International Conference on Space Optics—ICSO 2008

Toulouse, France

14–17 October 2008

Edited by Josiane Costeraste, Errico Armandillo, and Nikos Karafolas

Polishing, coating and integration of SiC mirrors for space telescopes

Jacques Rodolfo

International Conference on Space Optics — ICSO 2008, edited by Josiane Costeraste, Errico Armandillo,
Nikos Karafolas, Proc. of SPIE Vol. 10566, 105662I · © 2008 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2308212

Polishing, coating and integration of SiC mirrors for space telescopes

Jacques RODOLFO

SAGEM-REOSC
Avenue de la Tour Maury
91280 Saint-Pierre du Perray - France

ABSTRACT

In the last years, the technology of SiC mirrors took an increasingly significant part in the field of space telescopes. Sagem is involved in the JWST program to manufacture and test the optical components of the NIRSpec instrument. The instrument is made of 3 TMAs and 4 plane mirrors made of SiC. Sagem is in charge of the CVD cladding, the polishing, the coating of the mirrors and the integration and testing of the TMAs. The qualification of the process has been performed through the manufacturing and testing of the qualification model of the FOR TMA. This TMA has shown very good performances both at ambient and during the cryo test. The polishing process has been improved for the manufacturing of the flight model. This improvement has been driven by the BRDF performance of the mirror. This parameter has been deeply analysed and a model has been built to predict the performance of the mirrors. The existing Dittman model have been analysed and found to be optimistic.

1. Introduction

These last years, the technology of SiC mirrors took an increasingly significant part in the field of space telescopes replacing gradually more classical solutions based on lightweighted glass mirrors. The remarkable properties of SiC in terms of hardness, stiffness, thermal stability combined with a reasonable density are indeed of primary importance for all space applications and recent success of flight mission based on SiC mirror telescope (like ROCSAT…) tends to confirm all its usefulness.

SAGEM/REOSC works on the polishing, coating and integration technologies of SiC mirrors since ten year through various space programs and for various customers: Scan mirror INSAT 3D, ROCSAT and THEOS telescope , Spirale Telescope, GAIA Primary Mirror Demonstrator …).

This paper presents the manufacturing processes and the most recent results obtained by SAGEM/REOSC on the polishing, coating and integration of the three TMAs of the NIRSpec's instrument (ESA contribution of the JWST). The performances of the qualification model of the FOR TMA is presented both at ambient temperature and in operational conditions of use at 20K.

2. Sagem contribution to NIRSpec project

In the frame of the James Webb Space Telescope (JWST) program, the European Space Agency is in charge of the development of the NIRSpec instrument. The prime contractor of this instrument is EADS Astrium in Ottobrunn, Germany and thanks to its 10 years experience in SiC mirrors manufacturing, Sagem has been awarded the contract for the polishing, coating, integration and qualification of most of the optical components of the NIRSpec instrument.

The function of this instrument drives the optical design. The system is made of 3 Three Mirror Anastigmat Telescopes (TMA) in series. Each of these TMAs is composed of 3 off-axis aspherical mirrors. The first TMA, the FOR optics, is designed to provide a flat image of the field of view of the Primary Telescope. In this intermediate image plane, the Multi Shutter Array (MSA) will enable the instrument to select up to 100 points of interest to be observed at the same time in the Field of View. This plane is then collimated through a collimator (COL TMA) onto a grating or a prism mounted on a grating wheel (Grating Wheel Assembly). The beam is then focused on the detector through the last TMA, the camera (CAM TMA).

Besides these optical elements, several plane mirrors are used to fold the beam and compress the overall space of the instrument. Two mirrors are used to pick off the light from the focal plane of the primary telescope (COM1 and COM2 Plane Mirror Units (PMU)). A fold mirror (FOM PMU) is used between the MSA and the COL TMA. A last plane mirror (CAL2 PMU) is used to inject the light from the integration sphere source into the FOR TMA for periodic calibration of the instrument.
In total, Sagem is in charge of the polishing of 14 mirrors for this instrument. Including the qualification parts and spare parts, the global number of mirrors to polish in the frame of this contract grows to 34 pieces.
The size of the mirrors ranges from 90x80 mm to 300x300 mm. All the mirrors are aspherical and off-axis. The departure from the best sphere ranges from 10 µm to 380 µm.

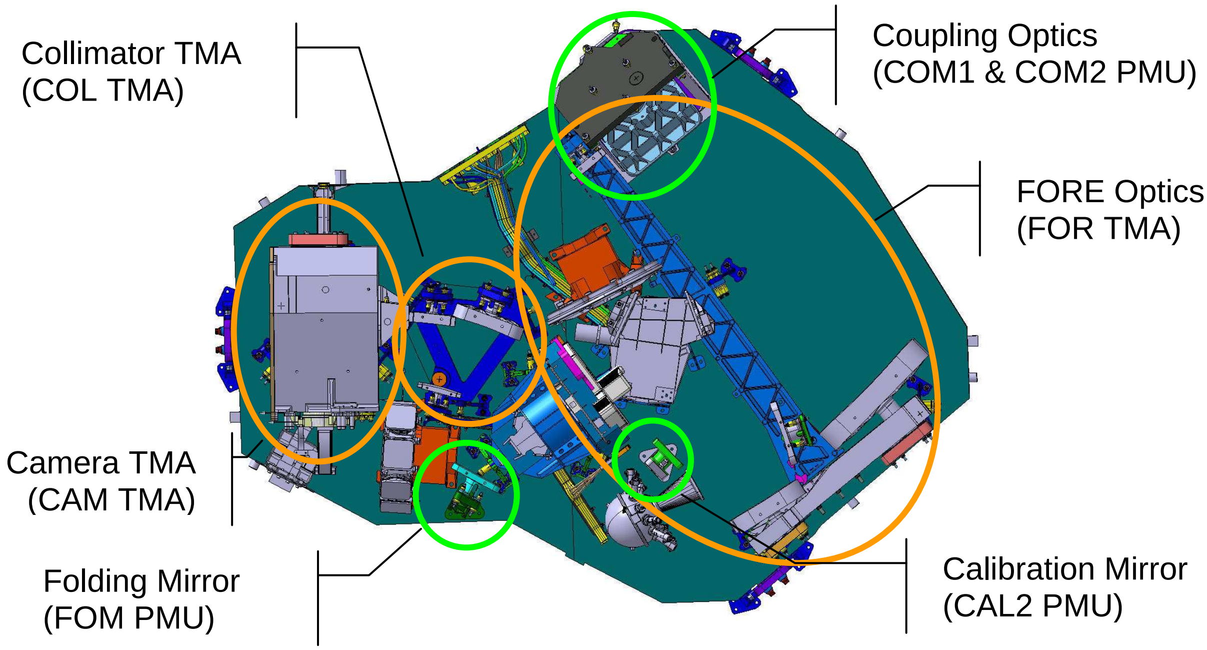


Figure 1 : Top view of the NIRSpec instrument with Sagem contribution

Almost all the parts of the NIRSpec instrumental are made of Silicon Carbide (SiC), from the optical bench to the mirrors. Sagem is delivered the mirrors blanks and the SiC structures. Sagem is then responsible for the CVD cladding, the polishing, the coating, the grounding of the mirrors and the integration and the alignment of the TMAs.

Sagem's expertise is also involved for the optical design and for the testing :
The design of the instrument has been elaborated by Astrium / ESA. Sagem has performed an optical verification of the system to elaborate the detailed manufacturing tolerances. One of the most important parameters in the alignment of TMAs is the off-axis position of individual mirrors. This parameter has been specified for each mirror taking into account the manufacturing and testing limits, the integration strokes and the impact on the performance (mainly vignetting). This approach has been supported by optical simulation performed with Code V.
Regarding testing, Sagem is responsible for the cryo testing of the TMAs. It includes the development of the optical cryo test bench and the specification of the cryo chamber. Sagem cooperates with the Centre Spatial de Liège (CSL) to perform the tests at operational temperature 20K.

3. Major performance requirements

As for all optical systems the image quality performance is a very important specification. The Wave Front Error (WFE) specification of the TMAs leaves very little margin for the manufacturing wrt the optical design. An example of error budget of the FOR TMA is presented in the following table.

Contributor	Provision (nm) (Center of FOV)	Provision (nm) (Edge of FOV)
Optical design + theoretical integration	37 nm	43 nm
Mirror polishing	32 nm	32 nm
Mirror mounting	19 nm	19 nm
Alignment residual	35 nm	35 nm
Ambient to cryo effect (structure, CVD SiC, coating effects)	25 nm	25 nm
Measurement error	10 nm	10 nm
Total budget	69 nm	72 nm
Specification	74 nm	74 nm

Table 1 : WFE budget of the FOR TMA (simple pass, RMS)

However, the WFE is not the only important parameter. In order to be able to observe the most faint objects, the instrument has to provide a very good transmission. This is ensured by the minimum vignetting, the highest spectral reflectance and the minimum micro-roughness. Regarding the vignetting, due to the tiny space allowed for the instrument, the mirror clear aperture is very close to the edge of the mechanical surface. The WFE specification has to be met up to less than 1 mm which is a very strong constraint for aspherical mirrors. Regarding the coating, the spectral reflectance of each mirror has to be higher than 95.8% from 600 nm to 2 µm and above 98.5% in the near IR range (2 µm to 5µm).
The molecular and particulate contamination is also a contributor to the spectral transmission and it has to be monitored very accurately during all manufacturing. The cleanliness specification is close to the measurement limit of the instruments and all precautions must be taken to avoid molecular and particulate contamination.

At TMA level, the object and image position specification is very stringent. Due to the system analysis of the instrument, these positions are to be aligned within 250 µm wrt the mechanical interface of the TMA. The object and image position have been monitored using a dedicated optical test bench which was aligned using a Coordinate Measuring Machine.

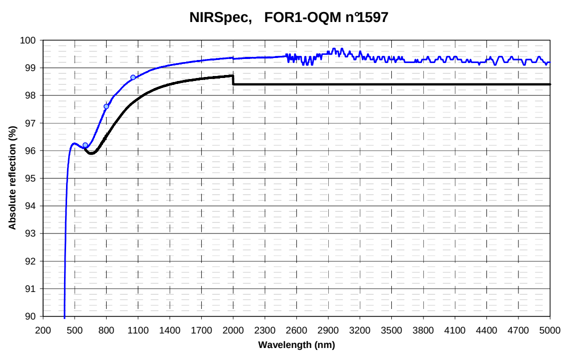
4. FOR OQM TMA performances

In the frame of the development plan, the Optical Qualification Model of the FOR TMA has been manufactured and qualified to qualify the manufacturing and testing processes. The polishing of mirrors has been performed according to the WFE budget and to the micro-roughness specification.

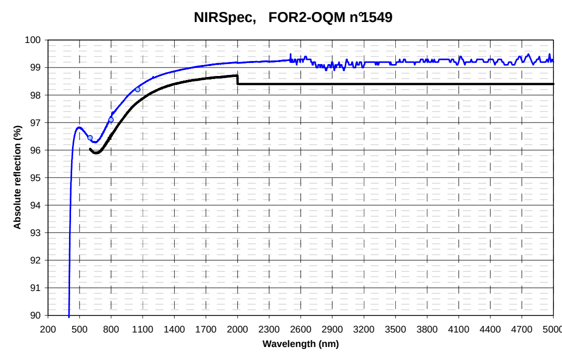
Requirement	Specification	Performance	Comment
WFE	16 nm RMS	14.6 nm RMS	Over each subaperture Best sphere departure 35 µm
Off axis position X/Y	0.6 mm	0.2 mm	surface error corresponding to 0.2 mm : 6 nm RMS astigmatism
Radius of curvature	0.2 mm	0.04 mm	surface error corresponding to 0.04 mm : 300 nm sag
Micro-roughness	1.6 nm	0.7 nm	RMS value

Table 2 : Typical mirror specification and performance

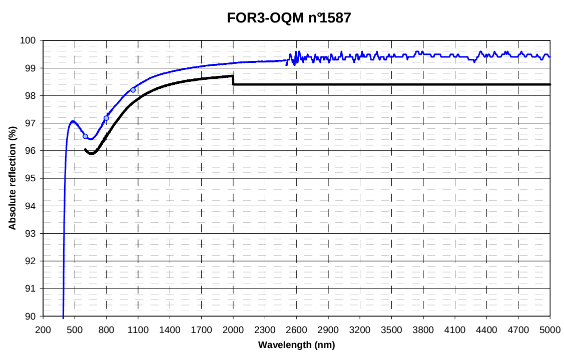
The coating of the mirrors has been performed successfully and has demonstrated full compliance to the specification. The qualification activities on samples proved that the spectral performance was met at 20K.



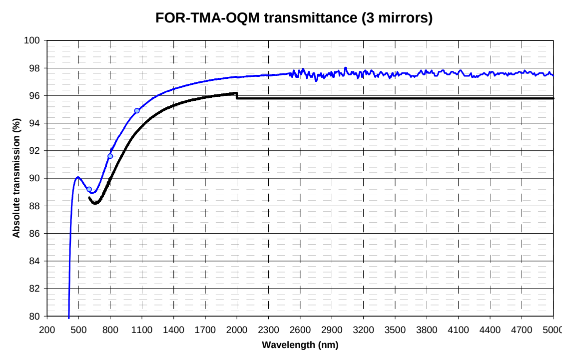
FOR1 OQM mirror spectral performance



FOR2 OQM mirror spectral performance



FOR3 OQM mirror spectral performance



FOR OQM TMA mirror spectral performance

Figure 2 : Coating performance of mirror

The mirrors have been integrated on the structure of the TMA and the alignment has been performed on a dedicated test bench. The main driving parameters for the alignment are the WFE in all the FOV (142mm x 138mm in the object plan), the magnification and the object and image position.

Figure 3 : picture of the FOR OQM TMA during integration

The alignment of the TMAs has demonstrated a fully predictable behaviour. Thanks to a dedicated alignment software, the alignment of the mirrors has been achieved in a reduced number of iterations. The achieved WFE performance is well within specification.
The final behaviour of the TMA has been fully modeled with Code V software and the model will be used for the global instrument simulator.

WFE Table (nm RMS)			
	Model	Measure	Difference
F1	39.3	37.5	-1.8
F3	37.2	39.2	2.0
F2	38.6	37.8	-0.8
F4	34.5	32.8	-1.7
F5	38.3	35.8	-2.5
F6	31.8	31.3	-0.5
F7	42.6	39.9	-2.7
F8	39.8	40.5	0.7
F9	35.4	36.3	0.9

WFE Maps (example field point F4)

Model | Measure

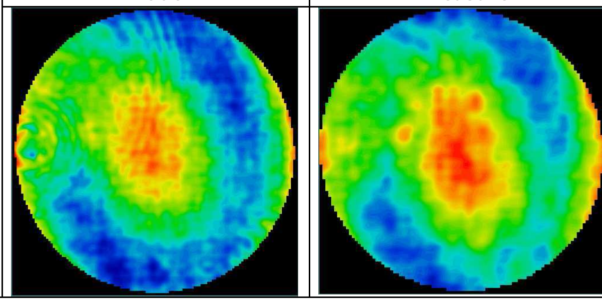
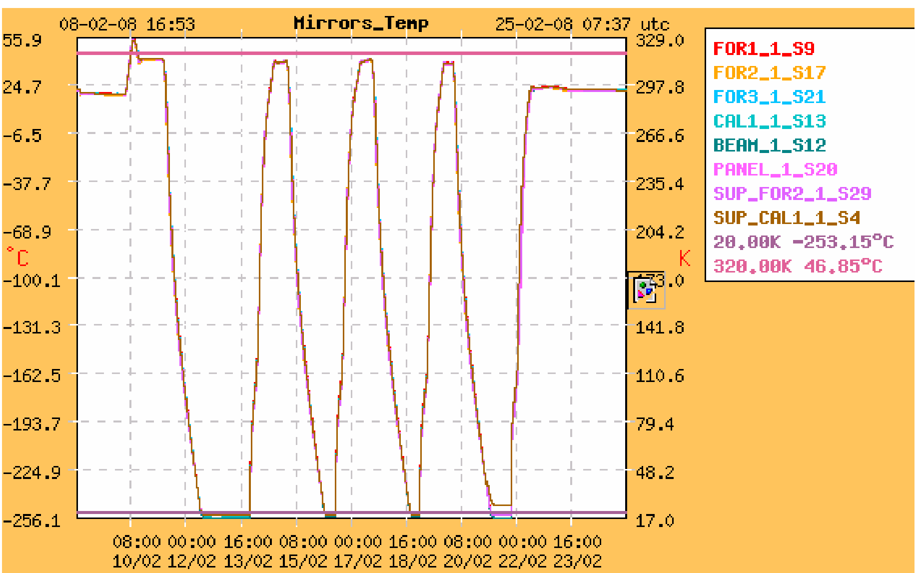


Figure 4 : As built model : fit of WFE measurement

The vibration qualification of the TMA has been performed by Astrium. The measurement after the vibration test has shown no evolution of the hardware performance.

The TMA qualification campaign ended with the operational temperature test at 20K. The cryo chamber behaviour demonstrated the capability to reach the required temperature over all the hardware with very little gradients. The optical performances have been checked during the cryo cycling and the optical parameters have been measured within the specification.



Warm temperature : 315.1K, gradient over all the TMA : 1.6K
Cold temperature : 18.8K, gradient over all the TMA : 2.2K
Figure 5 : Thermal cycling of FOR OQM TMA cryo test

5. Process improvement

Although compliant with the state of the art cosmetic specification, the manufacturing of the FOR OQM mirrors has shown that the residual micro-scratches due to the polishing could have an impact on the scattered light. The Bidirectional Reflectance Distribution Function (BRDF) is the measurement that describes this effect. In order to reduce the quantity of scattered light, Sagem has improved the polishing process to reduce any residual surface defects on the mirrors surface. This process shows very good results that will yield to Flight Model mirrors of very high quality. The micro-roughness reached on the flight mirrors is currently below 0.5 nm RMS.

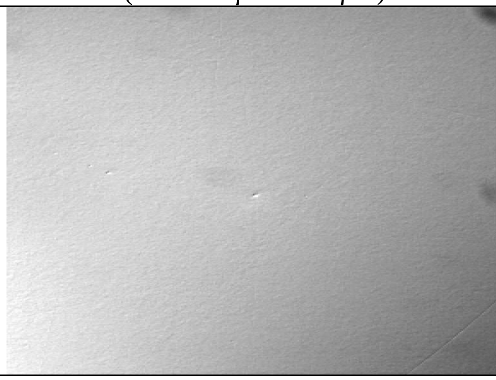
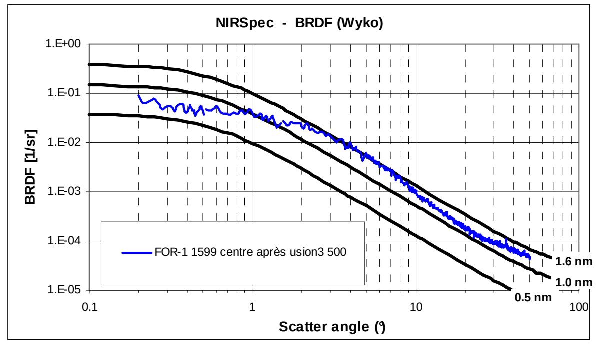
Nomarski microscope inspection (Field 570µm x 430µm)	BRDF plot
	

Figure 6: Process performance for Flight Model mirror (µ-roughness 0.4 nm)

The BRDF performance of optical surface can be easily measured in the case of flat surfaces but becomes more complicated in the case of spherical or aspherical mirrors. This topic has been extensively studied to monitor the process performance improvement. Sagem has set-up a procedure to derive the BRDF performance from the micro-roughness measurement. This model has been validated on samples thanks to the collaboration with ESA and shows a good correlation between the prediction and the actual measurement.
The BRDF derivation from micro-roughness measurement has been modelized by Dittman [1] and has been used to anticipate the impact of the micro-roughness. However, this model seems not to be fully applicable. A SiC sample has been polished with a very low micro-roughness (0.3 nm RMS) and the BRDF measurement has been performed. The measurement is plot against the prediction of the Dittman model for various micro-roughness (0.5 nm, 1 nm and 1.6 nm) on the next graph. It turns out that the measured BRDF rather fit the 1 nm micro-roughness prediction. This outcome is being analysed to be confirmed and the micro-roughness measurement are also being cross-checked.

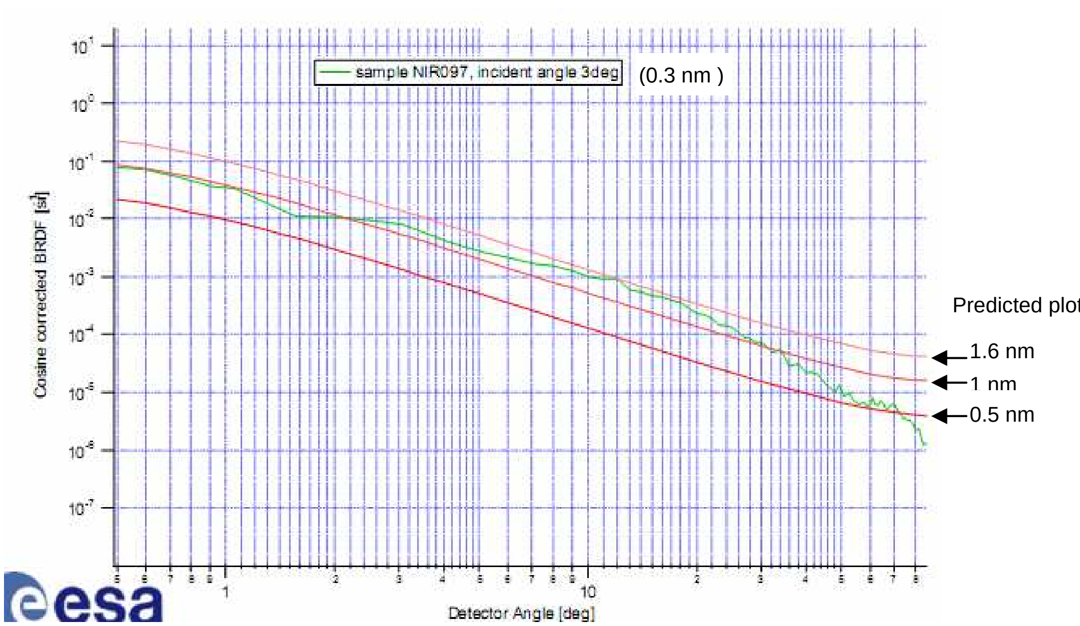


Figure 7: Comparison between actual BRDF measurement and prediction with Dittman model

6. Conclusion

This paper summarizes the contribution of Sagem to the NIRSpec project. It includes the polishing and coating of the mirrors to the alignment and the test of the TMAs. The design activities have shown that the manufacturing budget should enable to manufacture the TMAs in the specification. The manufacturing and the testing of the qualification model have validated most of the steps of the process up to the cryo testing.

The polishing process has been improved wrt BRDF criteria and the achieved micro-roughness is well under the initial value. A model of the BRDF prediction has been developed to derive the BRDF performance from the micro-roughness measurement.

Thanks

Sagem's manufacturing workshop, Sagem's testing workshop and Sagem's integration workshop engineers and operators.
Astrium's contribution and ESA's collaboration and fruitful discussion.
CSL's courtesy and professionalism.

[1] Contamination function of stray contamination analysis, M. G. Dittman, Proceedings of SPIE Vol. 4774 (2002).