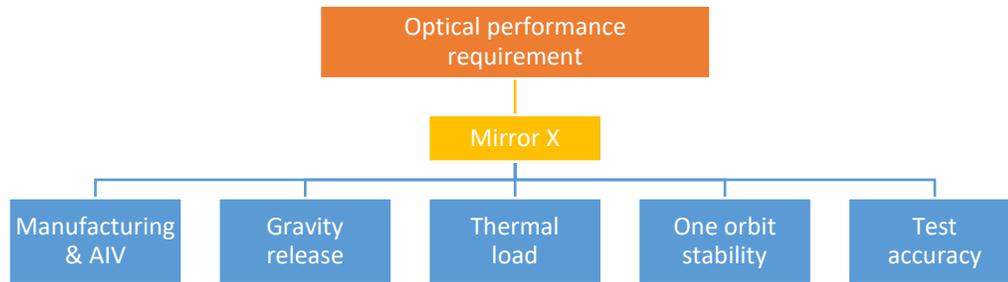


Figure 7. Optical performances error tree.

One particularity of this derotator is that the optical beam is not collimated but convergent, as shown on Figure 8. This non-collimated beam induces different footprint on the different mirrors, as shown in Figure 9. The sensitivity of each optical performance to the position and surface figure error of each mirror is thus not direct and shall be evaluated from the optical model. Final performance is obtained by combining these optical sensitivities with the mirror displacement/surface error computed by finite element analysis or specified to manufacturing (polishing) and alignment.

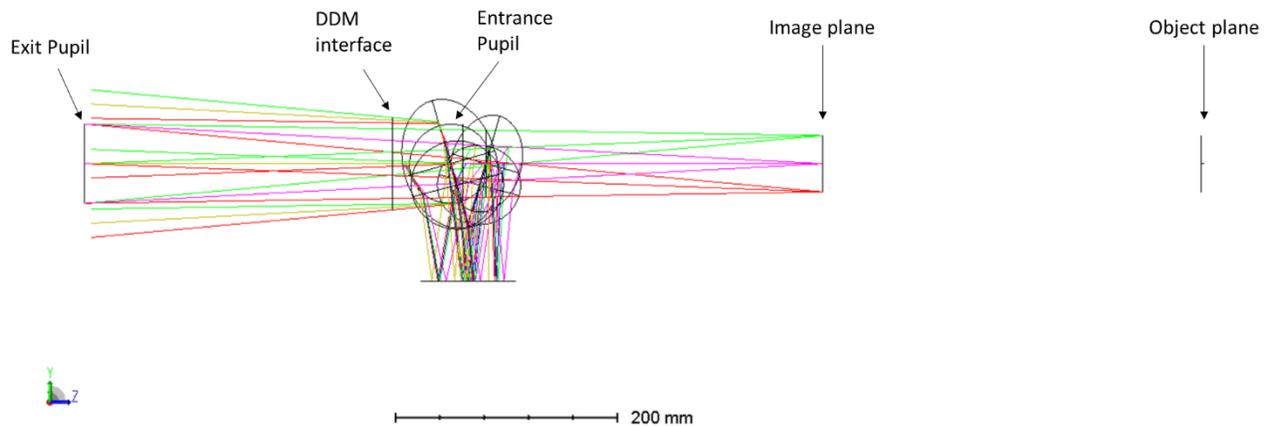


Figure 8. Optical design.

One of the tightest requirement is the Los/pointing performance, which allows only very small tilt/decenter on each mirror (a few arcsec). Hopefully, the main contributors (manufacturing & AIV) can be compensated by proper alignment between the derotator optics and the mechanism. The combination of the remaining contributors is in-line with the required performance.

Exit pupil wobbling cannot fully be compensated in the same way that the pointing. However, the requirement is less severe (170 μ m wobbling) and the desired performance is achieved with reasonable margins.

Image quality is specified in terms of wave front error (50 nm RMS) and wave front error gradient (7 μ rad RMS). This is quite tight for a set of 5 mirrors. The major contributors to these errors is obviously the polishing errors. The mechanical design of the mirrors, with integrated flexure, allows to keep the impact of integration errors to an acceptable level, and to reach the requested performance.

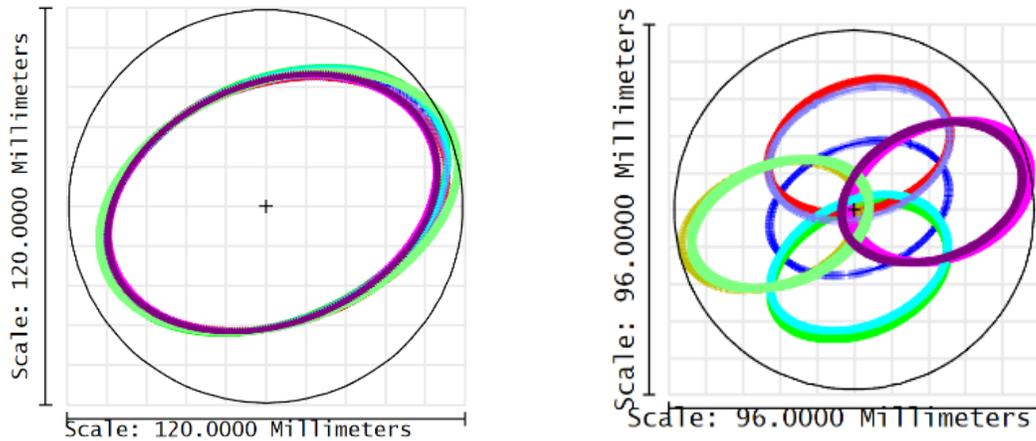


Figure 9. Footprint of different fields on M1 (left) and on M5 (right).

Transmission and polarization requirements are mainly dependent on coating design and manufacturing, and reflectivity measurement accuracy. The current coating design (including margins) leads to a transmission in line with the requirements on the whole spectral range except at one wavelength. However, design and manufacturing uncertainties strongly affect this theoretical performance. Measurement of real coating performance is thus in progress to reduce these uncertainties. Preliminary measures show strong reduction of the margins, and thus acceptable transmission performance.

4. MECHANICAL PERFORMANCE

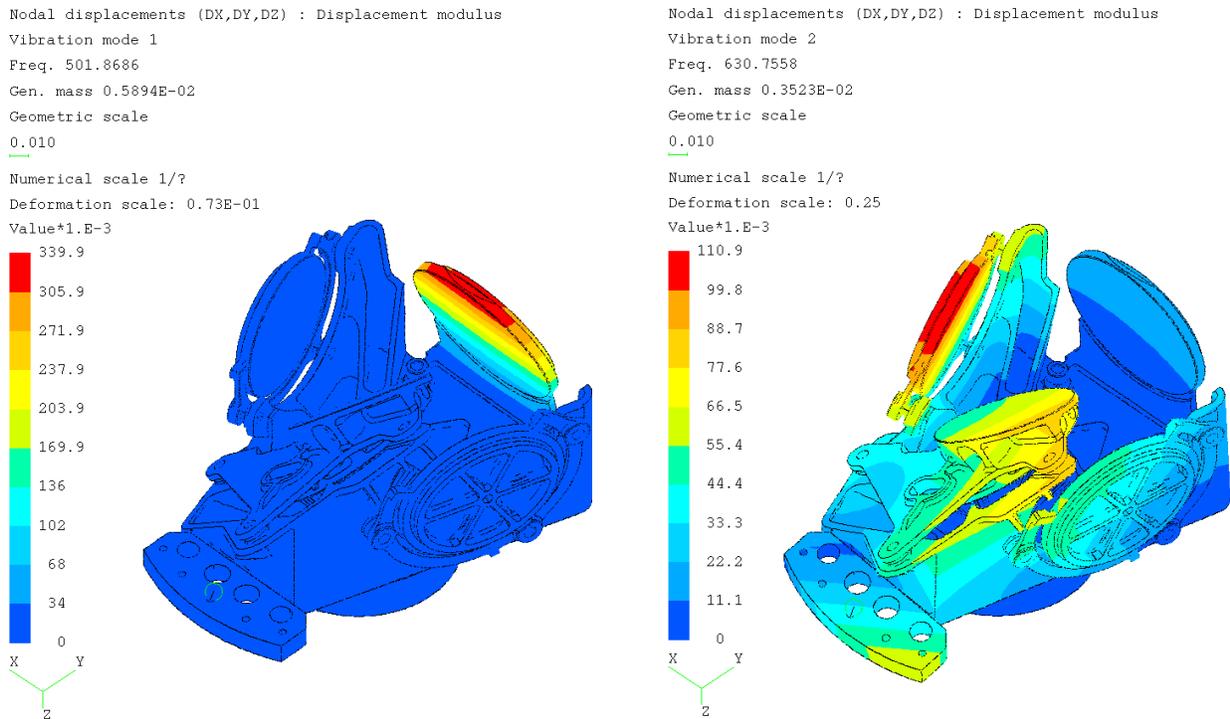


Figure 10. First two vibration modes at 502Hz and 631Hz evaluated by finite element modelling.

The proposed design has been modelled and verified for various load cases, operational and environmental constraints, including:

- Lifetime (up to 22 years on ground, plus 7.5 years in orbit)
- Mechanical envelope
- Mass properties (mass, moments of inertia, balance around rotation axis)
- Radiation hardness
- Stiffness (eigenfrequency)
- Gravity
- Mechanical loads (quasi-static loads, sine vibration, random vibration, shock)
- Integrity and stability of bolted joints
- Buckling
- Imposed displacements (resulting from imperfect contact surfaces)
- Thermo-elastic constraints (resulting from temperature changes and gradients)
- Venting of closed cavities
- Fatigue (damage tolerance)

The preliminary analyses performed so far (before PDR) have demonstrated that the design is compatible with all physical requirements (mass, dimensions, stiffness...) imposed by the instrument accommodation. Fig. 10 shows the first two natural vibration modes (502Hz, 631Hz) of the Derotator Optics.

When exposed to mechanical loads, the shock and random vibration appear to be the most severe solicitations, which will require adequate notching of the input levels. This is still in work at the time this paper is submitted.

With respect to the fatigue, the SiC is not subject to crack propagation and the Titanium bolts will be preloaded not more than 60% of their yield limit.

In absence of compression loads, the system is not subject to buckling.

5. DEVELOPMENT & VERIFICATION APPROACH

5.1 Model Philosophy

Table 1. Derotator model philosophy summary.

Model	Representativeness	Use
Structural & Thermal Model (STM)	Mechanical/thermal representatives, not optical (no CVD, no coating)	Assembly training, I/F fit check, design qualification
Engineering Qualification Model (EQM)	Refurbished STM (semi-polished mirrors, without CVD)	To support instrument level verifications
Flight Model 1 (FM1)	full flight standard	Flight use, to populate instrument FM1
Flight Model 2 (FM2)	Identical to FM1	Flight use, to populate instrument FM2
Flight Model 3 (FM3)	Identical to FM1	Flight use, to populate instrument FM3
(Optional) Flight Spare (FS)	Identical to FM1	(Optional) spare

The STM is based on the flight design but the optical surfaces are not optically finished. i.e. no CVD SiC, no mirror figuring, no mirror polishing, no optical coating, no alignment. The STM is intended for AIT training, interface fit-checks and design qualification. The STM shall be submitted to full mechanical & thermal qualifications of the assembly including the glued interface ring.

The EQM shall reuse the STM hardware with refurbished mirrors polished to roughly 5nm_{RMS}, 2 fringes and coated (without CVD). The Derotator Optics EQM shall be aligned to flight standard and shall be submitted to thermal and mechanical acceptance (1-axis).

The Derotator Optics flight models (FM1, FM2, FM3) shall use qualified materials, parts and processes according to all configuration control and product assurance provisions. The Derotator Optics FM2 & FM3 shall be identical copies of the FM1. The FM1, FM2 and FM3 shall be submitted to the full sequence of acceptance testing prior to delivery.

The FS is an optional model, not activated.

5.2 Assembly, Integration and Verification Overview

An overview of the AIV sequence is shown in the following chart.

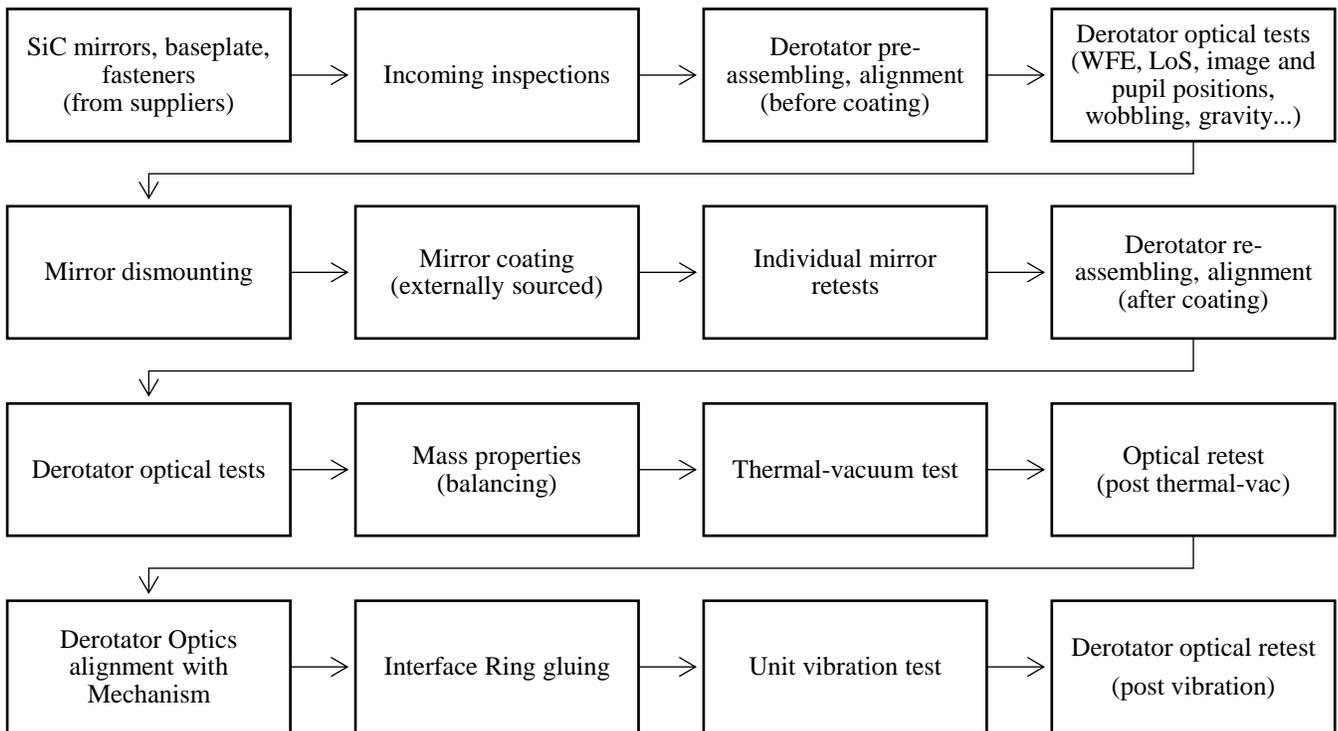


Figure 11: AIV Flow Chart (FMs).

5.3 Alignment

The integration and alignment of the individual mirrors on the baseplate will be done sequentially as sketched below:

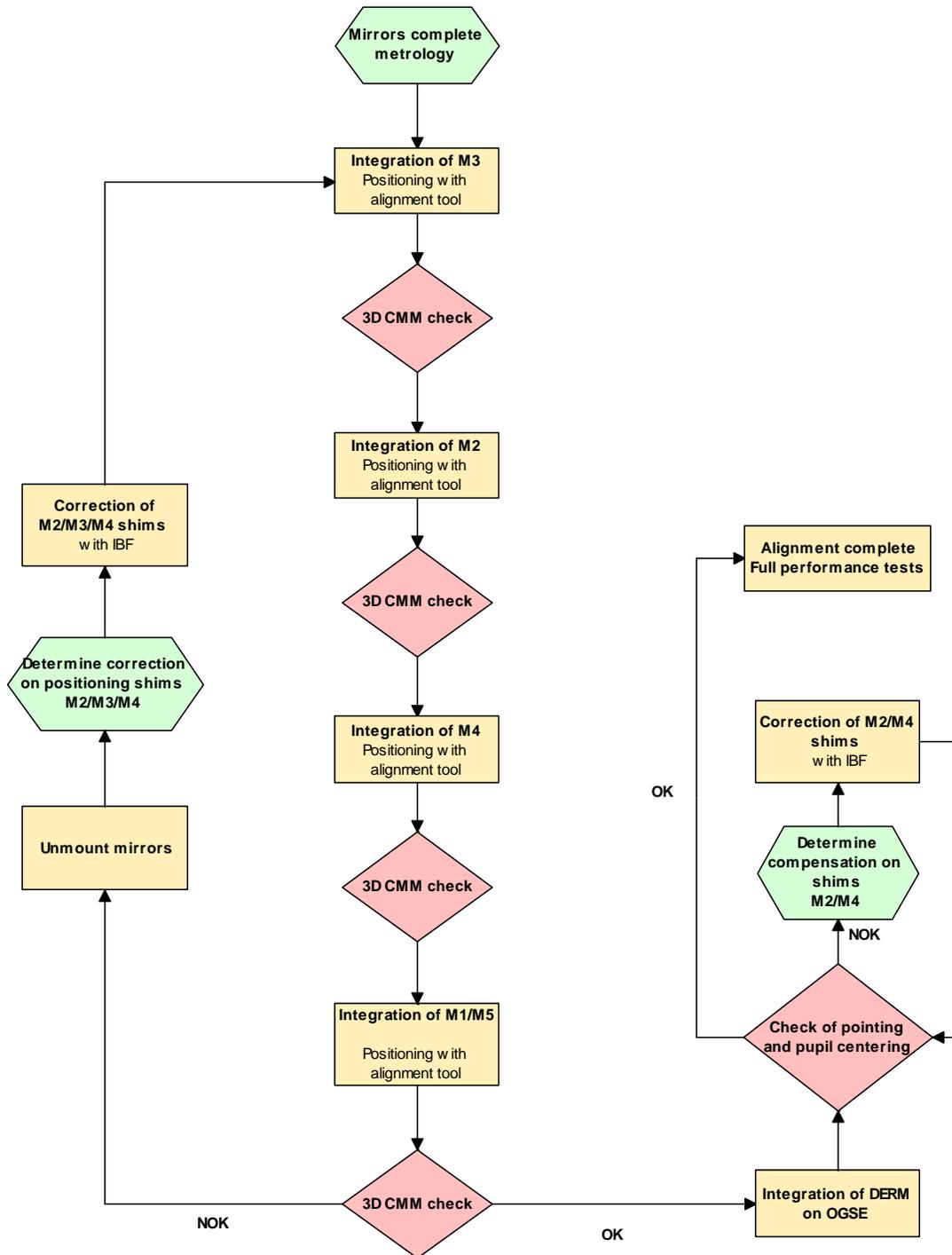


Figure 12: Derotator optics alignment sequence.

5.4 Ground Support Equipment

A specific OGSE (Fig. 13) shall be developed for the verification of the alignment and geometrical performance of the Derotator Optics, i.e.

- Entrance pupil size and position
- Exit pupil position
- Object size and position
- Image position
- Pointing,
- Co-registration
- Exit pupil size and wobbling

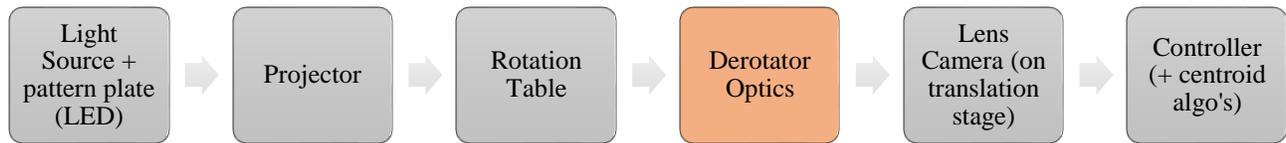


Figure 13: Derotator OGSE block diagram.

A variant of this OGSE, with additional adjustment provisions and without rotation table, is going to be developed to support the alignment of the Derotator Optics with the mechanism rotor and its verification after assembling.

6. FUTURE WORK

The derotator subsystem is developed in accordance with the classical design and engineering cycle of space projects. However, the SiC optics have been identified as long lead items compared to the project planning and their procurement shall be released before going through the whole design review cycle. This paper is presented before the PDR indeed. The derotator optics design is nonetheless believed to show a sufficient maturity to release the manufacturing of the SiC parts in the very short term. Prior to releasing the complete production of the flight hardware there are open works to complete the verification of the design with respect to random vibration and shock loads, to complete the materials and processes validation and qualification, e.g. optical coating and gluing, and to complete the design of the ground support equipment.

7. CONCLUSIONS

This paper presented the preliminary design of a full-SiC five-mirror derotator for the METImage instrument. The SiC design has been preferred over other options because of its compactness, mass and robustness. The proposed design fulfills the accommodation constraints in terms of mounting interface, mass, envelope and stiffness. It satisfies the optical performance requirements, except the throughput and polarization marginally in some spectral bands. It also satisfies most thermal and mechanical requirements

ACKNOWLEDGEMENTS

The METImage Instrument described herein will be developed by an industrial team led by Airbus Defence and Space GmbH on behalf of the German Space Administration DLR with funds from the German Federal Ministry of Transport and Digital Infrastructure and co-funded by EUMETSAT under DLR Contract No. 50EW1521. The Derotator Optics are developed by AMOS s.a. for Airbus Defence & Space GmbH under R&D contract No. F.45706/G01000-6593.

REFERENCES

- [1] T. Pagano, R. Turtle; "Five mirror, two perpendicular plane image derotator", US Patent 4,929,040 (29 May 1990).
- [2] O.Wallner, T. Reinert and C. Straif, "METimage – A Spectro-Radiometer for the VII Mission onboard MetOp-SGS", Proc. SPIE 10562, International Conference on Space Optics — ICSO 2016.
- [3] X. Gnata, M. Weidinger, F. Schmülling, "Metimage: calibration and performance verification", Proc. SPIE 10562, International Conference on Space Optics — ICSO 2016.