NIRSpec OPTICS DEVELOPMENT – FINAL REPORT

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I. INTRODUCTION

As shown and discussed on a Sagem poster presented at the ICSO 2010 conference [1], scientific or commercial earth observation space instruments are more and more taking advantage of the remarkable properties of Silicon Carbide in term of hardness, stiffness and thermal stability combined with a reasonable density which are indeed of primary importance for all space applications.

Sagem-REOSC High Performance Optics Unit works on the polishing, coating and integration technologies of SiC mirrors since more than ten year through various successful space programs for various customers: INSAT 3D scan mirror, ROCSAT II and SPIRALE main telescopes, GAIA large primary mirrors and Auto-collimation flats, …).

This paper aims to provide to the international space community an exhaustive vision of the work performed by Sagem-REOSC on the polishing, coating and integration of the three Three Mirror Anastigmats of the NIRSpec spectrographic instrument which is the main ESA contribution to the JWST.

2. JWST AND NIRSpec

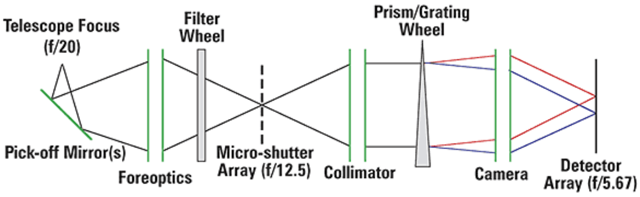
The European contribution to the James Webb Space Telescope (JWST) program includes the launch service by Ariane V and the **N**ear **I**nfra**R**ed **Spec**trograph (NIRSpec). The prime contractor of this instrument is EADS Astrium in Ottobrunn, Germany and, thanks to its 10 years experience in SiC mirrors manufacturing, Sagem has been awarded the contract for the polishing, coating, integration and qualification of most of the optical components of this innovative and challenging instrument.

NIRSpec is a multi-object spectrograph instrument which will take the spectra of more than 100 celestial objects within a 3x3 arcmin field of view either at medium spectral resolution over 1 – 5 µm spectral band, or at lower resolution over the 0,6 to 5 µm spectral band. To this purpose, the instrument starts with a re-imaging optics (the FOR optics) which brings the telescope focal plane on a Micro-Shutter Array (MSA) which enable the instrument to select the astronomical objects of interest within the filed of view.

The system then continues as a conventional spectrograph with a collimating optics (the COL optics) which sends an afocal light beam through a filter selected on the Filter Wheel Assembly (FWA) onto the diffractive grating or dispersing prism, selected within the Grating Wheel Assembly (GWA). The dispersed light is then focused on the detector thanks to the camera optics (CAM).

One of the very new and innovative feature of NIRSpec is the strategic choice of performing all these optical functions only with reflective optics, i.e. Three Mirror Anastigmats (TMA) made from three off axis aspheric mirrors each, providing perfectly achromatic performances and avoiding the many problems linked to the use of glass (transmission, dispersion, weight, dn/dT, etc…). Figure (1) below shows the overall design.

Another strategic choice made by Astrium was to use only Silicon Carbide for all the optics, their mounts, and the global structure of the instrument. In this way, the system becomes perfectly athermal down to the 20 K cryogenic temperature of operation, a key design feature.



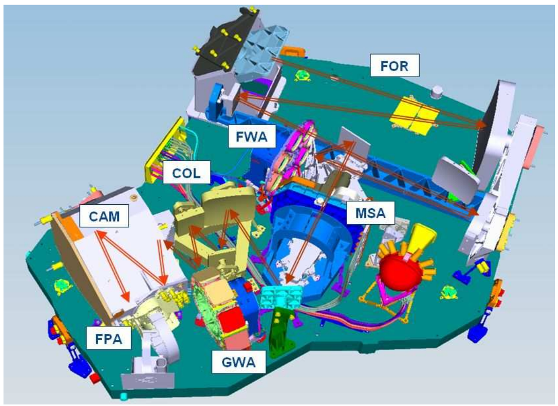
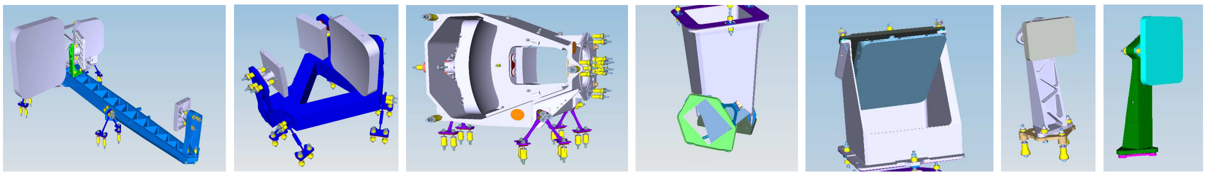


Fig (1): From concept to real opto-mechanical design

3. SAGEM TASKS AND RESPONSIBILITIES

Besides the three TMA, several plane mirrors are used to fold the beam and squeeze down the overall volume 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 folding 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 Model and spare parts, the total number of mirrors to polish in the frame of our contract goes up 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. The figure (2) below shows the various TMA assemblies and other folding flats and calibration mirror assemblies delivered by Sagem.



FOR COL CAM COM1 COM2 FOM CAL2

Fig (2): The various mirror assemblies to be delivered by Sagem

As explained above, almost all the parts of the NIRSpec instrument are made out of Silicon Carbide (SiC) produced by Boostec Industries. This includes the mirror blanks and their support structures which are delivered to Sagem. Sagem is then responsible for the CVD cladding, the polishing, the coating, the electrical grounding of the mirrors, their integration on their structure and the alignment of the TMAs.

But Sagem's expertise has been involved during the design phase. We performed an optical verification of the whole lens design model elaborated by Astrium / ESA, especially with respect of the tight element packaging and in order to elaborate a detailed set of manufacturing tolerances. TMA's are difficult objects and one of the most important parameters in their alignment is the exact off-axis distance of each 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 extensive optical simulations performed with Code V.

Sagem was also responsible for the cryogenic testing of the various TMAs down to the operational temperature of 20K. This includes the development of the optical cryo test bench, the specification of the cryogenic chamber and its thermal, electrical, mechanical and optical interfaces. These tests have been conducted at the Centre Spatial de Liège (CSL) within one of their cryogenic vacuum chambers.

4. OVERVIEW OF THE MAIN REQUIREMENTS

The design performance of the various NIRSpec TMA's is shown on the table below :

WFE (nm RMS)	Min	Max	Average	Specification
FOR	24	36	31	74 nm
COL	53	81	63	100 nm
CAM	66	86	72	NA
COL+CAM	38	65	51	130 nm

One sees that the individual TMA telescopes are of rather high performance level while being well compact and of fast relative aperture. CAM & COL TMA are partially compensating one to the other and therefore specified globally. The difference between specified performance and design performance includes all the contributors to image quality up to flight of the system, thus leaving tiny room for polishing residuals As an example, the manufacturing and test performance budget has been established for the FOR TMA as follow :

Performance contributor (single pass WFE in nm RMS)	
Optical design	36
3 mirror polishing (18 nm each)	32
Effect of mirror mounting (11 nm each)	19
TMA alignment residual	35
Cryo effect on full TMA	25
Measurement errors	10
Total budget	74 nm RMS WFE

At first order, one can state that the specification for the optics is that all manufacturing, mounting, alignment and cryo induced errors shall lead to a final performance no more than twice the design performance.

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. Due to the tiny space allowed for the instrument, but also as a way to improve nominal WFE residuals, and specifically for COL & CAM TMA, the mirror clear aperture is very close to the edge of the mechanical surface as shown on the figure (3) at right. The WFE specification has therefore to be met up to less than 1 mm from mechanical edge of some critical mirrors. This represents a very strong constraint during the polishing of such off-axis aspheric surfaces.

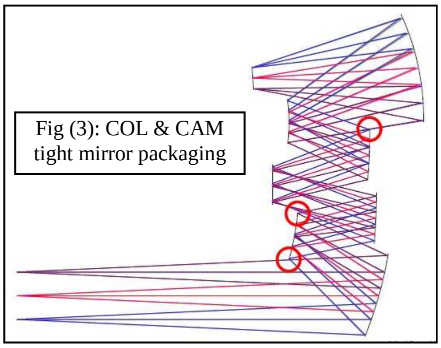


Fig (3): COL & CAM tight mirror packaging

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 in order to allow modular assembly of the whole instrument on its breadboard plate. As a result from system analysis of the instrument, these positions are to be aligned within 250 µm wrt the mechanical interface of the TMA.

5. MIRROR SUBSTRATES AND CVD SIC DEPOSITION

The mirror substrates are made by Boostec Company near Bordeaux in France, according to their sintered SiC technology and were delivered to Sagem by Astrium. Most of them are of "mushroom" shape with open-back lightweight structure. After incoming inspection we carefully lapped the mounting flanges to be well coplanar and pre-lapped the aspheric optical surface a few micrometer from its final shape.

SiC material remains porous with about 1% open porosities on the optical surface, even after precise lapping and polishing operations. Such porosities could be tolerated for Far IR or sub-millimetric applications but cannot at all be tolerated for Vis and near IR application requiring low flare and stray light level. Therefore, after some surface preparation, the parts were shipped to Schunk Company in Germany where they received a dense CVD SiC layer, about 100 to 200 µm thickness, which can be well polished to a roughness level compatible to visible applications. CVD SiC has a Coefficient of Thermal Expansion (CTE) very close to the one of sintered SiC leading to very low bi-material effect when the temperature is dropped down to 20K.

6. OFF-AXIS ASPHERIC SEGMENTS POLISHING

The NIRSpec TMA mirrors are all of conic shape + higher order aspheric terms and with off axis contour. Due to the all-SiC design with integrated fixture device in the mirror substrate and the off-Axis distances, they could not be produced by cutting from a parent mirror but needed to be produced directly off axis.

The mirrors are all with square or rectangular contour with dimension ranging from 90x80 mm to 300x300 mm. The aspheric sag is significant, up to 380 µm departure from best sphere. The goal was to polish them down to 15 nm RMS WFE residual error or less. In parallel we had to master the off-axis distances and optical axis position with respect to mounting interfaces down to 0.2 mm accuracy. Sagem applied its latest generation of Computer Controlled Polishing "multi-tool" technology. IBF technology was also applied, especially in the final steps of operation in order to reach the targeted performance level.

NIRSpec also benefited from our recently developed Optical Manufacturing Expert System. This data base and linked processor have a main purpose to capitalize the delicate knowledge acquired during the various steps of optical processing. Data are then very precious to help the optical technician to select the processing parameters, to avoid gross mistakes and construct a more robust polishing strategy, leading to better convergence, thus improved cost and schedule control. Fig (4) shows a typical progression curve displayed by the Expert System.

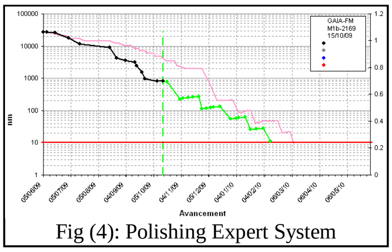


Fig (4): Polishing Expert System

For the critical edges where roll-off shall be kept at minimum, we applied specific processes and tools in order to maintain this turn-down effect very low below the 1 mm limit that was set there.

Micro-roughness and scattered light requirement appeared to be a source of concern. While the specified 1.6 nm micro-roughness was not considered as an issue to be achieved on Silicon Carbide, even with such significantly aspheric components, we faced a higher level of scattered light, Bidirectional Reflectance Distribution Function (BRDF) and Total Integrated Scattering (TIS) as measured on samples. This brought the achieved polishing quality at that time significantly out of the corresponding stray light requirement. The point lied in fact within the residual micro-scratches and other small cosmetic defects which contributed more than expected to the diffused light, i.e. leading to a TIS value higher than 0.1%.

The BRDF performance of optical surface can be easily measured in the case of flat surfaces but becomes more complicated in the case of curved spherical or aspherical mirrors. The BRDF derivation from micro-roughness measurement has been modelized by Dittman [2] and has been used to anticipate the impact of the micro-roughness. However, this model appeared to be not fully applicable in presence of micro-scratches and other cosmetic defects. Therefore we developed our own refined model for BDRF & TIS prediction and calibrated it thanks to the database of the many samples produced and measured within ESA laboratories.

With this tool in our hand we could then concentrate on the set-up of an optimized polishing strategy leading to same WFE quality but improved micro-roughness and cosmetic residuals. The micro-roughness reached on the flight mirrors is below 0.5 nm RMS.

The photo and figure below show the photo of a Nomarski microscope inspection of a Flight mirrors with the corresponding BRDF plot, meeting the global diffused light requirement.

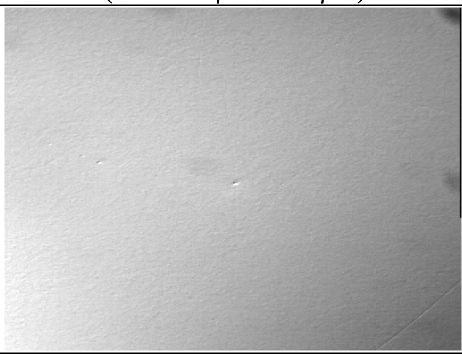
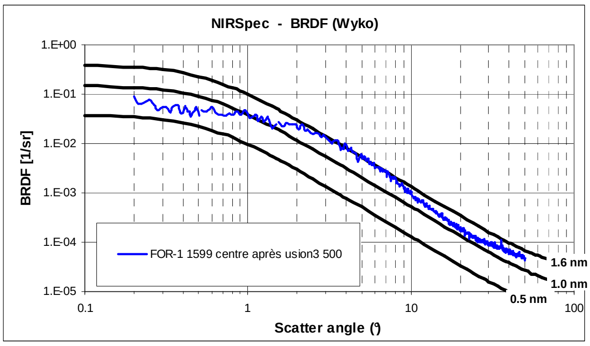
Nomarski microscope inspection (Field 570µm x 430µm)	BRDF plot
	

Fig (5): Process performance for Flight Model mirror (µ-roughness 0.4 nm)

8. OPTICAL COATING AND STRAP BOUNDING

The next step is to deposit the reflective coating on the mirrors. This is of enhanced silver type in order to provide maximum reflectivity over broadest spectral domain. Proper selection of the dielectric materials ensures best protection against humidity and vacuum shift of the performances combined with best performances over the broad spectral domain. The measurements have been made by combined use of a Visible and IR spectrophotometer and show a performance about 0.5% above specification.

Cryogenic measurements of the reflectivity have been done at the Stuttgart Physic Institute and have shown a slight increase of reflectivity, especially in visible light.

Small areas along the edge of the mirrors were masked during the dielectric coating operation in order to allow bonding of electrical grounding straps according to our space and cryo qualified procedure.

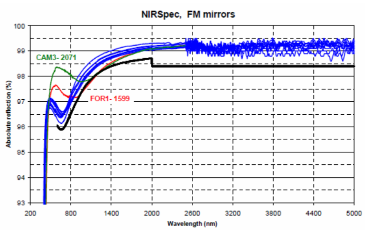


Fig (6): Typical reflectivity curve

Fig (7): Coated COM with grounding straps

9. TMA INTEGRATION AND ALIGNMENT IN THEIR STRUCTURE

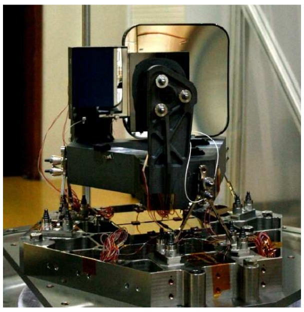
Once the individual mirrors polished and coated, we had to align and integrate them in their structure. This phase starts with a precise measurement on a 3D Coordinate Measuring Machine of all mirror vertex position and optical axis tilts with respect to their mounting interface as well as the structure element.

Then a Code V model of the optics is fed with these data and an optimization sequence conducted toward required object and image position as well as maximum image quality through the field of view. The computed shims are then manufactured and physical integration process starts under theodolite control.

Finally the last (or most effective) mirror is moved thanks to new sets of shim plates determined on the basis of the observed residual WFE through the field of view.

The photo below show the 3 TMA integrated on their structure.

FOR



COL

CAM

10. CRYOGENIC TESTING AT CSL

For the conduction of the cryogenic tests at the Centre Spatial de Liege we integrated the various TMA on a breadboard plate made from Invar and attached the thermal straps designed to minimize the temperature gradients through the material during the cooling sequence.

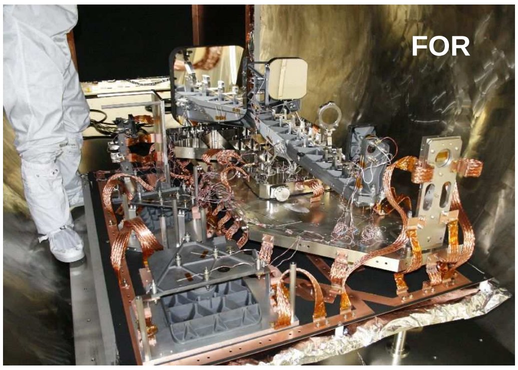
After a reference optical measurement at ambient, the hardware was submitted to the various cycles down the 20K. Instrumentation demonstrated the effectiveness of the cryo chamber to reach the low temperature and the good uniformity of temperature distribution through the parts.

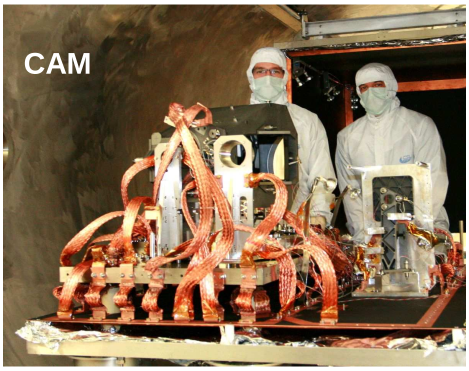
The optical parameters (focus position and WFE) were measured at low temperature and after return at ambient. The results are in fact very simple :

No noticeable evolution of the WFE quality and focal point position between ambient and 20K

No noticeable hysteresis effect observed also after return at ambient.

The photo below show the FOR and CAM TMA installed within the cryo chamber, ready to start the tests.

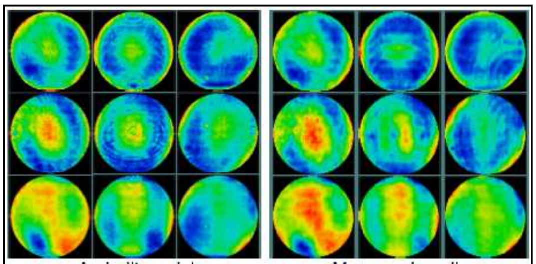




11. OPTICAL MODEL OF NIRSPEC AS BUILD OPTICS

One of the final tasks dedicated to Sagem under the project was to deliver to Astrium an optical model of the "as-built" configuration of the various TMA.

This was made on the basis of the Code V optical model of each TMA. The measured optical surface residuals were injected in the model as well as the tilts and decenter corresponding to the mechanical design. Then, it was proceed to a virtual alignment sequence so that the WFE residuals through the various points of the field of view fitted to the best with the as measured WFE residuals.



The model came out with an accuracy better than 2.7 nm WFE

12. CONCLUSION

NIRSpec is a key contribution of Europe to the JWST under construction and Astrium has designed for it an innovative all-mirror and all-SiC optomechanical assembly that constitute the most elegant and most efficient solution that today technology could develop for this high performance instrument.

The key objective have been reached :

Precise, smooth, low diffusing and clean polishing of numerous tough off-axis SiC elements

Elimination of roll-off effect along the most critical mirror edges

Coating and electrical grounding space and cryo qualified

Integration and alignment of fast and wide field of view TMA's within all-SiC structure

Cryo testing within CSL facility that demonstrated perfect cryo behaviour of the optics

Sagem-REOSC has been proud to participate to this challenging project and thanks ESA and Astrium for the confidence put in our engineers and technicians. This project has also a unique opportunity to consolidate Sagem's skill and expertise in precision space optics.

Looking forward to NIRSpec's first spectrum !

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[1] Large precision optics at Sagem – From Zerodur to SiC, R. Geyl, Proceedings of International Conference on Space Optics 2010 – P38

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[3] Sagem SiC technology and NIRSpec, J. Rodolfo, Proceedings of SPIE Vol 7018-15 (2008)