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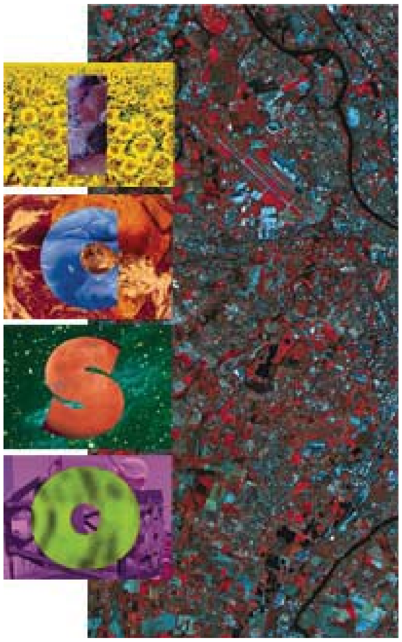

Telescope and mirrors development for the monolithic silicon carbide instrument of the osiris narrow angle camera

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TELESCOPE AND MIRRORS DEVELOPMENT FOR THE MONOLITHIC SILICON CARBIDE INSTRUMENT OF THE OSIRIS NARROW ANGLE CAMERA.

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RÉSUMÉ *- Le satellite ROSETTA de l'ESA sera lancé en 2003 pour une mission d'une dizaine d'années. En orbite autour de la comète 46P/Wirtanen, l'instrument NAC OSIRIS permettra d'observer en 2013 la comète et son activité avec une définition inégalée.*

Il est présenté la conception, le développement et les performances de cet instrument et de son télescope en Carbure de Silicium qui permettront des observations dans le visible. La fabrication des miroirs est plus particulièrement détaillée.

Les pièces en SiC ont été réalisées par BOOSTEC, polies par STIGMA OPTIQUE et l'usinage ionique a été réalisé par IOM sous maîtrise d'œuvre ASTRIUM. ASTRIUM a aussi réalisé l'alignement et obtenu une qualité finale de surface d'onde pour le télescope meilleure que 30 nm rms.

ABSTRACT *- The international Rosetta mission, now planned by ESA to be launched in January 2003, will provide a unique opportunity to directly study the nucleus of comet 46P/Wirtanen and its activity in 2013.*

We describe here the design, the development and the performances of the telescope of the Narrow Angle Camera of the OSIRIS experiment et its Silicon Carbide telescope which will give high resolution images of the cometary nucleus in the visible spectrum. The development of the mirrors has been specifically detailed.

The SiC parts have been manufactured by BOOSTEC, polished by STIGMA OPTIQUE and ion figured by IOM under the prime contractorship of ASTRIUM. ASTRIUM was also in charge of the alignment. The final optical quality of the aligned telescope is 30 nm rms wavefront error.

1. PRESENTATION

The OSIRIS Narrow Angle Camera is an instrument mounted on board the ROSETTA spacecraft. Its aim is to take pictures of the 46P/Wirtanen comet during the mission from a distance that can get as close as 300 meters. As a long part of the mission is made at a large distance from the sun the available power is very low. Because of this constraint and of the needed small mass it was decided to manufacture an all Silicon Carbide telescope with a SiC structure, SiC mirrors and SiC shims as an interface between them. This design is not sensitive to thermal changes: the high conductivity prevents the apparition of gradients and the monolithic concept ensures that the image quality and focus is kept at all temperatures. The manufacturing of the mirrors was a challenge in itself: SiC mirrors are not common, one of the mirrors is an off axis aspheric and it needed to be CVD coated to have a good microroughness. This challenge was met as we describe below and concluded with the successful alignment of the TMA telescope.

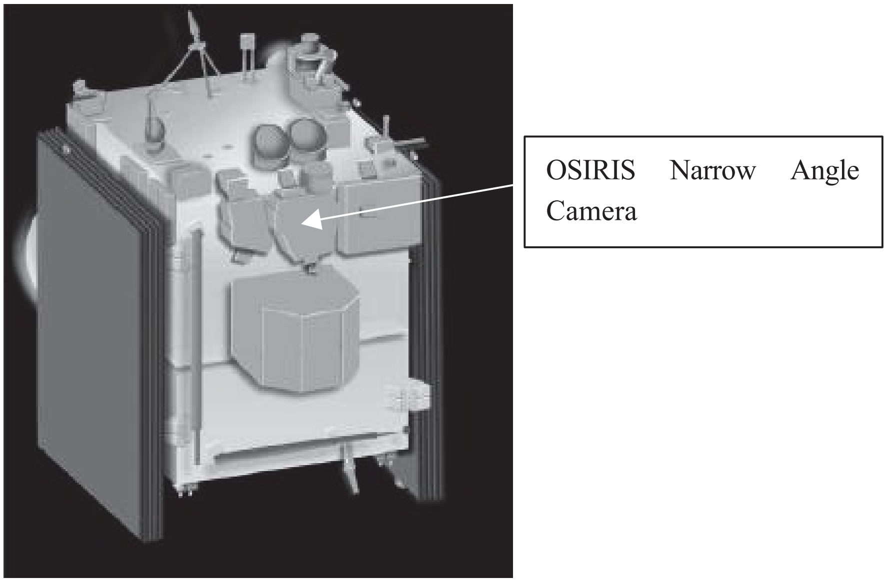

Fig. 1 : Layout of the ROSETTA spacecraft with the OSIRIS Narrow Angle Camera.

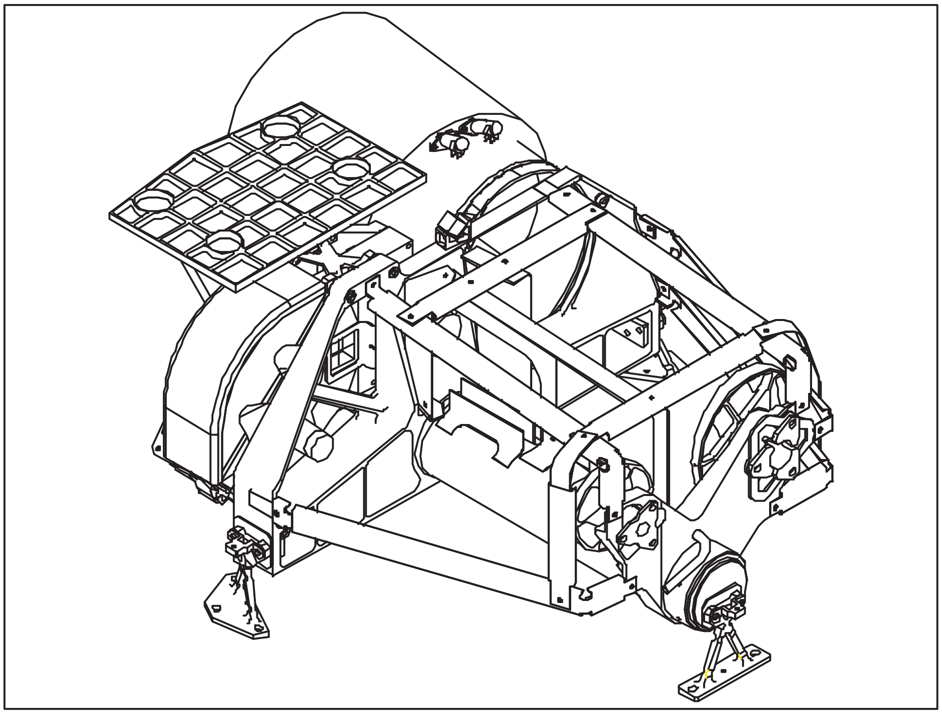

Fig. 2 : 3D model of the OSIRIS Narrow Angle Camera.

2. INSTRUMENT OVERVIEW

2.1. Overall instrument description

The instrument comprises a telescope entirely made of SiC, using the same material for the mirrors and for the structure. The structure is a U-shaped one with a central tube and two walls bonded together. The mirrors are bolted onto the walls with interposed SiC spacers. The optical adjustments are made by machining these spacers to the required values. An aluminium baffle is placed at the entrance of the telescope and is closed by a rotating front door which is attached onto the front SiC wall using a low conductive spacer.

A dedicated plate (Equipment holder) holds the Shutter, the Filter Wheel Mechanism and the Focal Plane Detector. This plate is mechanically and thermally decoupled from the SiC structure thanks to the use of titanium blades and low conduction shims. The protection against dust and external stray light is done by wrapping the camera within a 50 microns thick black painted Kapton foil. The Multi-Layer Insulation will be put over this foil. The NAC is fixed onto the spacecraft interface via three titanium bipodes.

The key instrument design drivers are as follows: very low mass, launch loads compatible with Ariane 5 and a thermal power consumption below 5 W.

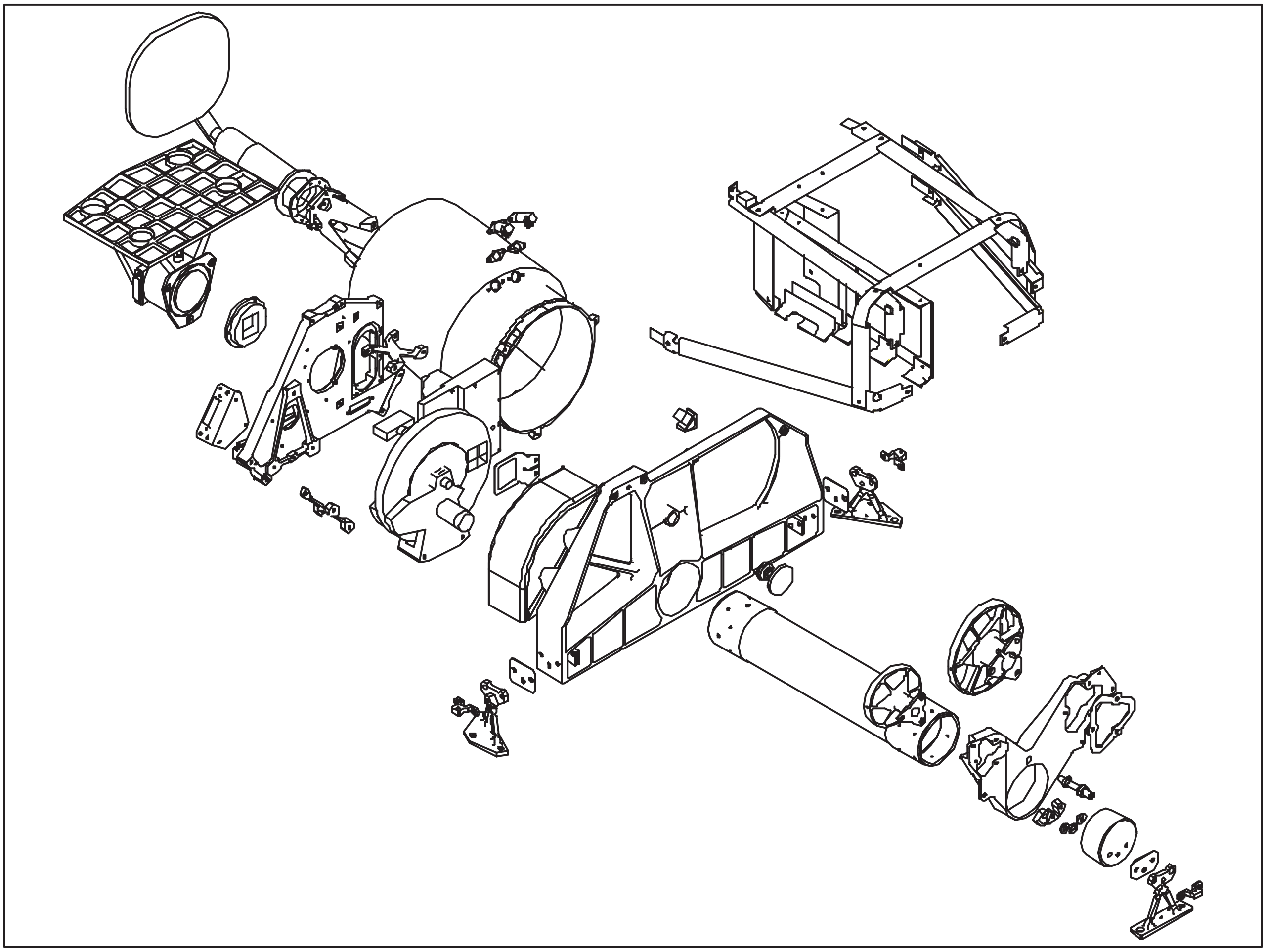

Fig. 3: the NAC instrument design

2.2. The OSIRIS telescope

The OSIRIS telescope is a Three Mirror Anastigmat (TMA) consisting of conic surfaces: a concave hyperbolic primary, a convex parabolic secondary and a concave spherical tertiary. The mirrors are symmetric about the common optical axis but only M2 is centred, M1 and M3 are used off axis. This is not a problem for the spherical M3 but for M1 we had to manufacture an off axis hyperbola. The pupil is mounted on the M2 mirror.

A number of filters are placed before the final focus as well as a radiation shielding window. The spectral range extends from the ultra-violet (270 nm) to the near infra-red (900 nm). The image is acquired with a cooled CCD in the focal plane.

This design presents a 2.35° square unobstructed, unvignetted and flat Field Of View. The focal length is 730 mm with a focal ratio of F/8.

The wavefront error requirement for the final on orbit telescope is 63 nm rms. This allocation was dispatched between the various contributors. This left a specification of 30 nm for the wavefront error of the M1 mirror.

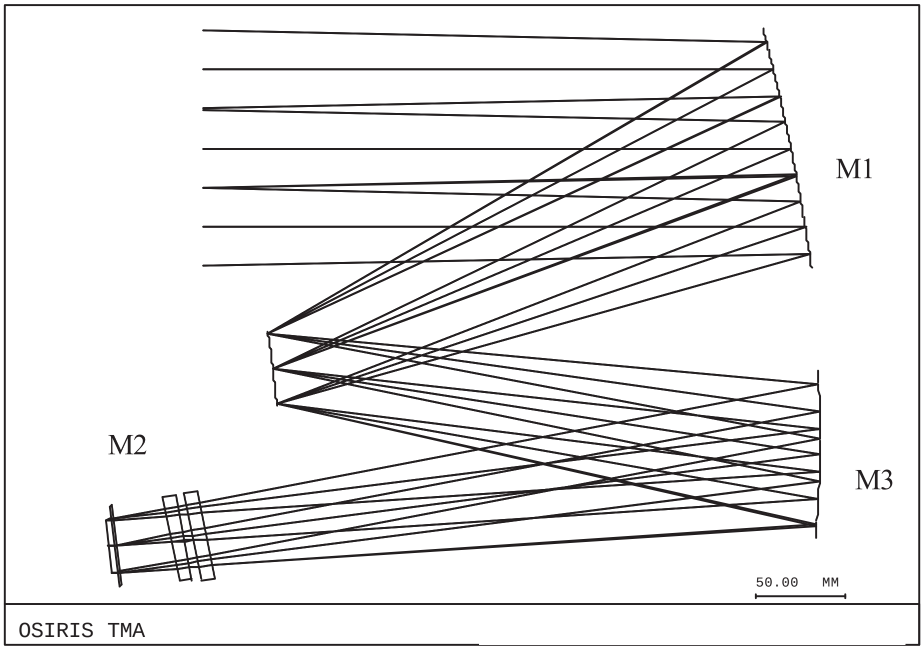

Fig. 4 : OSIRIS TMA optical layout. The M1 mirror is an off axis aspheric.

Item	Performances
Telescope concept	All reflective three mirrors off axis design, unobstructed, unvignetted
Optical characteristics	FOV 2.35°, focal length 700 mm, Wavelength range 250 to 1000 nm
Mechanical characteristics	Less than 12 Kg, frequency up to 100 Hz, compatible with spacecraft and Ariane 5 launcher requirements
Thermal Characteristic	Telescope operating temperature –100°C to 70°C, No thermal control on telescope
Refocusing	Two switchable focusing ranges (1 km to 2 km, 2 km to infinity)
Filter wheel	Dual filter wheel, 8 positions each
Shutter	10 ms minimum exposure time
Focal plane	Full frame 2048 x 2048 pixels^2 of 13,5 x 13,5 µm operating temperature -113°C to -93°C

Fig.5 : Summary of the NAC instrument performances

2.3. Telescope structure

The telescope, mirrors and primary structure are entirely made up of Silicon Carbide. The primary structure has a U shape for the optimisation of thermo-elastic performances. It is composed of a front plate and a back plate joined together by a tube. The telescope is used as a primary structure and thus interfaces directly with the other elements of the instruments and with the satellite. The three mirrors are directly mounted on the Silicon Carbide plates using titanium bolts. Such a telescope does not need any thermal control as its behaviour under homogeneous temperature changes is perfectly homothetic and thus keeps the image focused onto the detector. In addition its excellent conductivity avoids the introduction of temperature gradients. The use of monolithic SiC has enabled us to cleverly answer the requirements with this extremely simple concept made up of only three structural elements and three mirrors.

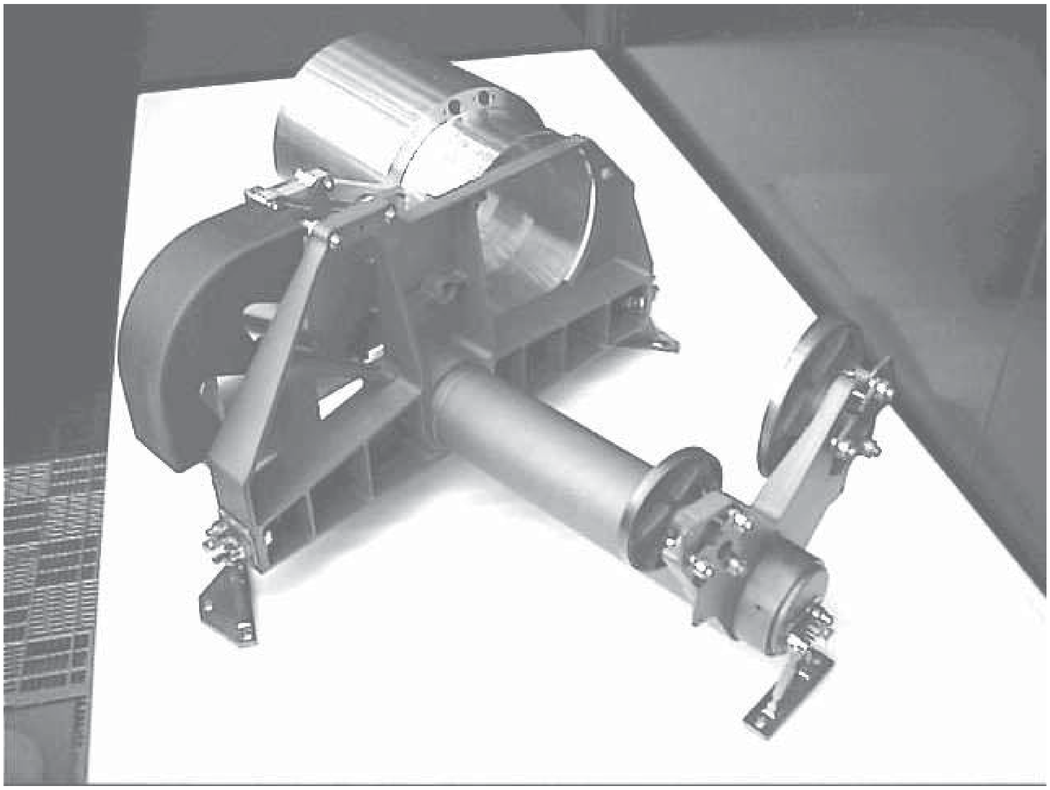

Fig. 6: Mechanical model (flight primary structure and equipment holder plate) equipped with spare mirrors and equipment dummies

2.4. Mechanical structure design

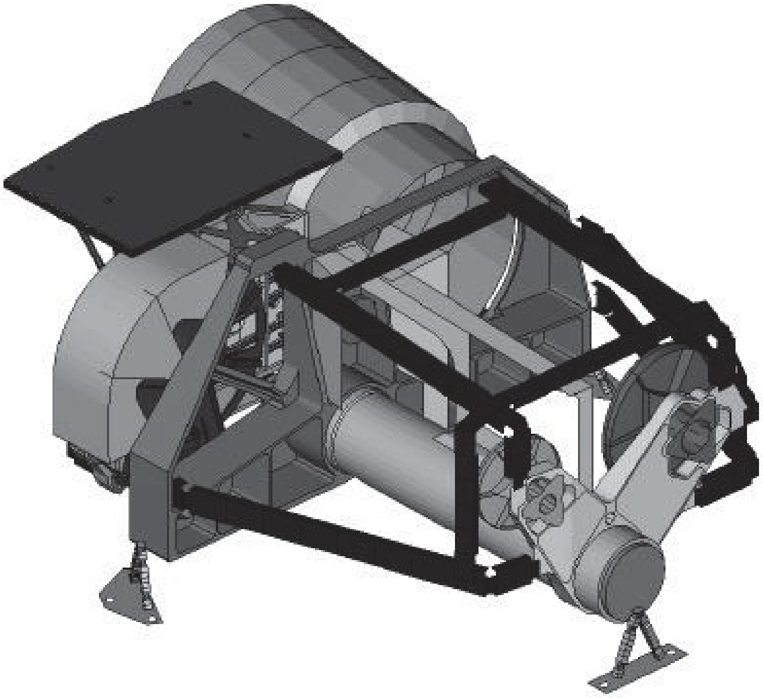

Fig. 7: A Nastran finite element model of the NAC has been built. It includes models of the sub-systems with maximal masses in order to take into account the worst case.

Mode number	Frequencies [Hz]	Description
1	86.7	Secondary structures
2	94.9	M2 wall torsion mode
3	110.3	Equipment holder plate
4	119.7	Telescope
5	124.3	Door supporting mechanism
14	144.5	Equipment holder plate, filter wheel, secondary structures
23	176.5	Equipment holder plate and equipments
26	186.7	Equipment holder plate blades

Table 1: Main frequencies for the major vibration modes

The static dimensioning has been done under 25 g, independently in the 3 directions. From these computations, the direction of the worst case loading has been found. Stresses in the SiC are computed considering normal stress, shear stress and according to the Hoffman criteria. Forces at the satellite interface have led to the use of M6 bolts.

2.5. Thermal control

The NAC is an individually controlled unit. The basic concept is an athermalized telescope, well focused in any thermal environment. The sub-systems, which dissipate power and need thermal control, are mounted on a common plate decoupled from the SiC telescope. The isolated Front Door Mechanism is attached onto the SiC structure through a low conductive attachment.

Thermal conduction through the mounting feet is low due to their design. Radiative exchanges will be inhibited by the use of Multi Layer Insulation foils. Thus the current NAC design is not sensitive to the spacecraft temperature variations. No heater is needed for the NAC telescope structure which fluctuates freely between –100 and +70°C; only the equipment plate assembly and the front door mechanism are thermally controlled around –40°C in order to fulfil temperature requirements for the sub-systems.

The Focal Plane Assembly has a dedicated radiator directly connected to the CCD with a cold finger in copper.

The whole instrument only needs a thermal control power of 5 W to fulfil its mission.

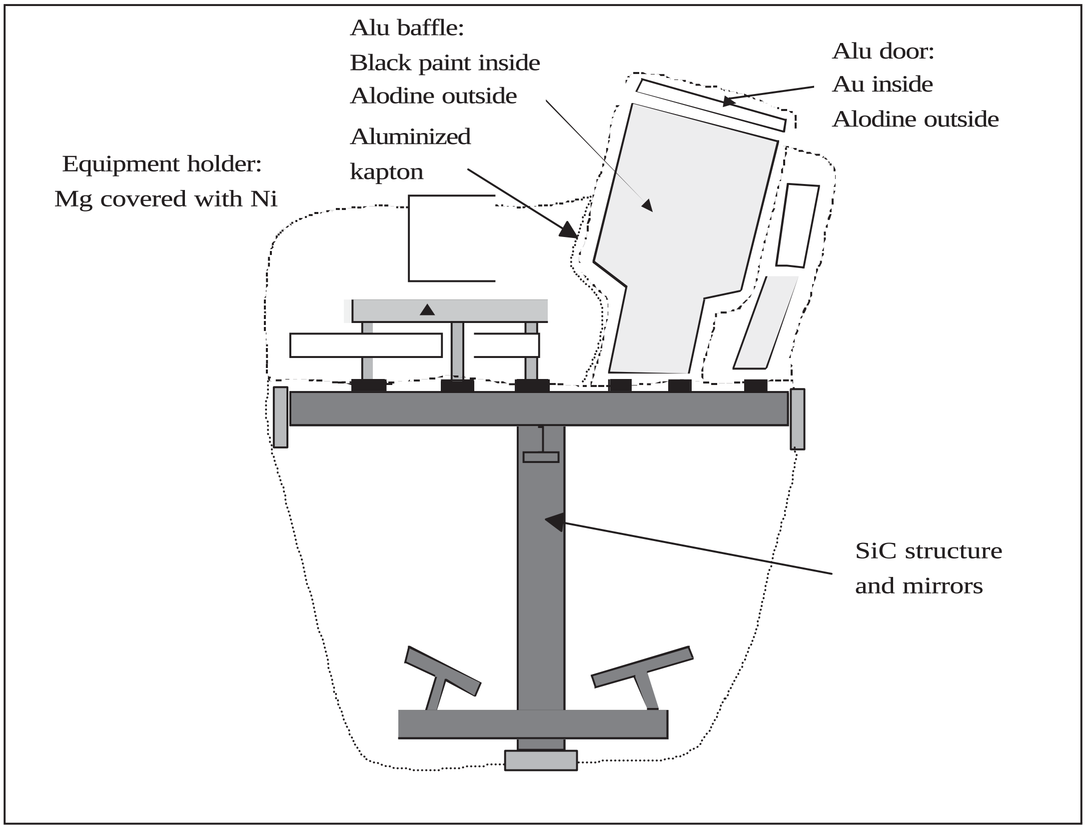

Fig. 8 : Thermal control of the NAC. The telescope is left free to fluctuate between –100°C and +70°C while the equipment are controlled. This allows to maintain the dissipated power within the 5 required Watts.

3. DEVELOPMENT

The following three models are needed for the instrument and the ROSETTA satellite development:

- The Structural and Thermal Model (STM) : for the validation of the structure and the mechanical and thermal test on the spacecraft.
- The Mechanical Model (MM) for the qualification of the flight primary SiC structure and the Equipment holder, refurbished as Proto Flight Model.
- The Proto Flight Model (PFM).

3.1. Structural and Thermal Model (STM) development

The STM is dedicated to the mechanical and thermal validation at instrument and satellite level.

The STM representative of the camera and telescope architecture has been tested under mechanical loads (sine, quasistatic, random and shock) with success at instrument and satellite level. It also has been tested during the thermal test at satellite level. It has demonstrated the capability of the Silicon Carbide concept to fulfil the launch environment requirements.

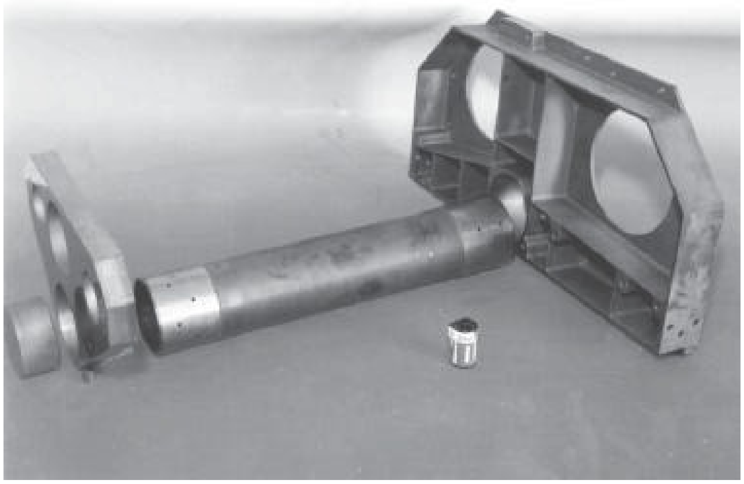

Fig 9 : STM primary structure

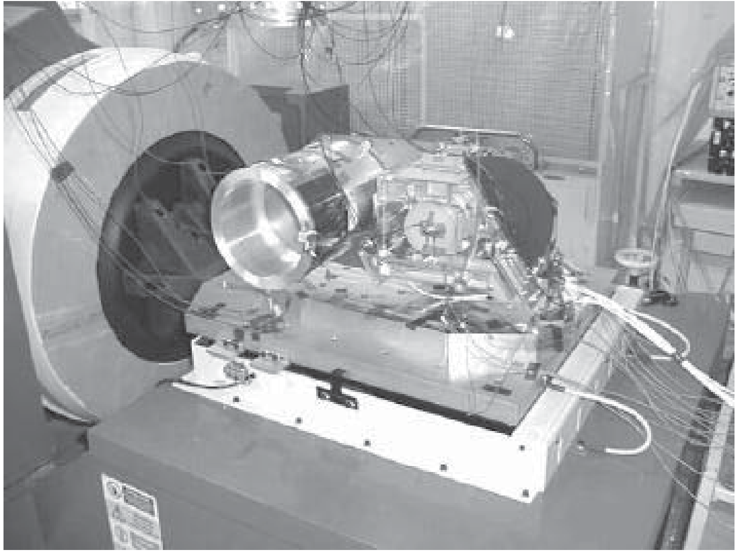

Fig. 10: NAC OSIRIS STM on the shaker at Laboratoire d'Astronomie Spatiale.

3.2. Mechanical Model (MM) development

This model has been manufactured and fully tested. The MM was composed of the flight SiC primary structure and the Equipment holder equipped with spare SiC mirrors and equipment dummies. This model allowed the qualification of the primary structure before the integration of the flight mirrors and equipments.

The MM has been tested under quasistatic loads with success. This load covers all low and high frequency specifications at instrument level. It demonstrates the capability of the SiC primary structure to fulfil the requirements.

The MM has been disassembled before starting the integration of the PFM telescope

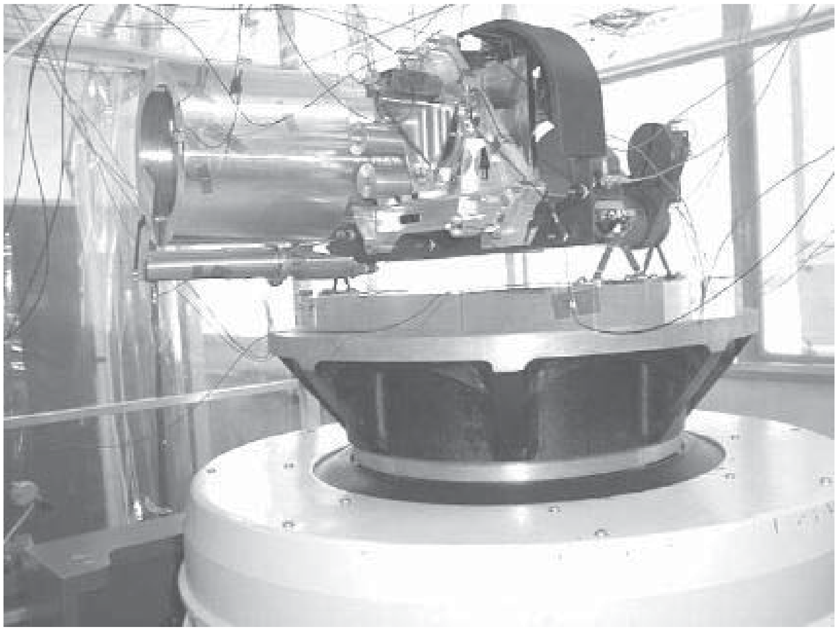

Fig. 11: NAC OSIRIS STM on the shaker at Laboratoire d'Astronomie Spatiale.

3.3. Proto flight model (PFM) development

All the parts for this model have been delivered to Astrium for the integration phase. The integration of the telescope includes the optical alignment of the three mirrors, the integration of the straylight internal baffles and of the entrance baffle, the mounting of the secondary structures and of the protection envelope.

4. SILICON CARBIDE MIRRORS

We recall here the major steps for the manufacturing of a SiC mirror. In this case mirrors are not different from other structural pieces and they go through the main following stages:

- Preparation of the SiC powder: fine SiC powder is mixed with organic binders and some additives.
- Isostatic compression: the powder is isostatically pressed at high pressure (> 1400 atmospheres) and at ambient temperature. This gives the so called green body.
- Green body machining: this green body is easily machined to the desired shape. On a mirror the lightweigting is obtained at that step.
- Sintering: the final piece is sintered at high temperature (~ 2000°C).
- Lapping: specific parts of the mirror are then lapped when a high surface flatness or geometrical accuracy is needed.

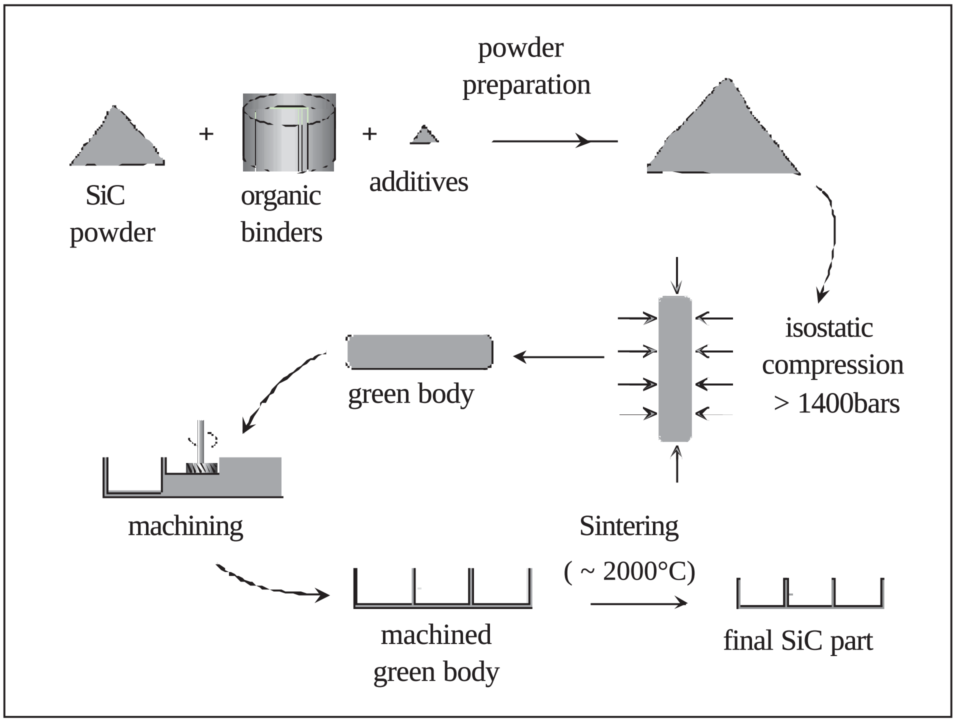

Fig. 12 : The main manufacturing stages of a SiC part.

Fig. 13 : The three types of mirrors after sintering. The optical surface and mechanical fixation are parts of a single SiC element. The diameter of the larger mirror is 130 mm.

5. M1 MIRROR MANUFACTURING PROCESS

We will detail below the manufacturing process of the off axis aspheric M1 mirror. The other mirrors have gone through the same phases, although without the specific constraints due to this off axis characteristic.

Direct off axis polishing was not readily available when the project started. It was thus decided to polish the M1 inside a parent mirror tool having a symmetry of revolution. Manufacturing of a parent mirror and cutting the off axis elements after polishing was not considered because of the difficulty to make this last operation. SiC is extremely hard and cannot be cut as it has been made on ZERODUR for example. In addition the expected deformation of the mirror after cutting was unknown and could have been far above the required optical quality. The parent tool and mirrors were thus manufactured separately. The tool however had to be made of SiC to present the same hardness as the mirrors during the polishing activities.

Fig. 14 : The SiC parent mirror tool. The external diameter is 330 mm.

5.1. Activities before CVD

The first activity was the lapping of the mirror. As the departure from the best sphere on the parent mirror is in the order of 26 microns and the foreseen thickness of the CVD layer was 80 microns, it was decided to apply the CVD coating on the substrate having a spherical shape. Thus the three M1 mirrors were mounted inside the parent tool and the whole assembly was lapped spherical. Because of the off axis it was necessary to index the three M1 mirrors in rotation and to centre them properly inside the tool so that the mirrors could be mounted and dismounted at various stages of the manufacturing with a good repeatability. This operation was performed by BOOSTEC.

The departure from sphere was in the order of 20 microns after lapping. This was followed by an optical grinding by STIGMA OPTIQUE to check the absolute value of the radius of curvature and to reduce the error to a few microns.

5.2. CVD coating

The sintered SiC without CVD coating presents micro-porosity which are responsible for some light diffusion in the visible spectrum. This is normally not a problem for an Earth observation instrument. However a comet is a grey type of object with some very bright parts and other very dark ones. It was thus required to reduce the diffusion to the maximum possible extent so that one could observe a small dark part surrounded by a very bright background. A CVD coating was thus mandatory on our mirrors.

The CVD coating is obtained in a high temperature chamber where a gas containing Si and C molecules is flowing. This coating is deposited on all parts inside the chamber but the thickness uniformity is not perfect in the whole volume. These requirements led to two major constraints. The mirrors had to be mounted inside the tool so that the thickness would be the same on both. Indeed the removal of a step between the tool and the mirrors implies to remove much more than the actual value of the step. Once this is decided one has to put some insulating material between the tool and the mirrors so that they do not stick together after CVD coating.

All these problems were successfully solved and the mirrors and tool were covered with a CVD layer with a thickness about 80 microns.

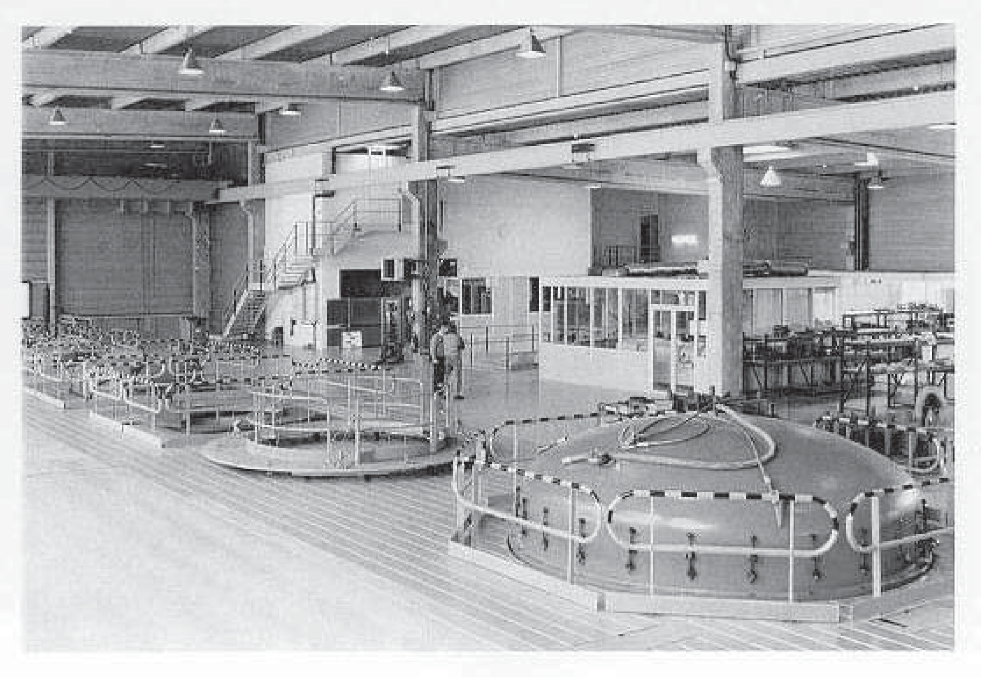

Fig. 15 : SiC CVD facilities at SNECMA.

5.3. Polishing

After CVD coating the mirrors went back to STIGMA OPTIQUE. The mirrors were mounted again inside the tool. The assembly was ground spherical, then polished and eventually underwent the aspherical figuring. The process went smoothly and was finished with a remaining thickness of CVD in the order of 40 microns.

The most critical step was the dismounting of the mirror. After disassembly the mirrors were effectively out of specification and showed a deformation linked to the lightweighting pattern on the back of the optical surface. The peak to valley deformation was in the order of .8 microns and thus perfectly compatible with ion figuring capabilities.

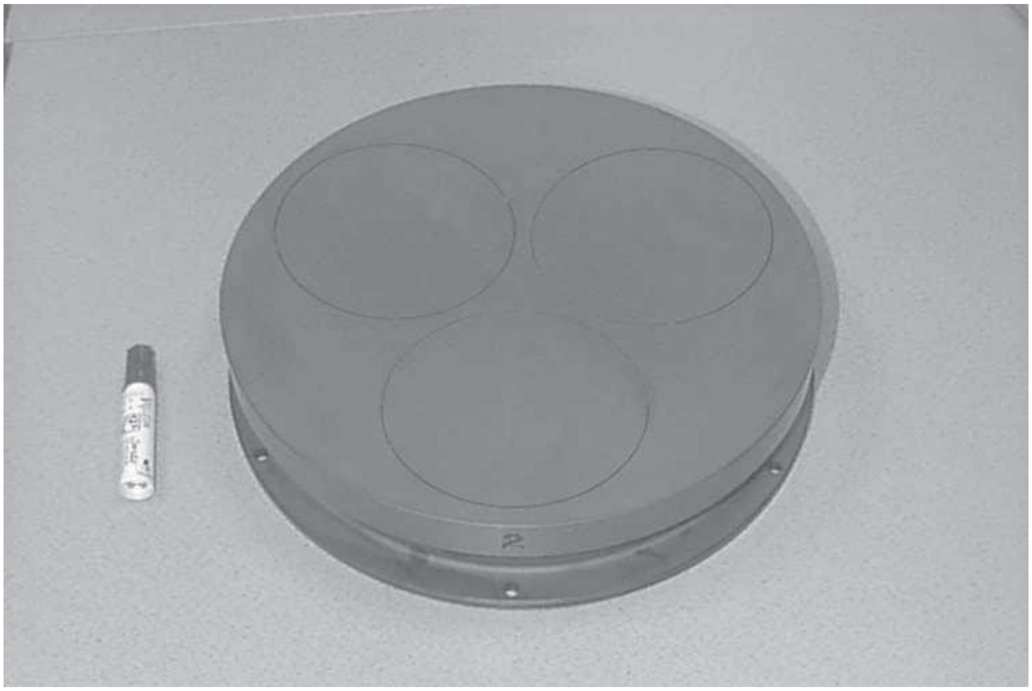

Fig. 16: The three M1 mirrors inside their parent tool ready for polishing.

5.4. Ion figuring

The ion figuring activities were performed by "Institut für Oberflächen Modifizierung" (IOM) in Leipzig. ASTRIUM was in charge of the mirror figure error measurement. The measurement files were then transferred to IOM were the ion figuring sequence was computed and executed on the mirror.

Some validations were performed prior to the figuring. For example the effect of ion figuring on the micro-roughness was checked on CVD coated SiC samples. A micro-roughness of 3 angstrom was not affected for an etching depth of 800 nm similar to the one foreseen on the mirrors.

One difficulty were the definition of a reference point to link the surface error map obtained with the interferometer with the actual position of the ion beam with respect to the mirror. This was solved by careful geometrical measurements at ASTRIUM and IOM. The final positioning error however was in the 1 mm range. A second difficulty was the presence of relatively high frequency defects because of the aspheric polishing zoning. Removing these defects implied the use of a very small beam and thus a long etching time. In addition such high slope defaults are very sensitive to positioning errors. However a good compromise was found and the mirrors were successfully etched. The final figure error was within the 30 nm specification.

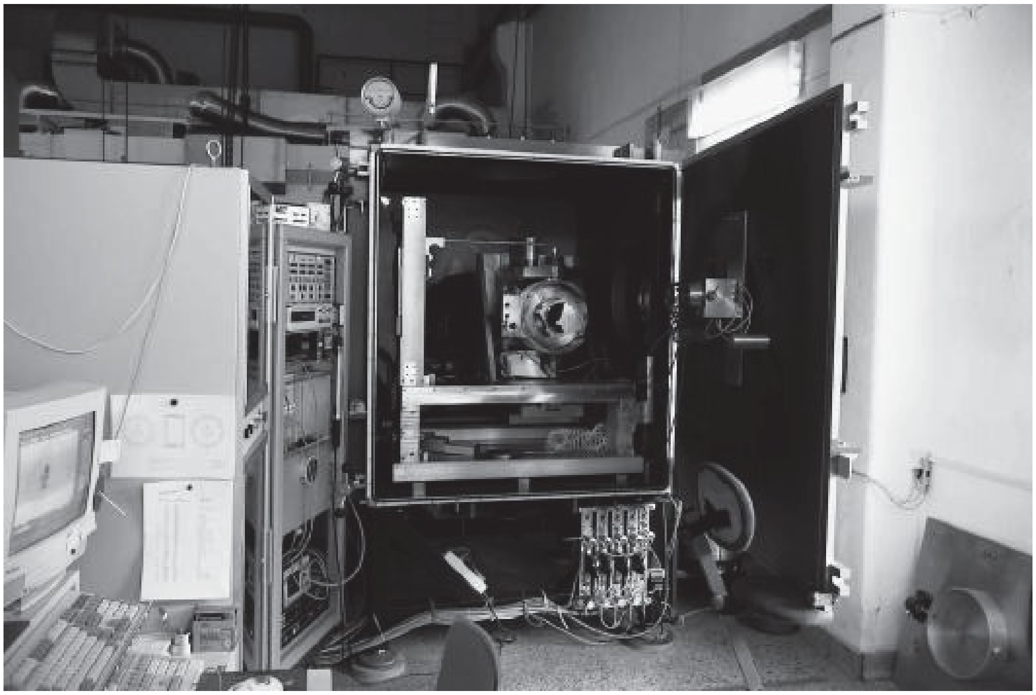

Fig. 17: The ion beam figuring facility at IOM. The mirror is mounted inside the vacuum chamber. The ion beam generator can be seen on the inside face of the door. The control computer is also shown on the left..

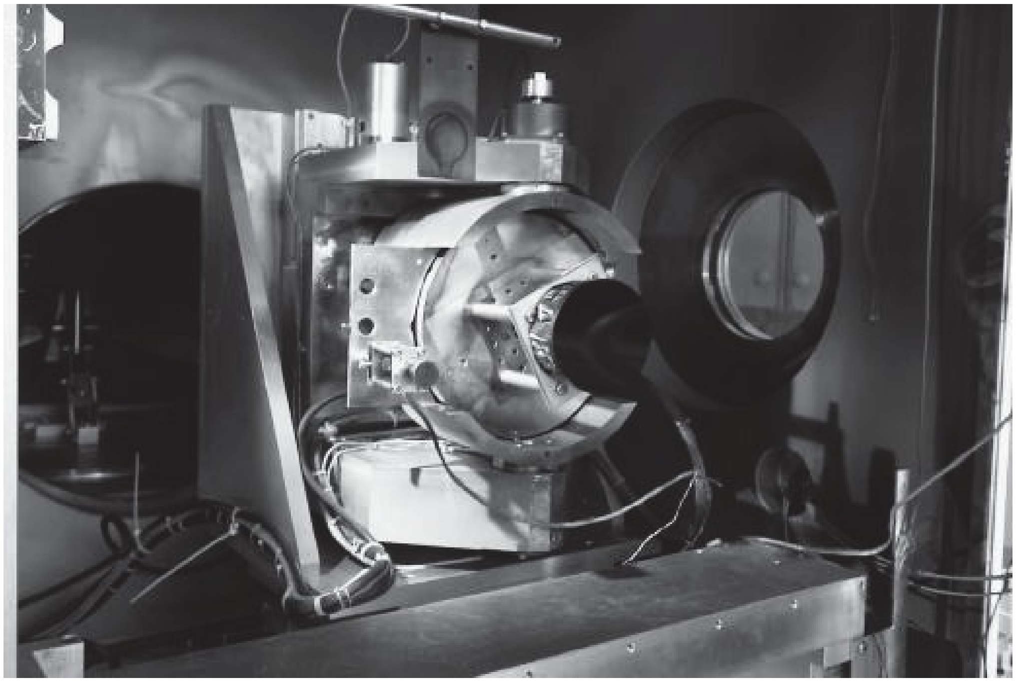

Fig. 18: The mirror is mounted on a 2D moving support piloted by the control computer. The displacement is such that the ion beam is slowly scanned on the mirror bumps and goes more rapidly over the hollow zones.

5.5. Coating

The last process was the optical coating using protected aluminium. In this case SiC is not different from the other optical substrate and the applied process is exactly the same as for a glass mirror. For space application there is however an advantage linked to the SiC electrical conductivity. Indeed there is no need to ground the coating with a specific strap in this case.

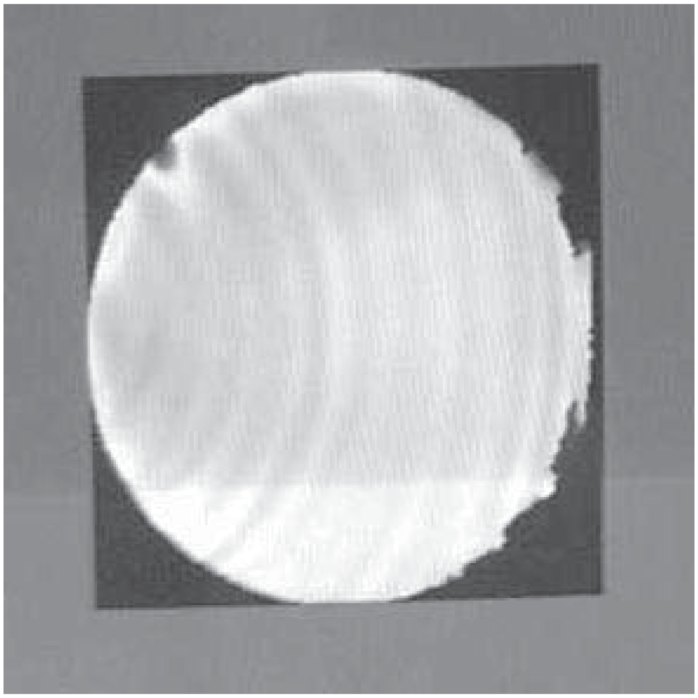

Fig. 19: Surface error of the M1 mirror after coating on the whole useful surface of 130 mm diameter. The zones created during aspheric polishing are clearly visible. The actual beam footprint on M1 has a diameter of 88 mm.

6. CONCLUSION

The development of the telescope as well as the manufacturing of the SiC mirrors, including an off axis aspheric has been a complete success. This success did materialise into the successful vibration tests and into the successful alignment of the complete TMA telescope. Indeed the final optical quality of the aligned telescope was barely different from the optical quality of the primary off axis mirrors as the figure errors of the secondary and tertiary were negligible (below 9 nm rms) and the alignment contribution very small (residual astigmatism below 20 nm).

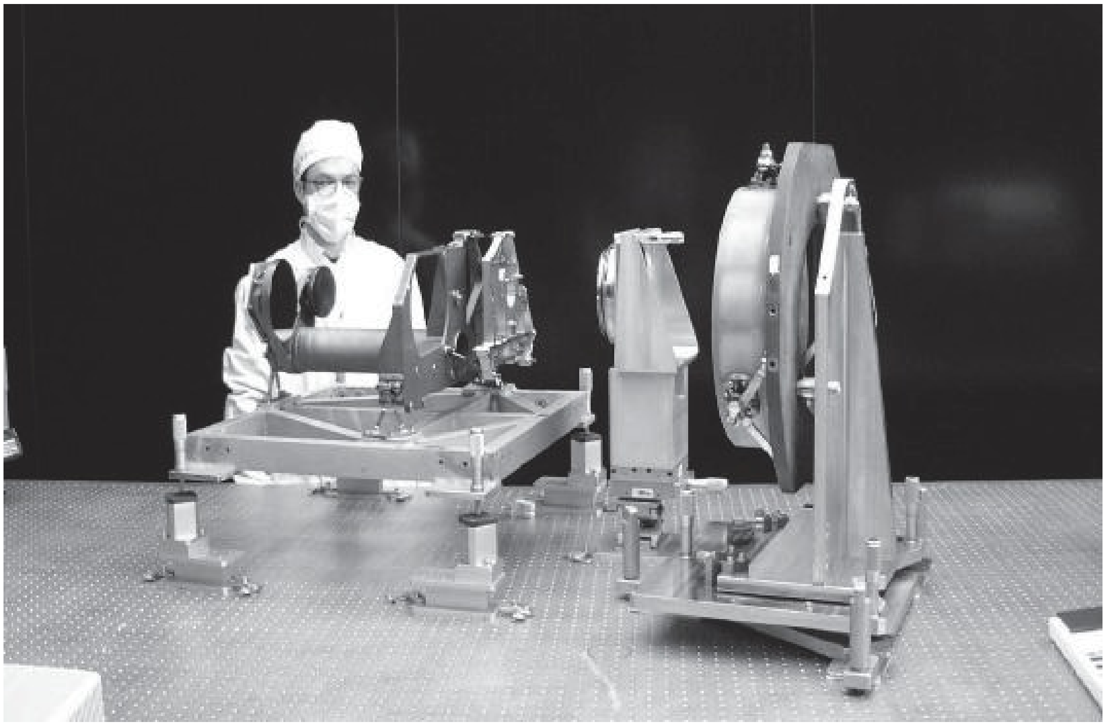

Fig. 20: The OSIRIS TMA under interferometric alignment at ASTRIUM.

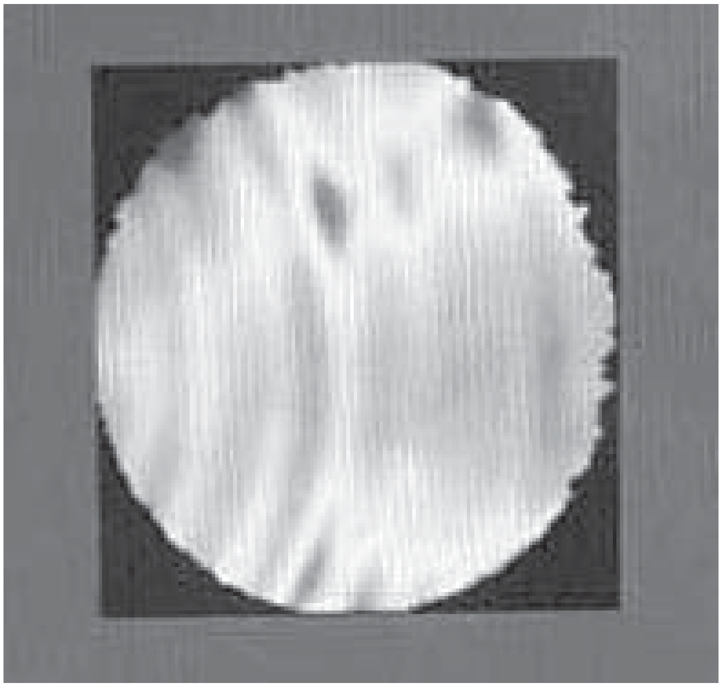

Fig. 21: Final telescope wavefront error. The similarity with the M1 mirror figure above is obvious.

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