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The monolithic SiC telescope of the OSIRIS Narrow Angle Camera for the cometary mission ROSETTA

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ABSTRACT

The ROSETTA mission, funded by the European Space Agency, will provide a unique opportunity to investigate the active life of a comet during its rendez vous with the P46/Wirtanen comet foreseen in 2012.
We describe here the design, the development and the performances of the telescope of the Narrow Angle Camera of OSIRIS which will give detailed images of the comet in the visible spectrum down to a distance of 600 m.
The telescope is a Three Mirror Anastigmat covering a 2.35° square field. The optical design requires the manufacturing of off axis aspheric mirrors with a diffraction limited quality in the visible spectrum. The straylight requirements also lead to a micro-roughness requirement around 1.5 nm rms. This was achieved using a CVD SiC layer deposited on the mirror surface.
This telescope is entirely made up of sintered Silicon Carbide, including the structure and the mirrors. The structure concept uses a small number of elements to improve the stability. The mirrors are also directly mounted on the structure thanks to an innovative design. The use of Silicon Carbide enables to have a high stiffness with a low mass. In addition the mono-material concept enables to be insensitive to the temperature variations of −100/+70°C seen during this very long mission.

Keywords: silicon carbide, telescope, performance, stability, mirror, structure

1. INTRODUCTION

The international ROSETTA Mission funded by the European Space Agency provides a unique opportunity to study a relic from the birth of the Solar System: the comet 46P/Wirtanen from the Jupiter family. OSIRIS (Optical, Spectroscopic and Infrared Remote Imaging System) funded by a consortium of European laboratories and made up of two instruments: the WAC (Wide Angle Camera) and the NAC (Narrow Angle Camera) presented herein, will play a major role in this investigation. The system shall provide data on the position, size and orientation of the comet nucleus, its mineralogy, activity, homogeneity and topography, the near dust environment and its evolution in time. The quantitative observations of active areas with a resolution of about 3 cm per pixel requires the orbiter to be closer than 600 m to the nucleus during extended time intervals. This "rendez vous" with a comet imposes to be particularly fit against the unfriendly environment encountered during the long trip. Every gram or watt gained on the instrument improves the chances of success in this type of mission. In these conditions, the performances of Silicon Carbide and the new telescope concept chosen for the NAC are an ideal choice to fulfill these criteria without any limitation on the scientific objectives.

The Narrow Angle Camera described herein is designed and constructed by LAS, MMS and SiCSPACE. The development of this monolithic Silicon Carbide telescope opens new possibilities in the frame of the space technologies for optical instruments, from the small instruments such as NAC to the future large systems as FIRST or the NGST.

2. INSTRUMENT OVERVIEW

2.1. Instrument description

The NAC is a Three Mirror Anastigmat (TMA) optical system. The telescope is 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 by glue. The mirrors are bolted onto the walls with interposed SiC spacers and the optical adjustments are made by machining these spacers to the required values.

A dedicated aluminum plate (equipment holder) holds the Shutter, the Filter Wheel Mechanism and the Focal Plane Assembly. This plate is mechanically and thermally decoupled from the SiC structure thanks to the use of Invar legs and low conduction shims. The Front Door Mechanism is attached onto the front SiC wall using a low conductive spacer. The NAC is decoupled from the S/C interface via three titanium bipodes. The protection against dust and external stray light is done by wrapping the camera with a 50μ thick black Kapton foil. MLI will be put over this foil. Venting devices will avoid over pressure and dust entrance.

The key camera design drivers are as follows: $\lambda/10$ rms optical quality in the field in the visible, lightweight, launch loads compatible with Ariane 5 and thermal power consumption less than 5 w.

Item	**Performances**
Optical concept	All reflective three mirrors off axis design, unobstructed, unvignetted
Field of view	2.35°
Nominal focal length	700 mm
Overall transmission	> 60 to 80 % depending on wavelength
Wavelength range	250 to 1000 nm
Refocusing	Two switchable focusing ranges (2km to infinity, 1 km to 2 km)
Filter wheel	dual filter wheel, 8 positions each
Shutter	10ms minimum exposure time 3,5s of dead time between exposures
CCD	full frame 2048 x 2048 px^2 of 13,5 x 13,5 μm operating temperature -113°C to -93°C
Mass	Less than 12 Kg
Mechanical	compatible with spacecraft and Ariane 5 launcher requirements

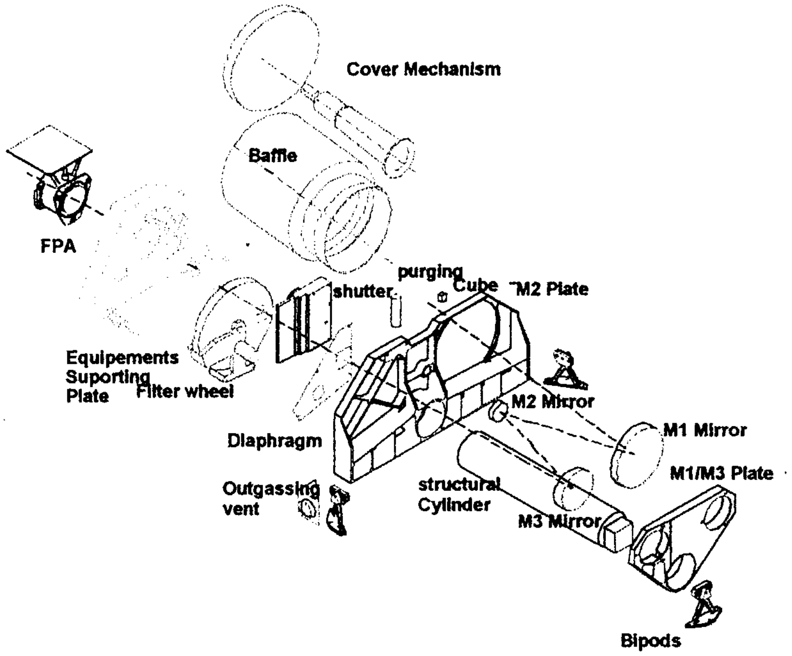


Fig. 1: NAT Instrument performances and design summaries

2.2. Equipment, telescope

The telescope, mirrors and primary structure are entirely made up of Silicon Carbide. The primary structure has a U shape for the optimization of thermo-elastic performances. It is composed of a front plate and a back plate joined by a tube firmly attached by cylindrical gluing. 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 fixed to the silicon carbide plates using three titanium bolts. Such a telescope does not need any thermal control as its behavior 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 six elements.

The equipment holder carries three equipments: the focal plane assembly, the filter wheel and the shutter. The focal plane assembly keeps the CCD in the correct position and cools it down to - 113°C during operation. The housing stability is ensured by a temperature compensation mounting of the cold part, via glass sphere in conical titanium rings, which also act as a thermal insulator. The dual filter wheel mechanism accommodates 8 filters plus one open position for each wheel resulting in a total of a selectable number of 14 filters of 40 x 40 mm^2 covering a range of 200 to 1100 nm. The filter wheels is driven by two stepper motors and encoders. The shutter allows to control the exposure time of the CCD with a shortest time of 10 ms. It contains two blades which are moved across the field of view via a linear actuator. The equipment holder is linked to the telescope by three isostatic Invar blades.

The front door provides a dust tight seal for the camera. It uses a stepper motor and moves the door sideways in order to protect the back side from dust contamination from the nucleus part of the comet. The current baseline is to use a stepper motor of the same type as in the filter wheel (commonality) and a fail-safe one-shot opening device.

The secondary structures provide protection from the internal and external straylight and the thermal insulation of the camera. The secondary structures include the entrance baffle, the internal vanes and the supporting frame of the multi layer insulation .

he thermal control hardware consist of heater and thermostats which control the equipment plate assembly and the front door mechanism.

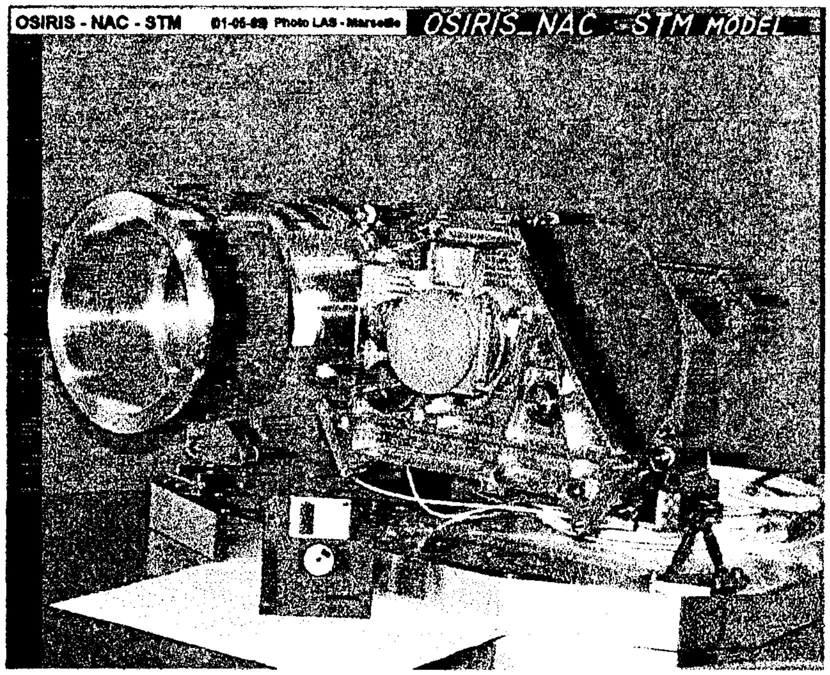


Fig. 2: STM Model with equipment dummies

3. TELESCOPE OVERVIEW

3.1. Optical design

The OSIRIS NAC telescope operates from 250 nm to 1000 nm. Its Field Of View is a square 2.35° on the side. The optical quality specifications are a rms wavefront below 63 nm in the field and a focus variation below 80 microns. The chosen optical design is a Three Mirror Anastigmat with an entrance pupil diameter of 88 mm and a f-number of 8.

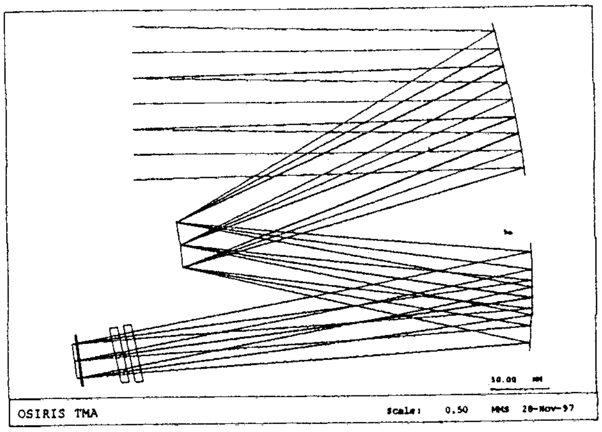


Fig.3: The chosen optical design for the OSIRIS NAC is a Three Mirror Anastigmat.

The primary mirror is an off-axis aspheric, the secondary is a convex parabola and the tertiary is a sphere. The mirrors blanks are light weighted. Their interface which is directly bolted onto the structure has been designed to avoid the introduction of deformations on the optical surface. The major component is of course the primary mirror. The manufacturing of the primary mirrors starts with the machining of three SiC 100 blank and of a SiC tool simulating a parent mirror having a symmetry of revolution. The mirrors are then mounted in the tool and ground to a best sphere shape. After this operation the assembly is coated with a CVD SiC layer, such a layer being necessary in this case to obtain the required micro-roughness of 10 Å rms. The final polishing is eventually made and the mirrors are dismounted from the parent tool to be mounted on the different telescope models after reflective coating.
The other mirrors are polished in a standard way as with glass mirrors except for the CVD coating.

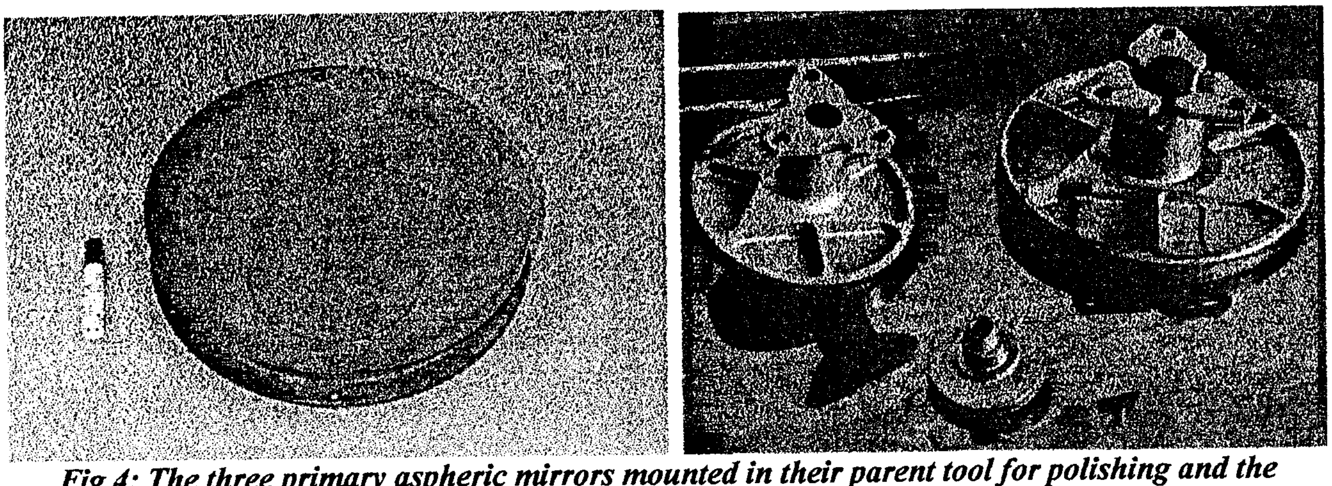
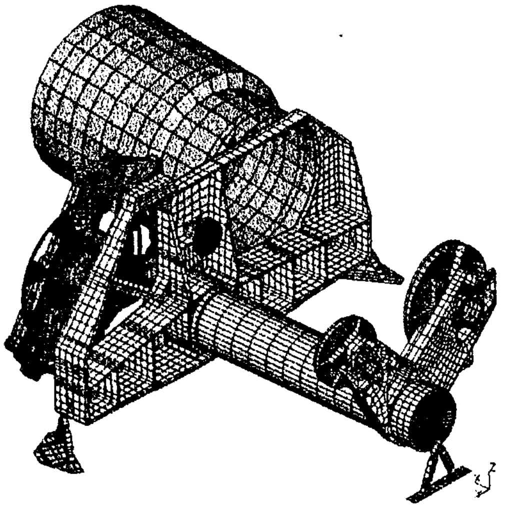


Fig.4: The three primary aspheric mirrors mounted in their parent tool for polishing and the OSIRIS mirror blanks

The alignment of the telescope will be made using interferometric measurements. The mirrors are first set in position within mechanical tolerances and wavefront error measurements are made in the field. The analysis of the obtained wavefront enables to define the required displacements of the mirrors. Such a procedure enables to reach the required optical quality within a few iterations.

3.2. Mechanical design

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



Mode	Frequency [Hz]	M_{xx} [kg]	M_{yy} [kg]	M_{zz} [kg]
8	116.78	3.1	0.5	1.1
9	118.28	0.6	2.9	0.1
11	134.34	1.1	1.9	0
Dynamic mass		5.5	6.9	2.2
Residual mass		5.8	4.4	9
Total mass		11.2	11.2	11.2

Fig. 5: Main frequencies and effective masses for the first fifteen modes

The principal mode of the structure is a coupling of the filter wheel with the equipment holder. Static dimensioning has been done under 81g, 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 Hoffman criteria. Forces at satellite interface have led to the use of M6 bolts for the fixation.

3.3. Thermal design

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

Thermal conduction through the mounting feet is low due to the feet design. Radiative exchanges will be inhibited by the use of MLI. 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 fulfill the sub-systems thermal requirements.

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 fulfill its mission.

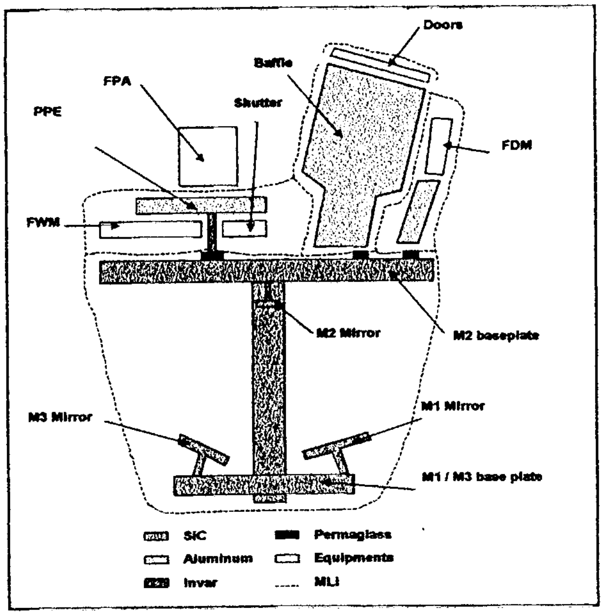


Fig. 6 : Thermal control of the NAC

4. DEVELOPMENT STRUCTURAL AND THERMAL MODEL

Three models are needed during the NAC development. The first one (STM) is dedicated to mechanical and thermal validation at instrument and satellite level. Today this model has been manufactured, tested and delivered to the LAS. The two other models are identical and flight compatible. The first one is the reference model used on ground during the operations, the second one is the flight model.

The STM representative of the camera and telescope architecture has been tested under mechanical loads (sine, quasistatics, random and shock) with success. It demonstrates the capability of the Silicon Carbide to fulfill the launch environment requirements.

The elementary parts of the remaining models are being manufactured for a foreseen delivery of the telescope during the second quarter of 2000.

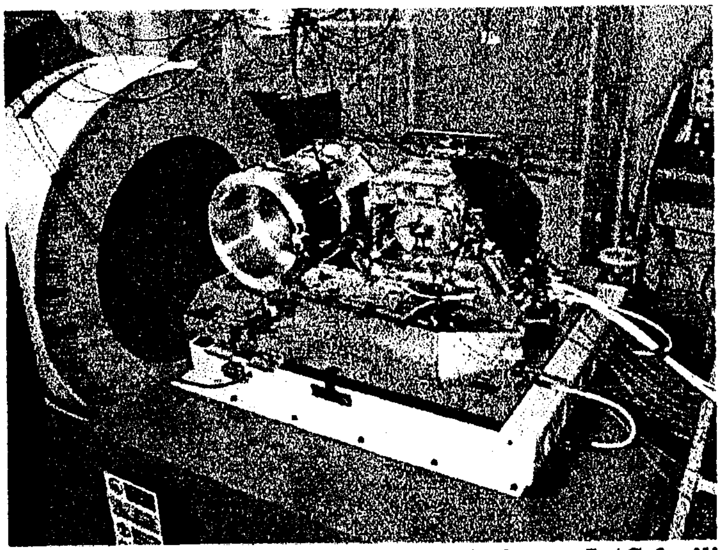


Fig. 7: STM NAC OSIRIS on shaker at LAS facilities

5. SILICON CARBIDE TECHNOLOGIES

5.1. Why Silicon Carbide for the OSIRIS NAC?

Silicon Carbide is recognized worldwide as a highly promising material for the development of mirror substrates and all the structural parts of telescopes, because of its many attractive properties such as:

- high specific stiffness (high stiffness and low density)
- low thermal susceptibility (low thermal expansion with very high thermal conductivity)
- it is a very hard and stiff material which allows tight mechanical tolerances in the µ range to be achieved, and very demanding figuring and polishing performances to be reached for mirrors.

The following table Fig.1 shows the superiority of Silicon Carbide compared to other possible materials for the development of space borne mirrors and telescopes.

	C&C SiC 100	Beryllium	Zerodur	Aluminum
Density ρ (g/cm^3)	**3,14**	1,85	2,53	2,73
Young Modulus E (GPa)	**420**	303	91	71
CTE α (ppm/K)	**2**	11,4	0,05	24
Thermal conductivity λ (W/m/K)	**180**	180	1,6	237
Specific heat Cp (J/K/kg)	**680**	1880	821	900
Ratio λ/α	**90**	16	33	10
Ratio E/ρ	**133**	164	36	26
Figure of merit (λ/α) x (E/ρ)	**11970**	2624	1188	260

Fig.8: The higher thermal toughness, associated to a very high specific stiffness, places SiC as the ideal material for the construction of lightweight athermal space based assemblies

The combination of a very low CTE -comparable to Invar- with a very high thermal conductivity -comparable to Beryllium- allows the design of assemblies only made from this material which are almost insensitive to uniform temperature excursions and to thermal gradient. Its very high stiffness, combined to a relatively low density and low thermal susceptibility, allows, on the other hand, the design of very lightweight structural parts with low thermal power consumption.

Still, the elaboration of SiC parts is achieved easily using well controlled processes thus insuring a very high constancy of the characteristics. The polishing process of mirror surfaces is comparable to glass. Because of the residual intrinsic porosity of the bulk material, the scattering of polished bare SiC remains about 40 times the one of glass. For more demanding applications, this performance is improved by applying a thin layer -50 to 100 µm- of SiC CVD still at good economical conditions. In this case, the achieved micro-roughness equals or overpasses the one achieved on glass [1].

All this fully justifies the approach followed by Matra Marconi Space to promote, through its joint venture with Boostec called SiCSPACE, the development of Space optical instruments using sintered C&C SiC-100 material as for the OSIRIS NAC telescope.

5.2. Structure (assembling technologies: brazing, gluing...)

Material manufacturing

Silicon Carbide can be obtained by various processes, which can significantly affect either its physical properties or its cost. We shall only consider here the sintered Silicon Carbide 100 manufactured by SiCSPACE according to a well-defined and cost-efficient process.

The material is not toxic and has been used for many years in various industrial domains, such as fluid pumps in car or chemical industries and heat exchangers. Most often, it is used for its good mechanical and thermal properties (high strength, no fatigue, high thermal conductivity) and/or its insensitivity to hard environmental constraints (no acid or alkali attack, ability to work over a very wide temperature range (0 K to 1800 K) and to withstand thermal shocks, no humidity effects).

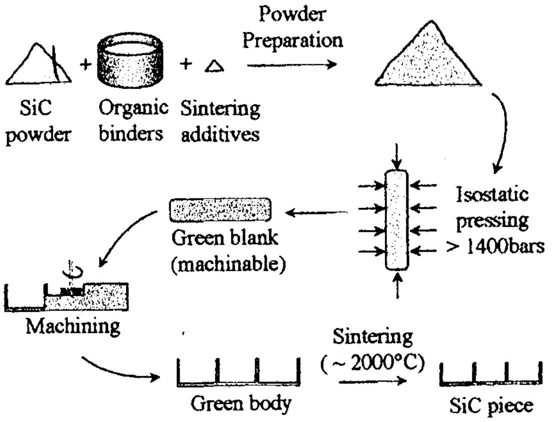


Fig. 9 : Major manufacturing steps for sintered silicon carbide.

The major manufacturing steps of a SiC blank are shown on figure 2 :

i) SiC powder preparation: a fine powder of Silicon Carbide is mixed with organic binders and additional elements.

ii) Isostatic compression: the powder is isostatically pressed at a high pressure (> 1400 bars) at room temperature, giving birth to an intermediate material called "green body".

iii) Green body machining: the green body is easily machined to the desired shape. For mirrors and structures, the lightweight shape is performed on the green body.

iv) Sintering: the machined green body is pressureless sintered at high temperature, about 2000°C.

The organic binders are removed during the sintering process and over 98.5% of the material is then composed of SiC. With the standard SiCSPACE process, this composition is controlled within 200 ppm.

The pressureless sintering of SiC makes possible to reach a densification level over 97%. As a consequence, the ceramic exhibits a residual porosity of less than 3% and typically 2% in volume. The sintering gives an isotropic shrinkage of SiC parts. The length contraction is about 20% and know-how allows to accurately master this phenomenon and therefore the size of the sintered component.

Assembling techniques

Available facilities allow to easily manufacture monolithic Silicon Carbide parts with dimensions up to 0.5 m x 1 m x 1.6 m. This covers practically most of the needs. Manufacturing larger monolithic pieces would require a significant industrial investment.

Therefore, the cost effective and safe approach for the realization of large pieces is to assemble together smaller pieces, which are well within manufacturing capabilities. Several techniques have been developed :

i) Mechanical assembling by bolting
ii) Epoxy bonding
iii) Brazing

Bolting together the elements is a straightforward technique which is probably the most efficient for joining structural parts. The joint present good performances and allows to mount and dismount the assembly.

Epoxy bonding (SiC/SiC or SiC/metal) is also well mastered and provides strength properties about 20 MPa in shear. It appears as the most simple and cost efficient technique, in particular for connecting SiC to metallic parts (e.g. fittings) or gluing small pieces on a SiC structure. This technique is largely used for structural application.

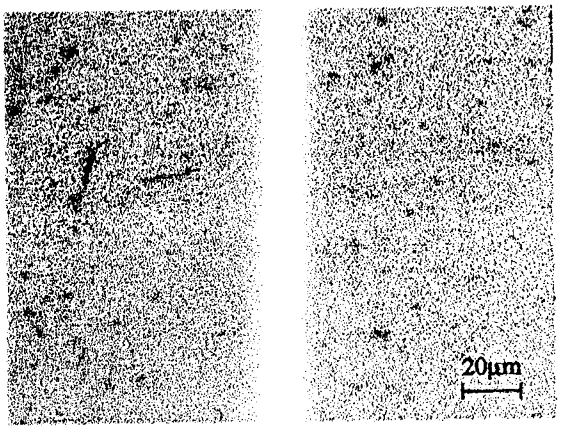


Fig. 10 : Microscope inspection of a brazing joint. Brazing is non-reactive and ultra thin joints of few μm are achievable.

The brazing technique consists of adding a material between two SiC pieces. MMS technique is a high temperature brazing with Brasic® process which provides several remarkable properties :

- Its Coefficient of Thermal Expansion can be matched to the one of Silicon Carbide,
- The brazing joint can be very thin : a few microns to a few tens of microns. But thick joints of thickness as high as 300 microns have been achieved. For thin joints, the brazing strength is comparable or better than for SiC. Numerous tests performed at liquid nitrogen temperature showed that the brazing strength is practically not affected at low temperatures.
- The brazing is *non-reactive*, i.e. SiC is not attacked. Therefore, de-brazing is possible (for example by re-heating) without any damage of the SiC parts.

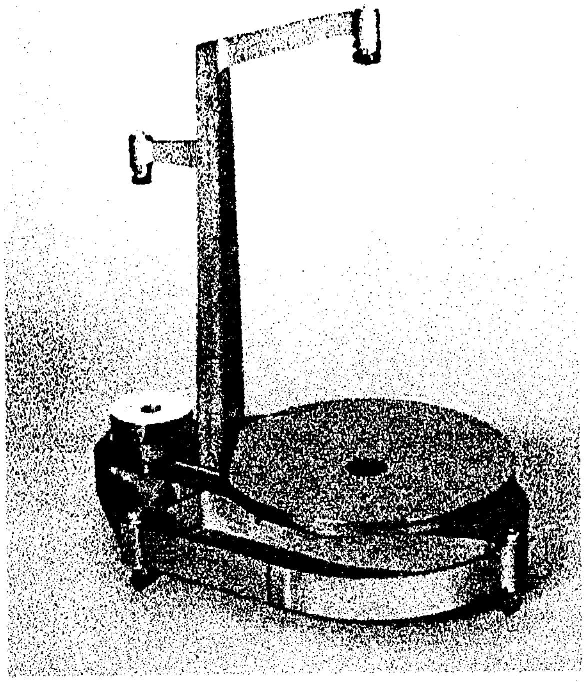
These techniques are well mastered and make use of non destructive test and witness samples to reach high and controlled performances.

6. OTHER PRODUCTS

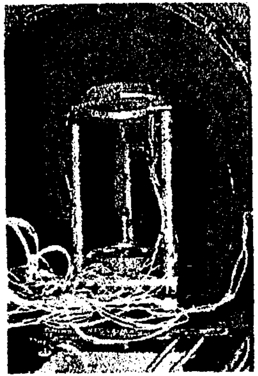
6.1. Matra Marconi Space: a major player in the development of SiC optics

Since the start of its coordinated R&D program related to SiC optics development, major achievements have been reached by Matra Marconi Space, amongst which:

- the successful development and testing of a ϕ 200 mm / ϕ 60 mm bi-telescope demonstrator (called DTELSIC), using sintered SiC as the only material for mirrors and structure. This demonstrator, based on a free space laser communication telescope architecture, allowed MMS to fully validate this concept for any kind of optical arrangement including TMA's
- the figuring down to 5 nm rms of the ϕ 200 mm aspherical primary mirror of this demonstrator, with the help of Ion Beam Figuring (IBF) process.
- the successful development of the FIRST ϕ 1.35 m demonstrator mirror for the validation of the technologies necessary for the development of the future ϕ 3.5 m SiC primary mirror of this project
- the on going development of a ϕ 352 mm aspherical secondary mirror for the NASA/DLR SOFIA 2.5m airborne telescope project.
- the on going development of the OSIRIS NAC telescope to be flown on ROSETTA, using SiC for both structure and mirrors, as described herein.



vibration test



testing in the vacuum thermal chamber

Fig. 11: The DTELSIC monolithic SiC 100 bi-telescope : the final wavefront error of the large telescope is 20 nm rms including focus. This telescope showed no measurable defocus for a 160°C temperature change in vacuum. This demonstrator proved the capability to design and develop high performance monolithic SiC telescopes

	Measured performances	Predictions or specifications
Mass (with bipodes)	3.8 kg	< 4 kg
Number of parts	3 (+ shims)	minimum
Polishing optical quality (ϕ200 mm)	< 6 nm rms	< 21 nm rms
Focus (T1)	1.9 µm	± 5 µm
Coma fine radial setting (T1)	9 µm	± 10 µm
WaveFront Error	20 nm rms	< 32 nm rms
Mirror mounting	5 nm rms	5 nm rms
Bi-telescope first eigen frequency	232 Hz	215 Hz
Primary mirror qualification	35g QSL / 54g at 3σ	30g
Secondary mirror qualification	44g QSL / 100g 3σ /35 g^2/Hz	100g
Q factor	< 70	-
Optical quality after vibration tests	unchanged	-

Fig 12 : DTELSIC bi-telescope main performances

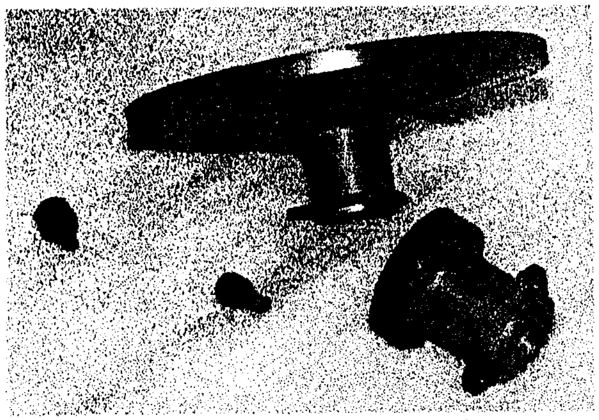


Fig 13: DTELSIC polished mirrors

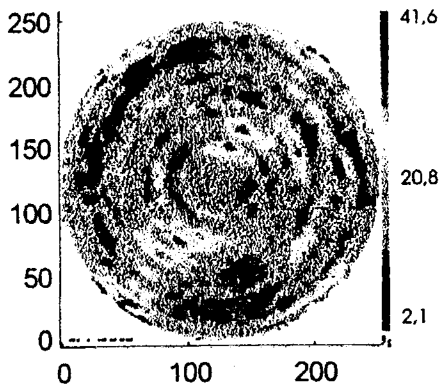


Fig. 14 : Primary mirror interferogram after ion beam figuring (< 6 nm rms)

	ϕ200 primary mirror	ϕ60 primary mirror	Secondary mirrors
WFE obtained after classical polishing:	25 nm rms (λ/25)	12 nm rms (λ/52)	6 nm rms (λ/100)
WFE by ion beam figuring:	**< 6 nm rms (λ/100)**		

Fig 15: Measured optical quality of finished mirrors for DTELSIC.
The Ion Beam Figuring is perfectly adapted to SiC mirrors, the good conductivity of the material avoids local stress due to the heating of the beam.

- A primary reflector (parabola), made of 12 brazed SiC segments, with pie-segmentation. The reflector provides 3 interface points where Invar inserts are fixed. There is no need for gluing the inserts : they can simply be bolted and centered in the Silicon Carbide.
- A secondary reflector (hyperbola), also made of SiC.
- A SiC tripod assembly, made of 3 legs connected on one hand to the primary reflector interfaces.
- Three isostatic mounts made of titanium
- A triangle interface mount. The triangle is made of 3 SiC tubes connected by titanium fittings.
- The primary reflector mass is 200 kg for a telescope mass of 250 kg.

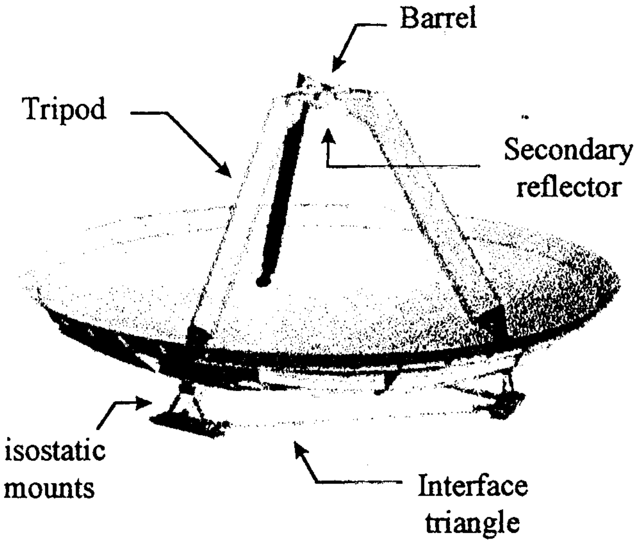


Fig 16:FIRST telescope elements.

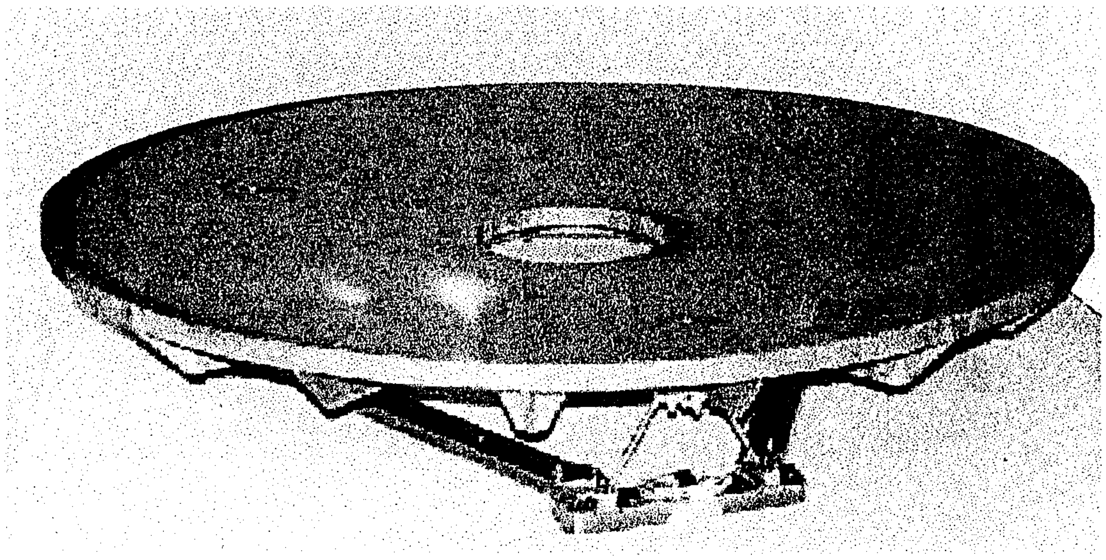


Fig 17 : FIRST 1.35 meter demonstration model made of 9 segments brazed together. It has been polished to a mirror error below 2.5µm and its optical quality measured in thermal vacuum down to 100 °K without any measurable effect (<0.5 µm). It has also been successfully tested for 35 g static loads.

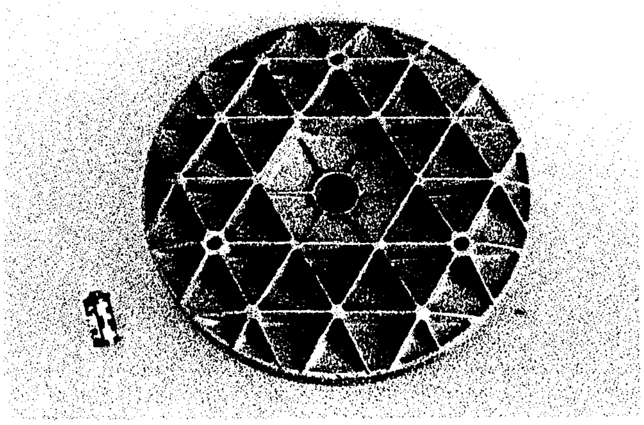


Fig 18: The ϕ 352 mm secondary mirror for the NASA/DLR SOFIA airborne project. Its mechanical design is optimized for a minimum deformation under gravity and under grinding and polishing efforts. It has a first eigen frequency above 1300 Hz for a mass of 1.7 kg.

7. CONCLUSIONS

The telescope design presented here takes the full advantages of the capabilities of sintered Silicon Carbide SiC-100. It is based on a monolithic approach were both structure and mirrors are made up of SiC. On the mechanical side it enables to have a low mass structure with a high first eigenfrequency. On the thermal side it allows to use the low available power on the delicate focal plane parts while letting the telescope itself uncontrolled. Thanks to the homothetic behavior of the monolithic telescope the focusing and optical quality is not affected.

All the processes used for the manufacturing of such an instrument are well mastered by MATRA MARCONI SPACE and its joint venture SiCSPACE.

The structural and thermal model of the OSIRIS Narrow Angle Camera has been manufactured and successfully tested. The flight mirrors are in the final phase of the polishing process and the manufacturing of the remaining flight hardware is under way for a launch scheduled in 2003.

The development of this instrument and of the other SiC-100 elements already manufactured and tested by MATRA MARCONI SPACE demonstrates the interest of SiC for the design of optical instruments of all types from the present OSIRIS NAC to the future NGST.

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