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Pierre Gloesener

F. Wolfs

F. Lemagne

C. Flebus

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Manufacturing, testing and alignment of Sentinel-2 MSI telescope mirrors

P. Gloesener, F. Wolfs, F. Lemagne, C. Flebus
AMOS
Angleur, Belgium
pierre.gloesener@amos.be

P. Gloesener, F. Wolfs, F. Lemagne, C. Flebus
AMOS
Angleur, Belgium
pierre.gloesener@amos.be

***Abstract*—The ESA Sentinel-2 mission developed by EADS Astrium will be devoted to Earth high resolution spectral imagery for the purpose of a global environmental monitoring. As a subcontractor of EADS Astrium, AMOS was responsible for the manufacturing of the instrument telescope mirrors and for the validation of the telescope alignment procedure. This paper details the mirror manufacturing sequences from mirror CVD-SiC cladding to surface figuring and coating, outlining the metrology steps and their corresponding accuracy budget. The telescope alignment process is described in connection with the tooling and techniques that helped achieve the required optical performance of less than 90 nm RMS wavefront error within the telescope field of view.**

***Index Terms*—Telescope, mirror, manufacturing, silicon carbide, alignment, anastigmat.**

I. INTRODUCTION

The Sentinel-2 satellite will embark a pushbroom multi-spectral payload including 13 channels which cover the visible, near infrared and shortwave infrared spectral bands with a large swath to provide systematic information about land surface evolution.

The imager telescope is a wide field three-mirror anastigmat with two concave off-axis aspherical mirrors (primary and tertiary mirrors) and one convex on-axis oblate spheroid (secondary mirror) which supports the aperture stop. The telescope field of view is 20.88 degrees across track and 3.46 degrees along track and its effective focal length lies around 600 mm in the field centre.

The telescope optical lay-out is pictured in the next figure.

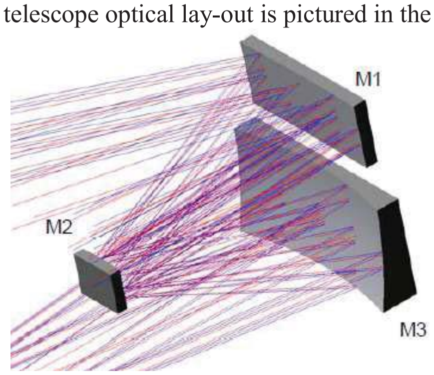

Fig. 1. Telescope optical lay-out

The mirror sizes and characteristics are displayed in the next table:

TABLE I. Mirror characteristics

MIRROR	TYPE	SIZES [USEFUL APERTURE]	REQUIRED QUALITY [SURFACE FORM ERROR IN nm RMS]
M1	Even aspheric, concave, rectangular off-axis	428mm x 180 mm	10
M2	Oblate spheroid, convex, rectangular on-axis	135mm x 109 mm	8
M3	Even aspheric, concave, rectangular off-axis	537mm x 274mm	8

II. MIRROR MANUFACTURING

The mirror opto-mechanical design was performed by EADS-Astrium on the basis of the SiC-100 sintered silicon carbide from BOOSTEC who produced the mirror blanks and delivered them to AMOS.

AMOS took in charge the deposition of a small layer of CVD-SiC on the mirror. The purpose is to generate a non-porous cladding on the mirror surface which allows the polishing process reaching a microroughness state, compatible with the system requirements regarding straylight.

The CVD-SiC cladding is carried out in a furnace where the part is equipped with some savings in order to avoid the deposition of new material on reference surfaces.

The cladding operation took place at SCHUNK premises.

A mirror blank after CVD-SiC cladding is pictured in the next figure, showing a typical baffling arrangement (courtesy of Schunk).

Fig. 2. Mirror blank after CVD cladding

After the SiC deposition and the removal of baffles, the mirror blank is cleaned and submitted to a dye check test to detect the presence of potential microcracks.

If the test is positive, the microcracks are removed by a local grinding and smoothing process.

The CVD layer thickness is measured (with respect to reference surfaces) and this parameter will be controlled throughout the overall mirror manufacturing process.

The target for the final CVD layer thickness stands around 100 microns.

After the preliminary control operations, the mirror blank front surface is processed.

Lapping with decreasing grain size is performed with a robot which generates a toolpath corresponding to the required material removal. The following figure illustrates a step in this process.

Fig. 3. Robot lapping of M3 mirror

In parallel, mirror metrology is performed using a coordinate measuring machine (CMM).

Fig. 4. CMM measurement on M3 mirror

When the mirror shape is measured around 1 micron RMS surface form error, the polishing step is started with the aim to get a surface microroughness Rq around 1 nm RMS.

The interferometric measurements are also initiated at this stage.

The mirror surface form quality is controlled thanks to a dedicated test bench which generates a null interferogram in a Fizeau configuration. Due to the aspherical mirror shape, this configuration requires an auxiliary optical component, here a computer-generated hologram (CGH) whose aim is to generate the phase function in accordance with the shape to be controlled.

The test configurations for the three mirrors are displayed hereafter.

The M1 mirror has a large radius of curvature. Hence the bench is very long, the CGH being located near the interferometer with the tested mirror at more than 10 m from both of them.

Fig. 5. M1 test support

The M2 mirror is convex and requires, in addition to the CGH, the use of an autocollimating sphere, as shown in the next scheme and picture.

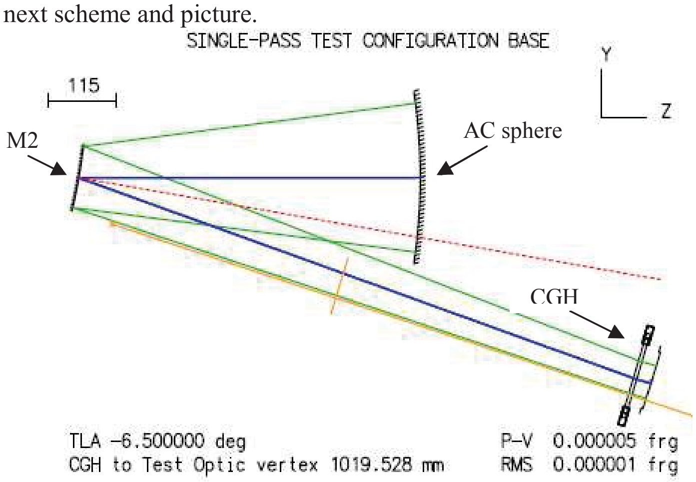

Fig. 6. M2 test configuration

Fig. 7. M2 test bench

The M3 mirror is tested in the same way as M1 but the bench length is rather short, as M3 is very fast.

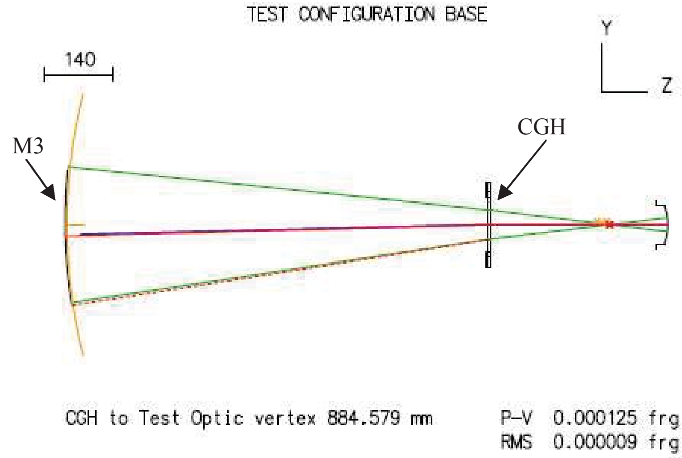

Fig. 8. M3 test configuration

Fig. 9. M3 test bench

The accuracy budget for the interferometric control of the mirrors is rather stringent. The error budget for the M3 mirror surface form error (SFE) is shown herebelow.

TABLE II. M3 ERROR BUDGET

Contributor	SFE (nm RMS)
Interferometer	2
CGH alignment	2.47
CGH encoding & digitisation	0.44
CGH E-Beam registration	0.76
Transmission wavefront distortion after patterning	0.4
Mirror vertex knowledge	2.4
Mirror tolerances on RoC	3
Og residuals	1.7
Ag coating effect	1
Polishing criterion	6
TOTAL	**8**
Specification	***8***

The CGH null is an e-beam master on a fused silica photomask substrate.

It includes auxiliary holograms which allow positioning the interferometer and the test optic at the correct distance and angle, in line with the accuracy budget.

The corresponding layout of the CGH for M1 mirror is the following:

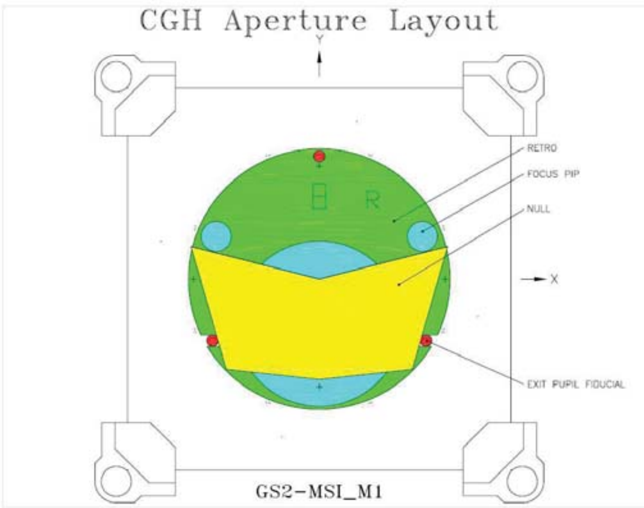

Fig. 10. M1 CGH layout

The finishing step on the mirror includes an ion beam figuring (IBF) operation coupled with slight smoothing runs. The IBF process ensures a good shaping convergence on the SiC material, while the smoothing allows keeping the roughness and cosmetic qualities of the surface.

Fig. 11. SiC mirror under IBF

The M3 mirror surface map at the end of manufacturing before coating is presented hereafter.

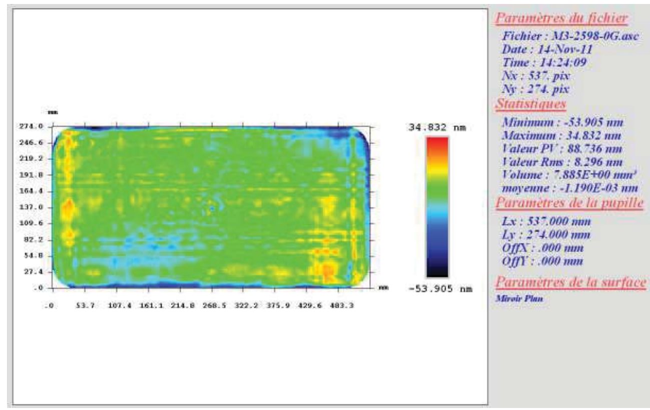

Fig. 12. M3 mirror final surface map

The last manufacturing step consisted in depositing a space-qualified protected silver reflective coating on the mirrors. This operation was performed by Sagem-REOSC.

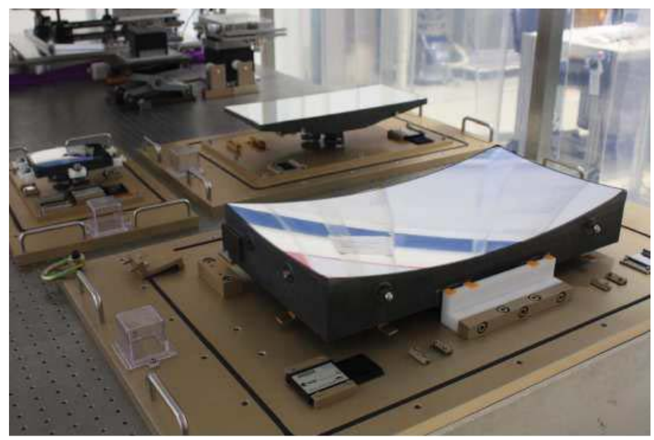

Fig. 13. Sentinel-2 mirrors after coating in cleanroom

III. TELESCOPE ALIGNMENT

As part of its contract, AMOS had to prove the matching of the mirror surfaces and the overall image quality of the aligned telescope. A dedicated support equipment was used for that purpose.

The telescope test set-up is illustrated hereunder.

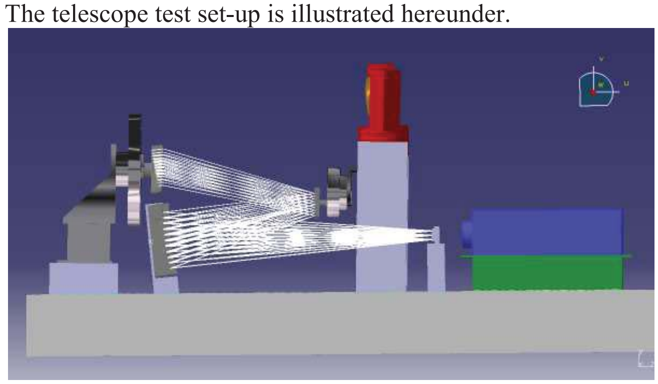

Fig. 14. Telescope alignment set-up layout

The telescope was aligned according to the following sequence:

- integration of M3 mirror, representing the reference for the telescope alignment process. The optical reference frame origin is given by the mirror vertex, the Z-axis by the mirror optical axis and the Y-axis is materialized by the two horizontal side interfaces of the mirror The coordinates in this frame can be probed through the sighting by a laser tracker of reference balls mounted on each mirror side.
- integration of M1 at its nominal position through the probing of its reference balls, themselves linked to the mirror vertex and axis.
- integration of M2 at its nominal position through the probing of its reference balls, themselves linked to the mirror vertex and axis.
- integration of a flat autocollimation mirror and alignment of the interferometer for a double pass test
- measurement of the WFE of 9 field points (centre and edge of field); computer-aided correction of third-order aberrations aiming for getting back the ones given by the telescope design, through M2 tilt and mirror de-centering operations.
- iteration of the last step till the specification is reached for the 9 field points with the quasi-nominal third order aberrations.
- measurement on the required 35 field points and confirmation of the fulfillment of the requirements.
- focal length measurements, line-of-sight control and focal plane characterization.

The M1 and M2 mirrors were mounted on translation stages; the autocollimation mirror was mounted on a robotic arm in order to ease the field points mapping operation. Pictures of the alignment bench are provided in the following sections.

Fig. 15. M1 and M3 mirrors on the bench

The overall tolerance budget for alignment stands as follows:

Tables III, IV, V, VI. Alignment overall budgets

M1-tolerances	Target	Method of control
RoC	+/- 5 mm	3D
Decentering	10 µm	Laser tracker
Defocusing	10 µm	Laser tracker
Tx	50 µrad	Laser tracker
Ty	25 µrad	Laser tracker

M2-tolerances	Target	Method of control
RoC	+/- 0.25 mm	3D
Decentering	10 µm	Laser tracker
Defocusing	10 µm	Laser tracker
Tx	50 µrad	Laser tracker
Ty	50 µrad	Laser tracker

M3-tolerances	Target	Method of control
RoC	+/- 0.25 mm	3D
Decentering	reference	Laser tracker
Defocusing	reference	Laser tracker
Tx	reference	Laser tracker
Ty	reference	Laser tracker

Focal Plane-tolerances	Target	Method of control
Defocusing	10 µm	Laser tracker
Tx	50 µrad	Laser tracker
Ty	25 µrad	Laser tracker

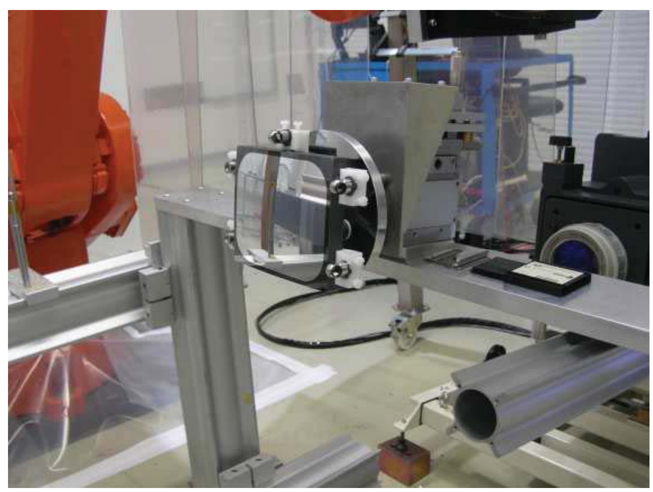

Fig. 16. M2 mirror on the bench

The alignment process was pursued till the specification was reached. The nominal design values of the telescope image quality within the field of view are displayed here:

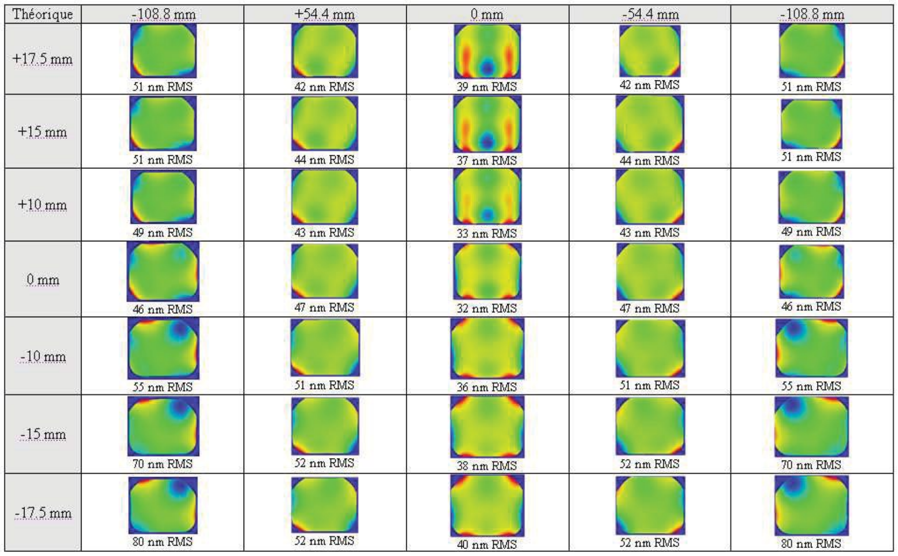

Fig. 17. Telescope image quality (design values)

The measured map over the 35 field points is the following:

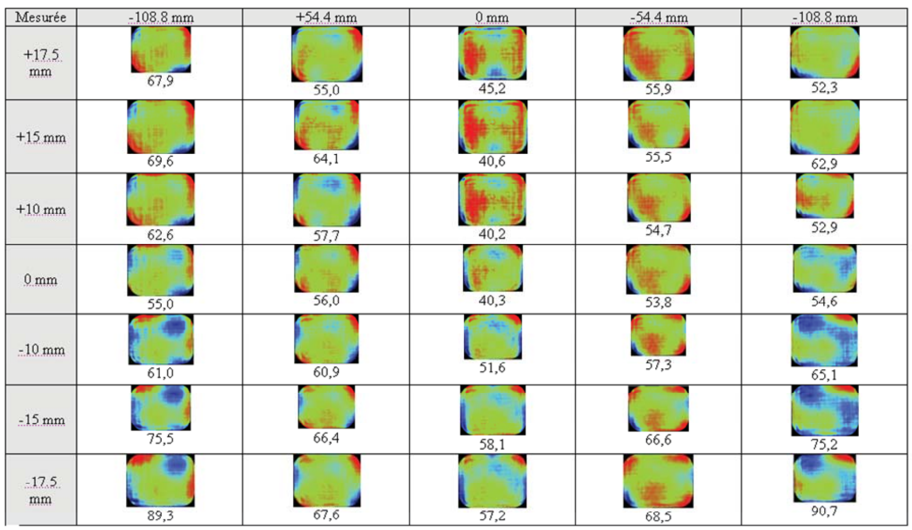

Fig. 18. Telescope measured marge quality

IV. CONCLUSIONS

This paper described the overall process of manufacturing, testing and aligning the three mirrors of the Sentinel-2 multi-spectral instrument telescope.

Critical areas were the achievement of the high figuring quality of the silicon carbide mirrors and the optimization process of the telescope alignment over the wide field of view.

The procedure of verification at AMOS of the mirror matching and telescope alignment allowed the customer accelerating his own integration procedure into the flight structural hardware.