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Full-SiC Derotator Optics for METimage: flight hardware status.

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Full-SiC Derotator Optics for METimage: flight hardware status.

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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.

The stringent alignment requirements of the derotator optics lead to an excellent pointing accuracy, confirmed by the measurements performed with a dedicated OGSE. The measured wavefront error of the system is very small, thanks to fine polishing of the five optics.

In this paper, we will present the overall design of the derotator, discuss the manufacturing of the key SiC elements and present the results of the FM1 test campaign.

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 (Figure 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 Figure 2.

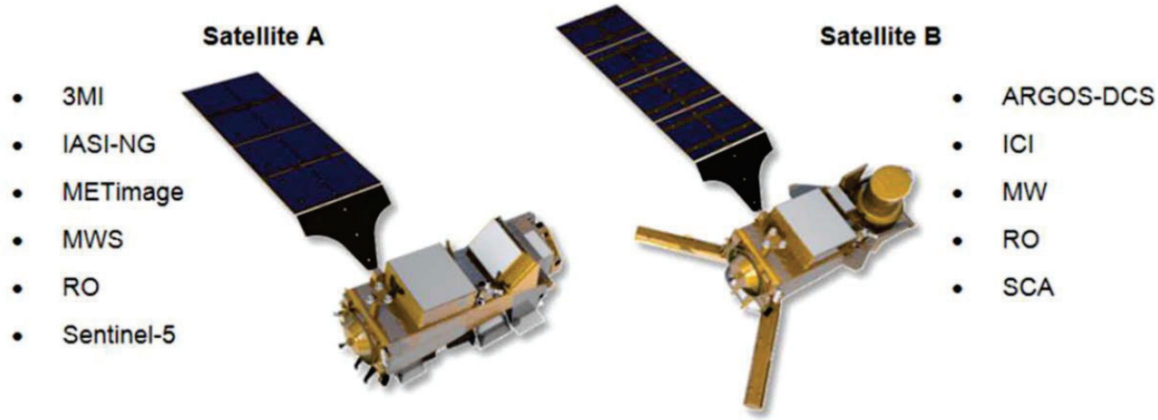

Figure 1. MetOp-SG, the two-satellite space segment of EUMETSAT's EPS-SG mission.

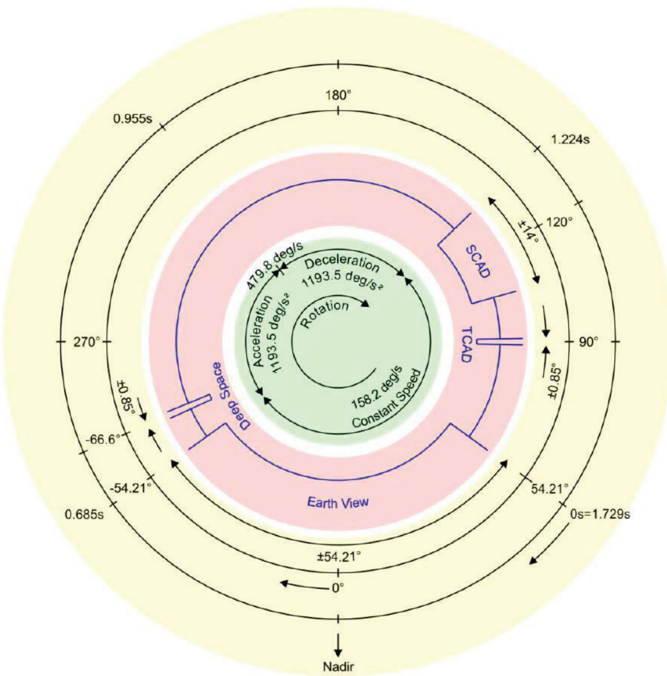

Figure 2. METimage observation principle.

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 synchronized 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 LVWIR bands) are actively cooled by a pulse tube cooler. Details on the optical design of the METimage instrument can be found in [5].

2 DESIGN DESCRIPTION

2.1 Derotator Overview

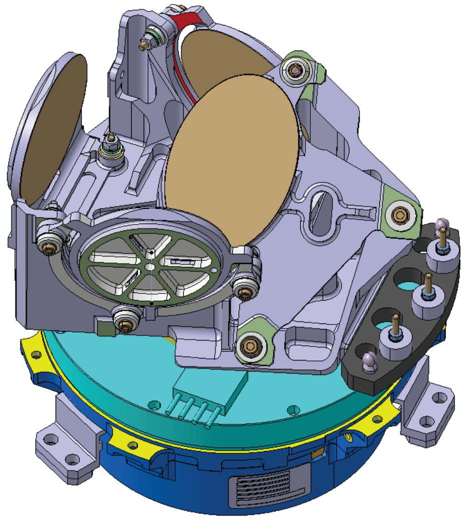

Figure 3. METimage Derotator Assembly (including mechanism, courtesy of Airbus Defence & Space).

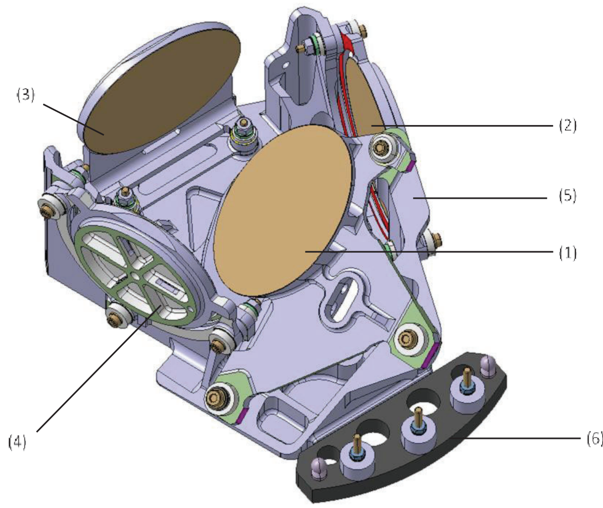

Figure 4. Derotator Optical Assembly.

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 (Figure 3) provided by Airbus Defence & Space (ADS). 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 is mounted to the rotor of the mechanism.

The Derotator Optics is shown in Figure 4. Its mass is 2.260kg (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 Figure 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

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 (Figure 5). An invar counterweight is added to the baseplate for mass balancing of the derotator around the rotation axis. The counterweight supports removable alignment references like e.g. CMM reference balls.

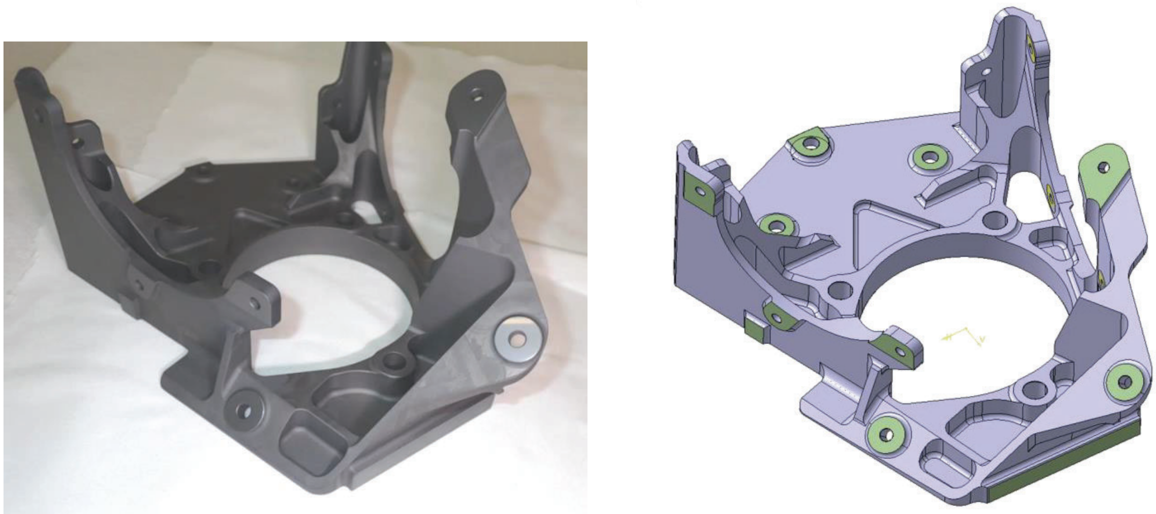

Figure 5. Derotator Baseplate.

2.3 Mirrors and Coating

Details of the mirror constructions are shown in Figure 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 are coated with a polishing layer of silicon carbide by Chemical Vapour Deposition (CVD). Per process, the CVD SiC is free of voids and can be optically polished. After polishing, a specific optical coating is applied on the mirror surfaces to improve the reflectivity and limit the polarization sensitivities. A protected silver coating with superior performance over the full wavelength range of METimage has been designed and space qualified for this programme.

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 aligning the mirrors (see below).

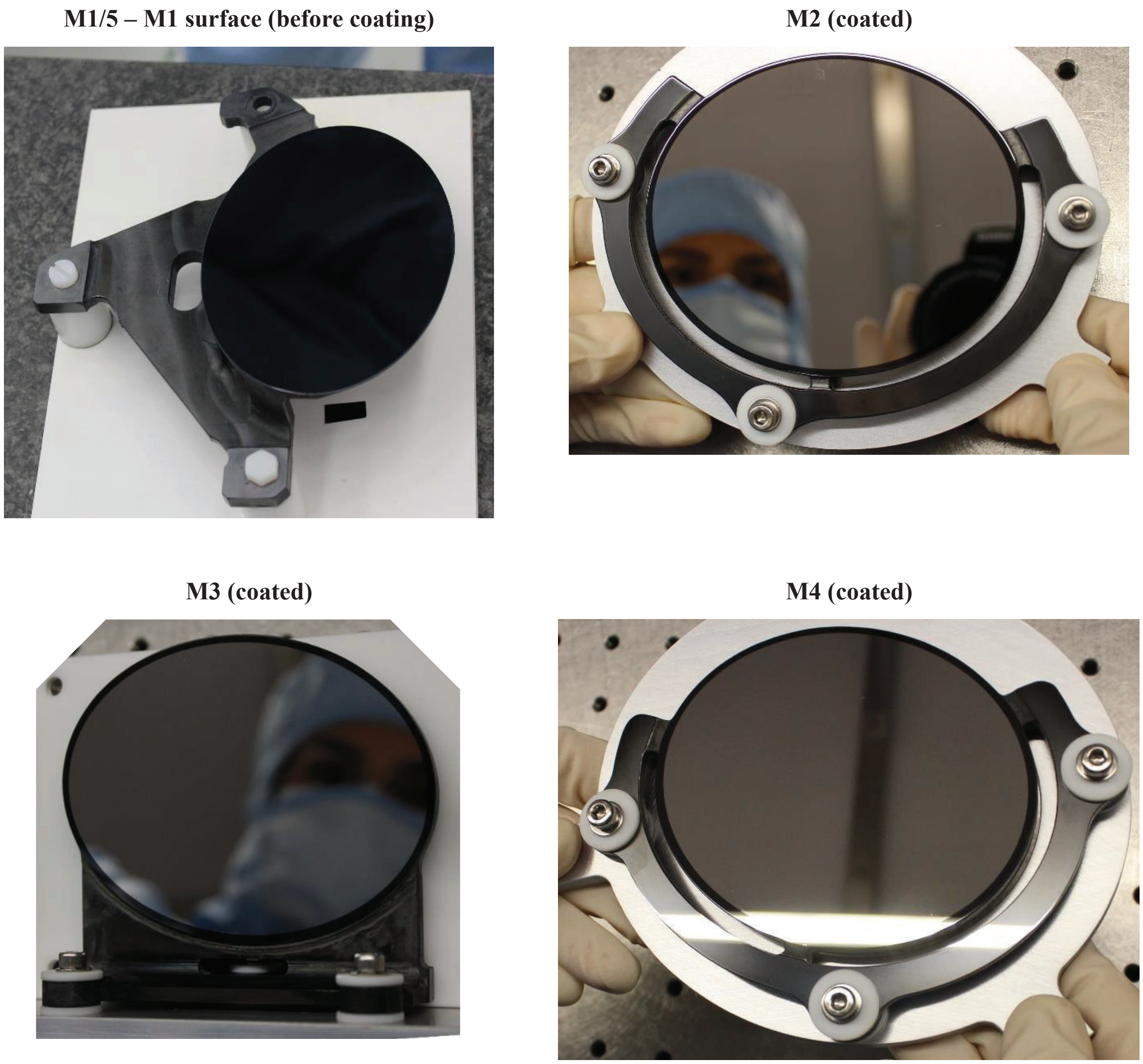

Figure 6. Mirror details (pictures of FM1 model).

2.4 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.

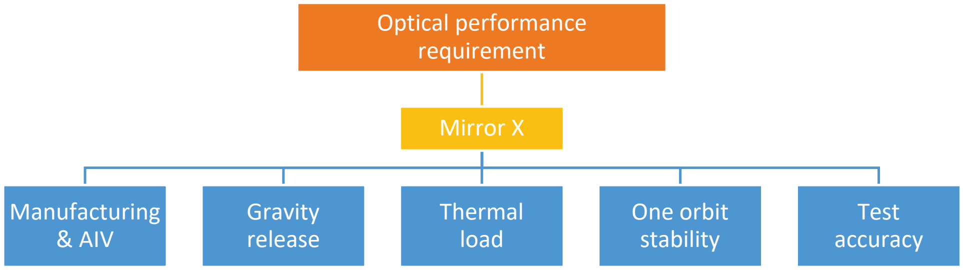

Figure 7. Optical performances error tree.

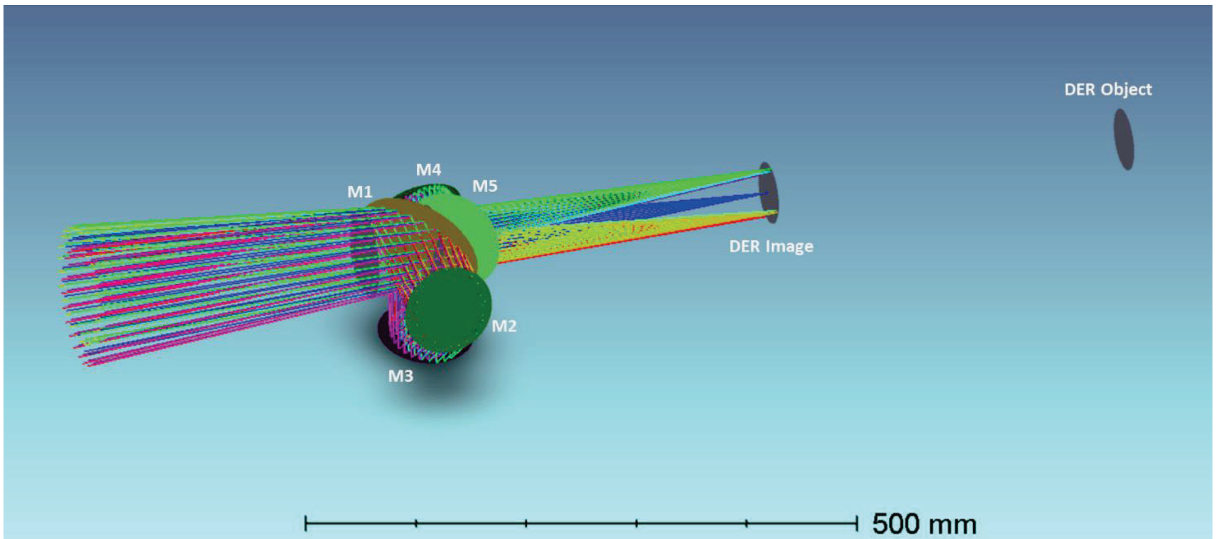

Figure 8. Optical design.

One of the tightest requirements is the LoS/pointing performance, which allows only very small tilt/decentre on each mirror (a few arcsec). Hopefully, the main contributors (manufacturing & AIV) can be corrected by proper alignment between the derotator optics and the mechanism. Exit pupil wobbling can also partially be corrected in the same way.

Image quality is mainly specified in terms of roughness and wave front error (WFE). The WFE is specified to 50 nm RMS, which is challenging for a 5-mirror configuration. The major contributor to these errors is obviously the polishing errors. The mechanical design of the mirrors, with integrated flexures, allows to keep the impact of integration errors to an acceptable level, and to reach the requested performance.

Transmission and polarization requirements are mainly dependent on coating design and manufacturing, and reflectivity measurement accuracy. The proposed optical coating has been optimised to approach at best the mission requirements. Its end-of-life performance was assessed through a severe qualification programme.

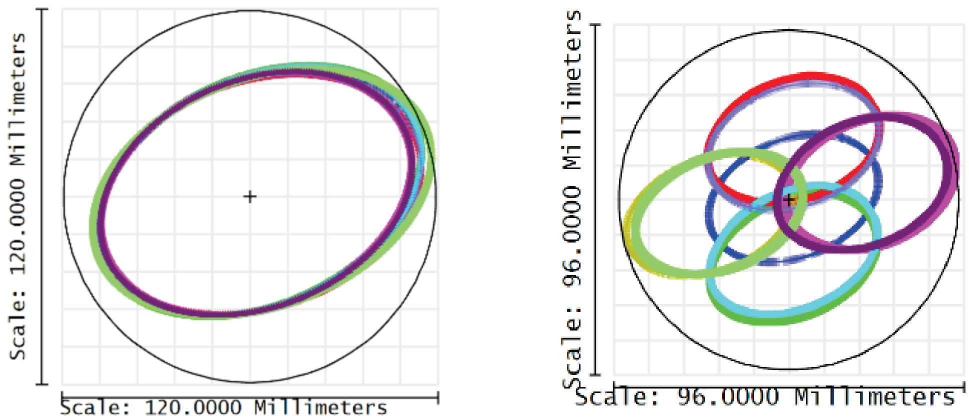

Figure 9. Footprint of different fields on M1 (left) and on M5 (right).

3 DEVELOPMENT & VERIFICATION APPROACH

3.1 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
Flight Spare (FS)	Identical to FM1	Replacement of faulty unit as needed

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 has been submitted to full mechanical & thermal qualifications of the assembly including the glued interface ring. More details can be found in [6].

The EQM reuses the STM hardware with refurbished mirrors polished to roughly 5nm RMS, 2 fringes and coated (without CVD). The Derotator Optics EQM is aligned to flight standard and shall be submitted to thermal and mechanical acceptance (1-axis). At the time of this paper, it has been delivered to the customer.

The Derotator Optics flight models (FM1, FM2, FM3) 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 intended to be a one-to-one replacement unit in case of accidental failure of a flight model.

3.2 Assembly, Integration and Verification Overview

A discussion of the AIV activities and GSE was presented in [4] and [6]. The AIV sequence is recalled in the following chart for reference.

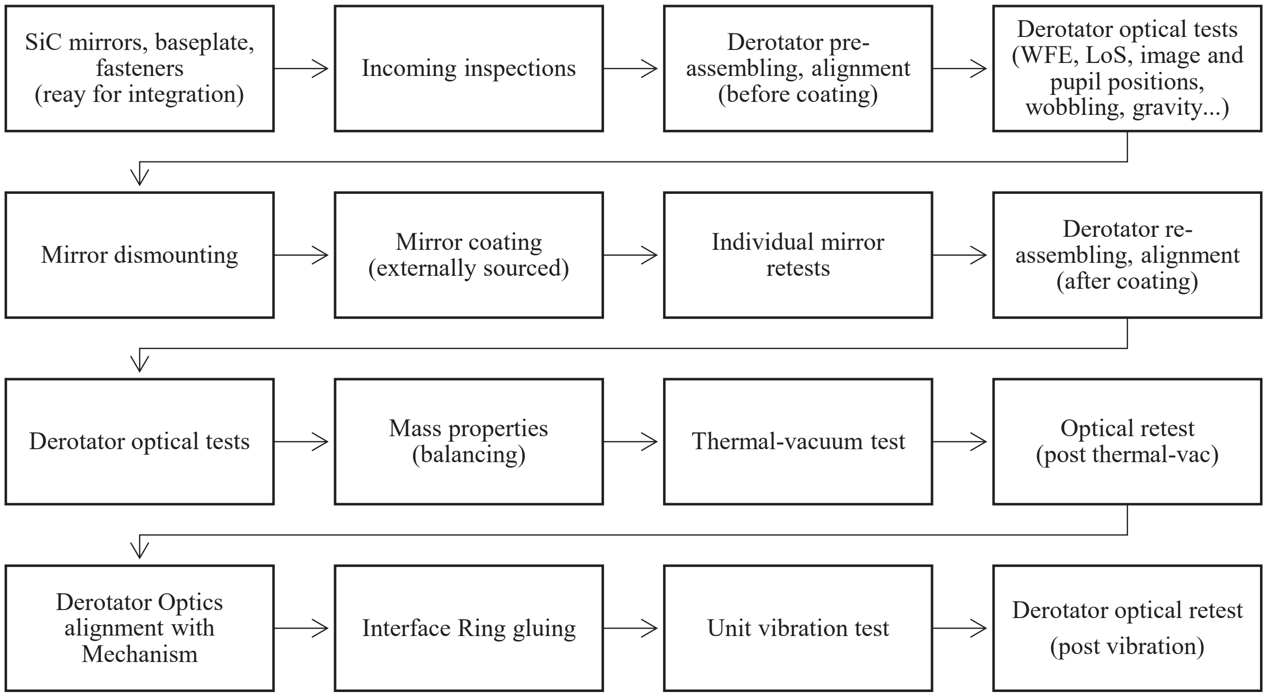

Figure 10: AIV Flow Chart (FMs).

3.3 Derotator optical ground support equipment (OGSE) description

Beside the derotator itself, the derotator OGSE is one of the main equipment manufactured within this activity. This OGSE is able to:

1. align the derotator optics wrt. the derotator mechanism
2. verify the compliance of the derotator optics wrt. its performance requirements
3. verify the mechanisms performance

Two version of this OGSE have been developed:

- **OGSE #1** for testing the derotator optics at AMOS premises, using a precise rotation table to achieve the requested testing accuracy.
- **OGSE #2** for aligning and testing the complete derotator (optics + mechanism) at customer premises (ADS).

The architecture of the OGSE, including the difference between OGSE#1 and OGSE #2, is shown on Figure 11.

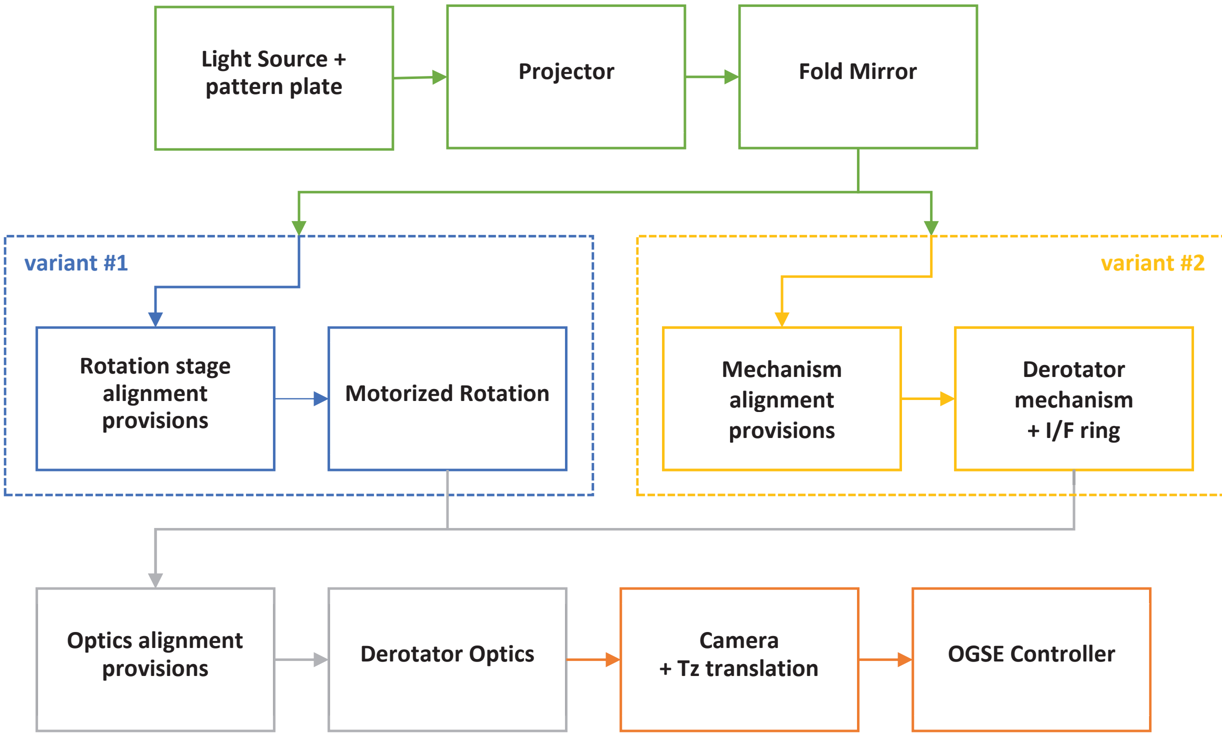

Figure 11: OGSE light flow description

Figure 12 depicts the mechanical design of the OGSE. Its overall dimensions are 2.8x1.7x2m.
It is composed of:

- A mechanical structure made of a baseplate (1) and a tower (2) which holds all the elements
- A source assembly which creates the beam light (3)
- A pattern plate which creates the optical object (4)
- A beam splitter assembly which shapes the light beam (with the help of the spherical mirror) (5)
- A spherical mirror assembly which shapes the light beam (with the help of the beam splitter mirror) (6)
- the camera assembly (7), which can address either the system image or its pupil

The derotator is installed inside the tower, with the rotation axis vertical.

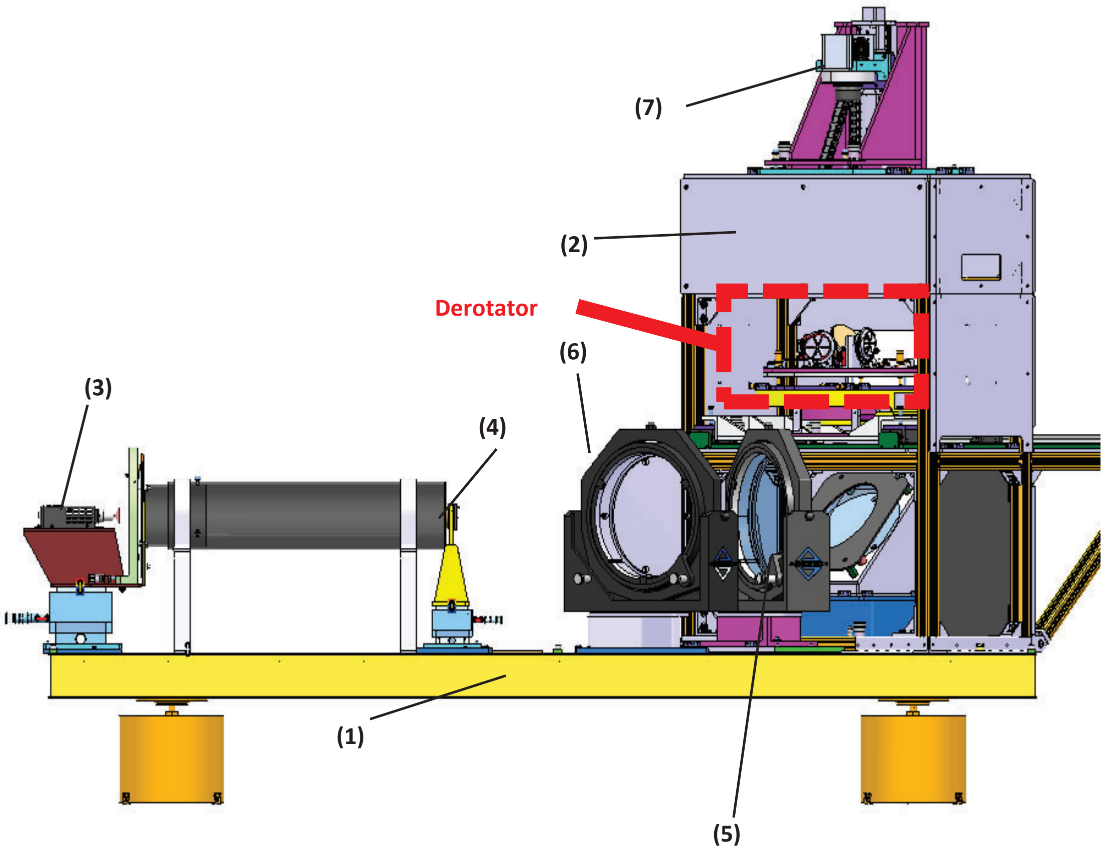

Figure 12: OGSE design overview.

The OGSE operation is automated to allow fast and precise measurement of the derotator performances. One measurement sequence consists in rotating the derotator step by step over 360 deg while taking pictures of the pattern plate through the derotator at each rotation step. The processing of the acquired images allows to estimate the derotator pointing performance and the alignment to be performed to improve this performance.

Alternatively, the OGSE can be set in pupil mode by installing a lens on the camera. The pupil wobbling (which is another specified performance) can then be measured with a similar sequence.

4 FIRST FLIGHT MODEL RESULTS

This chapter presents the main results achieved on the first flight model (FM1) of the derotator optics.

4.1 Mirrors optical quality

The FM1 mirrors have been polished at AMOS using different techniques (grinding, polishing, mechanical figuring and ion beam figuring) to achieve the stringent requested optical quality. The achieved surface figure error is below 10 nm RMS on each optical aperture (see Figure 13) and compliant to the requirement. The microroughness of each optical surface is measured by White Light Interferometry on several locations distributed over the optical surface. The achieved roughness is between 0.3 and 0.5 nm RMS on the 5 mirrors (for a requirement of 0.8 nm RMS). These measurements show the excellent optical quality of the manufactured mirrors.

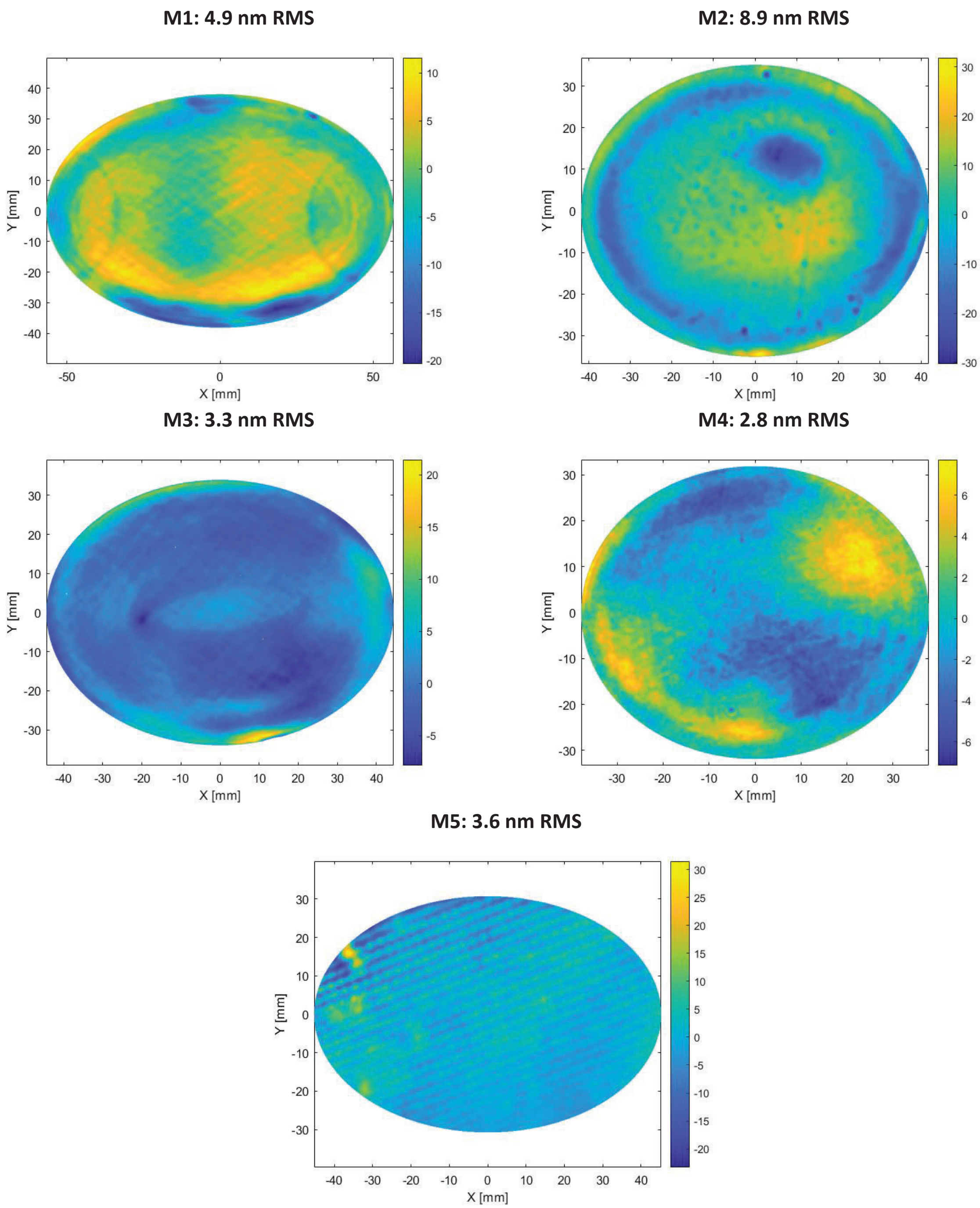

Figure 13: FM1 mirrors measured surface figure error (colour scale units: nm).

4.2 Integration and Alignment

After polishing, the derotator mirrors are integrated with the baseplate and aligned. The alignment is done in several steps:

- Blank mounting of the system without shims, metrology with 3D CMM and computation of the desired shim thickness to achieve proper alignment
- Shims manufacturing
- Complete mounting of the system and fine alignment of each mirror with 3D CMM
- Fine alignment between the derotator optics and the rotating table based on optical measurement with the derotator OGSE (see description in section 3.3).

Figure 14 shows the FM1 derotator completely mounted and aligned with 3D CMM.

Figure 14: Derotator FM1 assembled and ready to be aligned/tested with the OGSE.

4.3 Derotator fine alignment

The derotator fine alignment is performed based on measurements made with the OGSE. A measurement of the derotator FM1 before and after fine alignment is shown in Figure 15. The graphs show the evolution of the centroid on the camera plane during a complete rotation of the rotator. Before alignment, the pointing error is around 700µm PtV. From this error, the processing script computes the alignment to be performed at the interface between the derotator optics and the rotation table. Once this correction has been applied (using micrometric screws), the pointing error is dramatically improved, down to 50 µm PtV, which is compliant to the specification.

A similar approach is used to improve the alignment using pupil wobbling measurement.

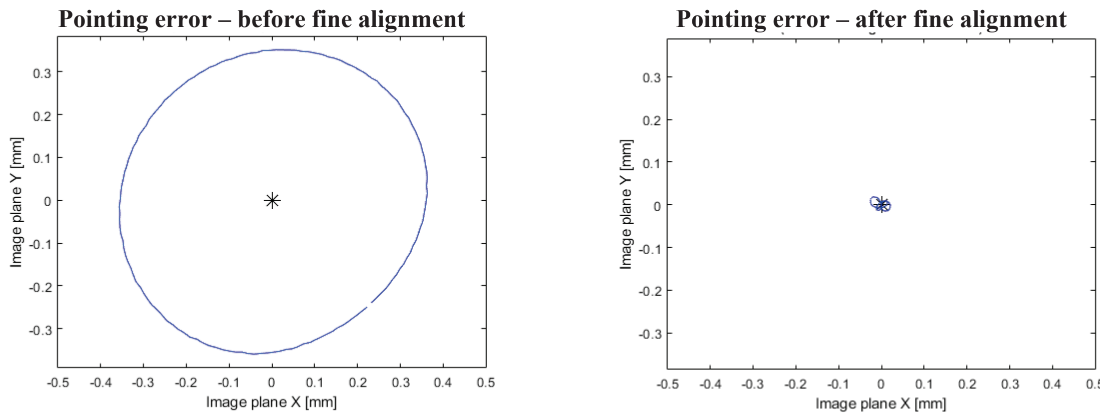

Figure 15. Derotator fine alignment example (FM1).

4.4 Verification campaign

Following the successful alignment of the derotator, the system was dismounted and the mirrors were sent to coating. The system was then reassembled in ISO5 clean room and realigned (see Figure 16). The FM1 was then submitted to the following test sequence:

- Pointing, co-registration and pupil wobbling performance measurement (with the derotator OGSE, see below)
- Wave front error measurement (see below)
- Detailed inspection (including optics cosmetics and electrical continuity check)
- Thermal-vacuum cycling (4 cycles between non-operational temperature limits + acceptance margins)
- Detailed inspection (including optics cosmetics and electrical continuity check)
- Pointing, co-registration and pupil wobbling check
- Wave front error check
- Mass properties measurement (mass, centre of gravity, balancing):
  Derotator FM1 weights 2.267 kg (for a design value of 2.260 kg)
- Detailed inspection (including optics cosmetics and electrical continuity check)
- Cleanliness check (molecular and particular contamination, monitored since coating deposition)

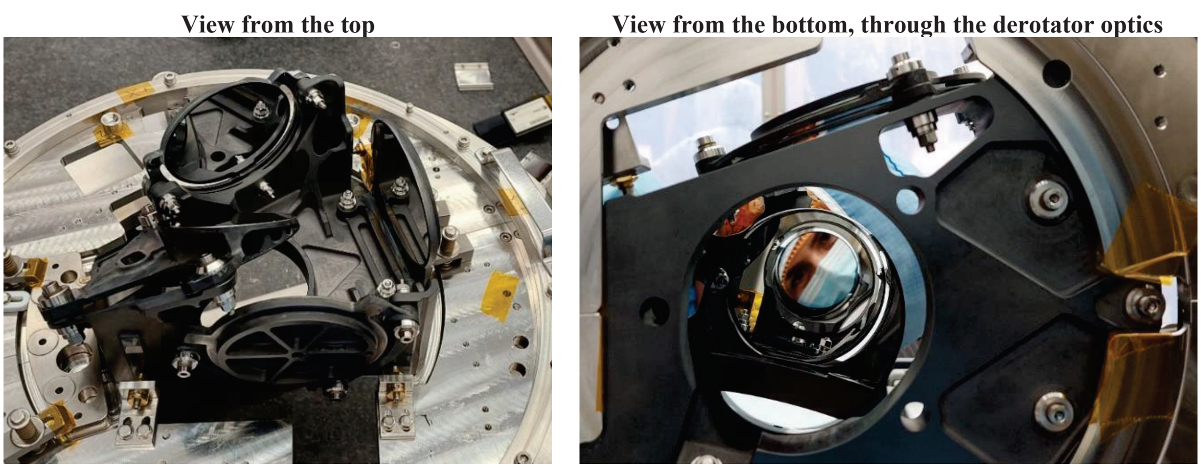

Figure 16. Derotator FM1 re-assembly with coated mirror.

These tests were performed successfully and the derotator optics was delivered to the customer (ADS), where it was integrated and aligned with respect to the derotator mechanism (using the second version of the OGSE). It was then submitted to another successful verification campaign:

- Pointing, co-registration and pupil wobbling performance measurement (with the second OGSE)
- Vibration test (frequency search, sine, random)
- Pointing, co-registration and pupil wobbling check

The pointing/co-registration and WFE tests are detailed below.

4.5 Pointing / co-registration performance

The derotator was retested with the OGSE after coating and after thermal vacuum tests. The measured pointing performance is similar to the one achieved earlier, compliant to the requirement and these tests are thus successful.

The co-registration performance was also tested. The co-registration error is defined as the relative pointing error variation between two points located in the same line in the image plane. This performance is assessed by measuring the differential distortion of several couple of points located on the same line in the OGSE pattern plate while rotating the derotator. The co-registration requirements are severe: for example the average distortion over 1 scan (~60 deg rotation) shall be less than 7.5µm in each direction, while the size of the pixels in the OGSE camera is 6µm.

Figure 17 shows the measured co-registration performance. The graphs show the distribution of the co-registration in the image space. The X and Y axis of each graph are the image coordinates (in mm). Each point represents the worst co-registration measured at this position in the image. The co-registration measurement has been performed by scanning the whole derotator angular range (360 deg). The measured mean co-registration over scan is compliant to the requirement.

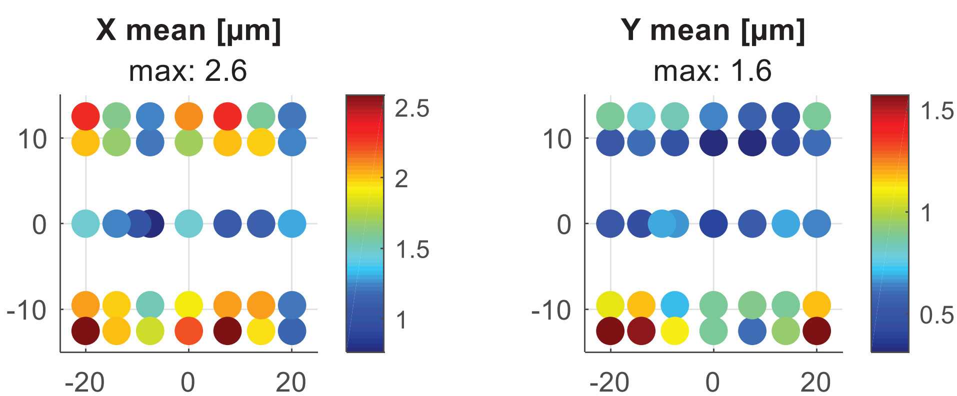

Figure 17. Derotator FM1 co-registration performance (mean over scan).

4.6 Wave front error measurement

The derotator Wave front error (WFE) is measured by interferometry. The test setup is presented on Figure 18.

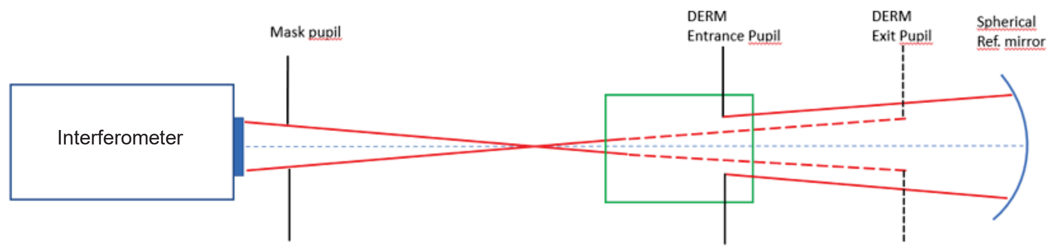

Figure 18. Derotator WFE test setup.

The interferometer is equipped with a reference sphere to create a spherical wavefront, which aperture is larger than the derotator aperture. A pupil mask is used to give the expected shape to the laser beam. A reference spherical mirror is located behind the derotator. The WFE of this mirror is calibrated before the measurement of the derotator to subtract its contribution to the derotator WFE.

The derotator is positioned so that the interferometer focal point is in its image focal plane. In order to address different field of views, the derotator is tilted using an hexapod, and the interferometer is moved accordingly.

The measured WFE of the FM1 derotator in the central field of view is shown in Figure 19. The other field of view show similar performance. This is compliant to the specified requirement (50 nm RMS). The performance is maintained after thermal vacuum tests, which demonstrates the excellent thermal stability of the system.

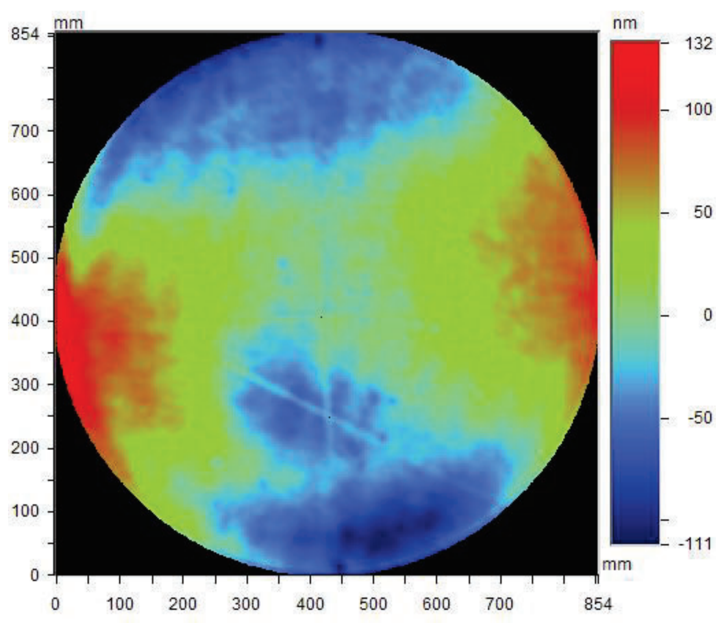

Figure 19. Derotator FM1 WFE measurement (central field of view). WFE RMS: 46 nm.

5 CONCLUSIONS

This paper presents the design and test results of the first flight mode (FM1) 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 fulfils the accommodation constraints in terms of mounting interface, mass, envelope, and stiffness.

The performed test campaign on FM1 demonstrated the good optical quality of the system (excellent micro-roughness and WFE, compliant to the requirements). The precise alignment of the optics lead to pointing and co-registration performances better than specified. Finally, thermal vacuum and vibration tests confirmed the robustness of the derotator against space environment.

This success was achieved thanks to a detailed preparation and anticipation of the different integration, alignment and tests (including a detailed design of a dedicated OGSE), and by capitalizing efficiently on the lessons learned from the early test models (STM and EQM).

6 FUTURE WORK

This paper is presented after the successful delivery of the first flight model. The second flight model is currently being integrated, while the optics of the third model are being polished.

ACKNOWLEDGEMENTS

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