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**A NEW CONCEPT IN TELESCOPE DESIGN
SiC AS THE ONLY MATERIAL FOR MIRRORS AND STRUCTURE**

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ABSTRACT - Silicon carbide is considered as a highly promising material for the development of mirror substrates. Indeed, its ultimate mechanical and thermal properties allow to consider this material as the one and only material for all the structural and optical parts of space based telescopes

Matra Marconi Space has set up with Céramiques & Composites (C&C, in Tarbes - France) a business joint venture named SiCSPACE to develop these applications. These two companies have conducted since 1990 a coordinated R&D program, to be completed by the end of 1997, for the mastering of all the development aspects of telescopes based on the use of sintered Silicon Carbide.

RÉSUMÉ - *Le carbure de Silicium est considéré comme un matériau très prometteur pour le développement des miroirs. De fait, ses caractéristiques mécaniques et thermiques conduisent à envisager ce matériau comme le seul et l'unique matériau pour toutes les pièces de structure et les miroirs des télescopes spatiaux.*

Matra Marconi Space s'est allié avec Céramiques & Composites (C&C, Tarbes-France) dans le cadre du GIE SiCSPACE pour le développement de ces applications. Ces deux compagnies ont réalisé depuis 1990 un programme de R&D se terminant à la fin 1997 dont le but est la maîtrise de l'ensemble des aspects du développement de tels télescopes basés sur l'utilisation du carbure de silicium fritté.

1. PRESENTATION

The review of the main characteristics of the C&C SiC-100 manufactured by Céramiques & Composites, compared to other materials and other types of SiC, shows it is the ideal material for the development of space based telescopes and instruments. This article focuses on the coordinated activities running in MMS and C&C for the mastering of all the development aspects linked to these applications. The core part of this R&D program is the development of a telescope demonstrator, for which the first technological test results, validating the major design options, are available. This already demonstrates the pertinence of the innovative approach proposed by MMS and C&C in the frame of SiCSPACE.

2. POTENTIAL APPLICATIONS OF SiC FOR SPACE BASED TELESCOPES

Silicon Carbide has been identified as a promising candidate for most of the space based telescopes. This covers:

- earth observation applications, with sizes running from 100 mm up to 1000 mm
- optical communications with sizes running from 100 mm or less to 300 mm
- scientific instruments, covering a wavelength range from the extreme UV, and even X-ray radiation to the sub-millimetre waves, with sizes which may reach, as planned for the ESA FIRST project, 3.5 m.

The optical arrangements are either Cassegrain for narrow field of view, either Korsch or TMA for wider fields of view. The Sun may be as close as a degree from the line of sight, or even be the observed object like in SOHO, thus reaching directly the primary mirror. At the other end, the application may require cryogenic temperature like in ISO or in the future for FIRST. Whatever the instrument, silicon carbide appears to be the ideal candidate to develop these applications.

The development of large mirrors is indeed covered by a specific R&D activity in the frame of the ESA FIRST project and is addressed separately.

The demonstrator which is described here covers applications in the 200 / 300 mm range and allows to validate specific optical communication needs such as the coalignment stability of dual telescopes. This innovative arrangement (patent filed by MMS) is shown in Fig. 6.

3. SiCSPACE SINTERED SILICON CARBIDE COMPARED CHARACTERISTICS

3.1 Comparison to potential candidate materials

Silicon carbide has been identified since many years as a very promising material for space based optics and structures. This can easily be understood when looking at the compared characteristics of this material with other candidate materials such as Zerodur, Beryllium, Aluminium, etc... as given in the Fig.1

	C&C SiC 100	Beryllium	Zerodur	Aluminium
Density ρ (g/cm^3)	3.16	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)	190	180	1.6	237
Specific heat cp (J/K/kg)	700	1880	821	900
Ratio λ/α	91	16	33	10
Ratio E/ ρ	133	164	36	26
Figure of merit (λ/α) x (E/ ρ)	12103	2624	1188	260

Fig.1: 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, comparable to Beryllium, combined to a relatively low density, comparable to Aluminium, allows, on the other hand, to design of very lightweight structural parts.

3.2 Comparison of the different types of Silicon Carbide

Silicon Carbide is obtained through various processes. This results in different characteristics of the elaborated material.

- The sintered SiC. This type is the one resulting from the process which is applied with success since many years by C&C / SiCSPACE to elaborate the C&C SiC-100.
- The pyrolysed SiC (or C-SiC) obtained by reaction at high temperature of liquid Silicon with short graphite fibres linked by an organic binder
- The reaction bonded SiC (RB SiC or Si-SiC) obtained in a two steps process. First SiC and carbon powders are pressed together with a chemical binding material, which is then pyrolysed. This leads to a sponge-like open cell structure. This structure is then filled with liquid silicon at high temperature which reacts with the carbon to form additional SiC grains.
- The vacuum deposited SiC (SiC CVD) obtained by Chemical Vapour Deposition

Among these 4 types of SiC, the sintered SiC, as elaborated by C&C / SiCSPACE under the trade name C&C SiC-100 gives the material which is the closest to pure SiC at the most economical conditions. The process is well controlled and insures a very high constancy of the characteristics. The polishing process of mirror surfaces is comparable to glass. Linked to the residual intrinsic porosity of the bulk material, the scattering of bare polished SiC remains about 40 times the one of glass, but still acceptable for most of the Earth observation applications. In case of more demanding applications, this performance can be improved by applying a thin layer of SiC CVD still at good economical conditions. Replication, mainly used for mass production, can also fulfil this need. Compared properties of these different types of materials (non-exhaustive list) is given in the Fig.2.

	C&C SiC-100	Pyrolysed C-SiC	Reaction bonded RB SiC / Si-SiC	CVD SiC-CVD
Starting material	SiC powder + organic binder	C fibres + liquid Si + organic bind	SiC powder + C powder + binder + liquid Si	SiCl ₄ + C ₂ H ₂ C preshape
Final product	SiC 98.5% others: 1.5% controlled	SiC 60% Si 25% C 15%	SiC 85% Si 15%	100% SiC layer deposited on the graphite skeleton
Microstructure	Monophase granular (<5 μm)	3 phasic larger grains	2 phasic large grains >40 μm	quasi amorphous and graphite
Bulk density	3.16	2.7	2.9	3.21 (out of C)
Young modulus (Gpa)	420	236	311	466 out of graphite
Polishing	medium	impossible	medium	good
Cost	low	quite low	low	very high

Fig.2: The superior characteristics of the C&C SiC-100, close to pure SiC, associated to a very low production cost, puts this material as the ideal one for space based assemblies

This trade-off fully justifies the approach followed in common by MMS and C&C in the SiCSPACE industrial structure.

4. MMS / C&C BACKGROUND EXPERIENCE IN SiC TELESCOPES DEVELOPMENT

A large number of SiC pieces have been realised so far. The pieces are extremely variable in shape and size, going from C&C ring serial production (thousands manufactured per day) to small shims of very high accuracy for optical alignments, or to medium size reflectors or blanks. We have selected here some realisations, which are somehow related to telescopes development.

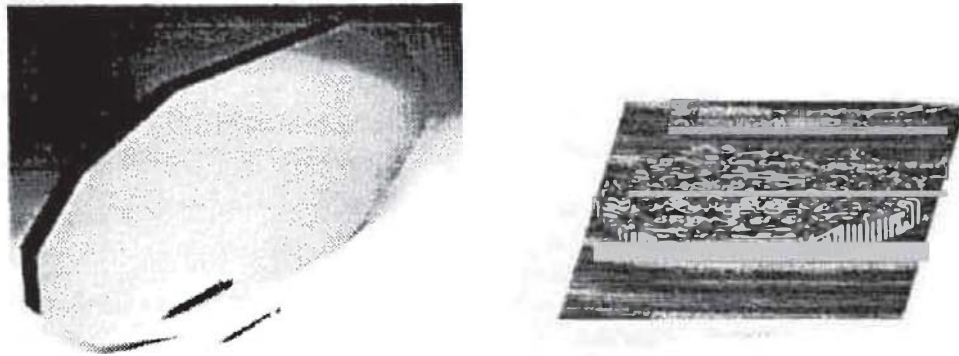


Fig. 3 : Polished optical reflector for visible wavelengths. Size : 720 mm x 350 mm, developed on MMS internal fundings. The reflector design is based on SPOT HRV Zerodur steering mirror and illustrates SiC lightweighting capability. The reflector mass is 5.9 kg, more than twice lighter than the equivalent Zerodur reflector, while still providing much better mechanical performance. The achieved WFE on bare SiC is better than $\lambda/20$ RMS.

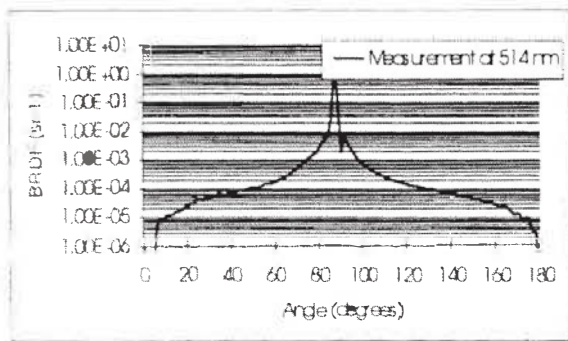


Fig. 4 : BRDF of polished mirror with SiC CVD coating

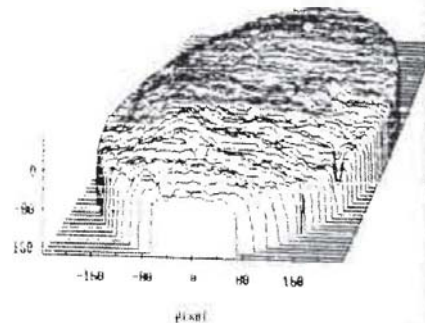


Fig. 5 : WFE of mirror after thermal cycling (-30°C / +40°C)

BDRF characteristics of polished SiC CVD overcoated mirror is shown Fig. 4. A specific R&D work has been successfully run on the development and the characterisation of polishing processes of SiC mirrors. Apart from classical polishing of bare SiC, one major step has been achieved through the mastering of the coating of bare SiC grinded surfaces with a thin layer of SiC CVD. After polishing, the coated surface displays scattering characteristics identical to glass. Interferometric measurement of a replicated mirror after thermal cycling between -30°C and +40°C is given Fig. 5. This shows $\lambda/20$ RMS WFE is not affected by thermal cycling.

5. THE SiCSPACE TELESCOPE DEMONSTRATOR

The demonstrator is made of two telescopes as shown in Fig. 6. Both are as simple as possible according to optical and mechanical constraints, in particular for alignments and tests.

Why two telescopes? The first one (named T1) is designed to be representative of OISL reception applications, with as large as \varnothing 300 mm centred mirrors. The second one (named T2) is also oriented towards optical inter satellite link applications, as proposed by MMS for satellites constellations. The coalignment stability of the dual telescope arrangement, in these applications, have to be maintained within a few microradians. This can be checked under environmental test conditions. Telescope T1 allows developments useful also for TMA applications.

What made this demonstrator innovative? The first innovating point is the use of SiC 100 all along the functional chain, including mirrors, structure and adjustments shims.

The central mirror mounting is, without any contest, the second innovating point. It allows simultaneously an isostatic attachment and a good filtering of interface efforts, without any blades. The third innovating point is the concept of the solid mast, brazed in the baseplate, to obtain a monolithic structure.

All these improvements lead to a simplified design, especially in optics, manufacturing, alignment and thermal control. This concept allows us to build high stability telescopes at low production costs.



Fig. 6: The telescope demonstrator (primary \varnothing 200 mm), entirely made of SiC, fully secures the design and development of SiC telescopes. Its integration/ testing is currently in progress at MMS.

5.1 Optical design

Both telescopes are afocal Dall-Kirkham ones. The primary mirror surface is an ellipsoid, while the secondary one is spherical. The limiting values of WFE are only defined to allow testability, but we can easily reach a better performance in the case of a project ($\lambda/30$ rms typically). For the two primary mirrors, a centred hole allows the beam to pass through.

The main specifications are summarised hereafter (Fig. 7)

	primary mirror	secondary mirror	inter-mirror distance	WFE (manufacture)	exit beam
Telescope T1	ϕ 200 mm R= 584 mm K= -0,955	ϕ 18 mm R= 26,6 mm spherical	278.7 mm	$\lambda/16$ rms	9 mm
Telescope T2	ϕ 60 mm R= 400 mm K= -0,850	ϕ 14 mm R= 60 mm spherical	170 mm	$\lambda/16$ rms	9 mm

Fig. 7 : Main optical telescope demonstrator specifications

5.2 Mechanical design

The main specifications are summarised hereafter (Fig. 8) :

Frequency	Mass	quasi-static loads	gravity release	number of pieces	
> 150 Hz	< 4 kg	30 g	minimal	minimal	

Fig. 8: Main mechanical telescope demonstrator specifications

The properties of the SiC allow to build a monomaterial telescope. Thus, the use of the SiC for each element of the telescope reduces thermo-mechanical coupling constraints, in particular, between mirrors and structure. This remark leads to the concept of the mirror central attachment.

For the primary mirror, the decoupling is achieved thanks to the central cylinder, on which the height and the thickness are optimised. The criterion is the minimisation of WFE and defocus induced by thermoelastic and integration effects. Mirror clamping is ensured by three local fixation points in a flange at the base of the cylinder. The effect of gravity release was also minimised to facilitate ground tests.

For the secondary mirror, we have developed a central clamped point compatible with adjustments needs and mechanical requirements.

The solid mast is selected to ensure a good stability for each telescope and also provide a good coalignment stability because the two secondary mirrors are fixed in the same structure.

This concept leads also to minimise the number of pieces : primary mirror, secondary mirror, monolithic structure and adjustment shims. Indeed, the use of mirror barrel and isostatic blades is avoided. Thus, the minimum number of elements leads to minimum price in engineering, production, integration and control.

5.3 Thermal design

For an homogeneous increase of temperature, the deformations are homothetic. So, the optical stability is maintained.

The robustness of the design toward thermal effects will lead to significantly simplify the thermal control (with respect to specifications), and consequently, to reduce its cost.

For gradients, we take simultaneously advantage of the small coefficient of thermal expansion, the high thermal conductivity and the radiative properties.

We favour radiative coupling between the primary mirror and the baseplate. We minimise thermal gradient all over the structure thanks to conductive coupling, in particular by the concept of the solid mast (the aim is to minimise the surface exchange) and with a brazed fixation on the baseplate.

5.4 Alignment

The main specifications are summarised in Fig. 9 :

	primary mirror	secondary mirror	WFE
Telescope T1	fine focus & radial settings	coarse adjustment	$\lambda/20$ rms
Telescope T2	no setting	fine focus & radial settings	$\lambda/20$ rms

Fig. 9 : Main alignment telescope demonstrator specifications

In addition, there is a constraint of coalignment between the two telescopes of less than 1mrad.

Adjustment means suitable, on one hand, for primary mirror (ϕ 200 mm) and, on the other hand, for secondary mirror (ϕ 14 mm) have been developed. In that way, the needs of TMA or optical communication program are covered.

6. FIRST RESULTS OF THE DEMONSTRATOR TECHNOLOGICAL PROGRAM

6.1 Result on material

In association with the ESA FIRST project, measurements of thermo-optic properties (α , ϵ) have been conducted in a large range of wavelength (from 2.5 μm to 450 μm) and for different surface roughness. In that way, natural sintered surface as well as grinded or polished surfaces have been characterised.

The SiC/SiC static friction coefficient on grinded surface has also been checked to values close to the ones found in the literature.

6.2 Design

The high value of the SiC/SiC static friction coefficient allows engineers to adopt technological solutions based on it. This can lead to reduce the need for positive contact design, and consequently, to reduce the costs. This approach has been checked through a mock-up representative of the secondary mirror assembly.

6.3 Mirrors

The main mirror design and manufacture technologies have been mastered. Of course, one has to distinguish between secondary mirrors ($\phi < 20$ mm) and primary mirrors. The major results are without any doubt, on the ϕ 200 mm mirror.

Today, the analysis has shown the good decoupling effect of the central fixation, in respect to integration strengths (better than $\lambda/20$ in WFE and values negligible for focus)

Furthermore, the various effects during the mirror's manufacture are mastered as far as the sintered piece is concerned.

Then, we have shown that aspherical surface grinding is also possible with a very good accuracy. For instance, on the ϕ 200 mm mirror, we have reached better than $20 \mu\text{m}$ PTV on the real surface in comparison with the theoretical surface. These good results confirm that we can consider, at this step, three methods to obtain the reflective surface. Firstly, to polish directly the surface is demonstrated. Secondly, to realise a SiC CVD deposit, and next a polish. Thirdly, a replication is immediately possible after the grinding. This method is particularly well fitted to mass production.

The fields of off-axis mirrors is now explored, using the same approach. The feasibility is however still shown through the demonstrator mirrors (Fig. 10).

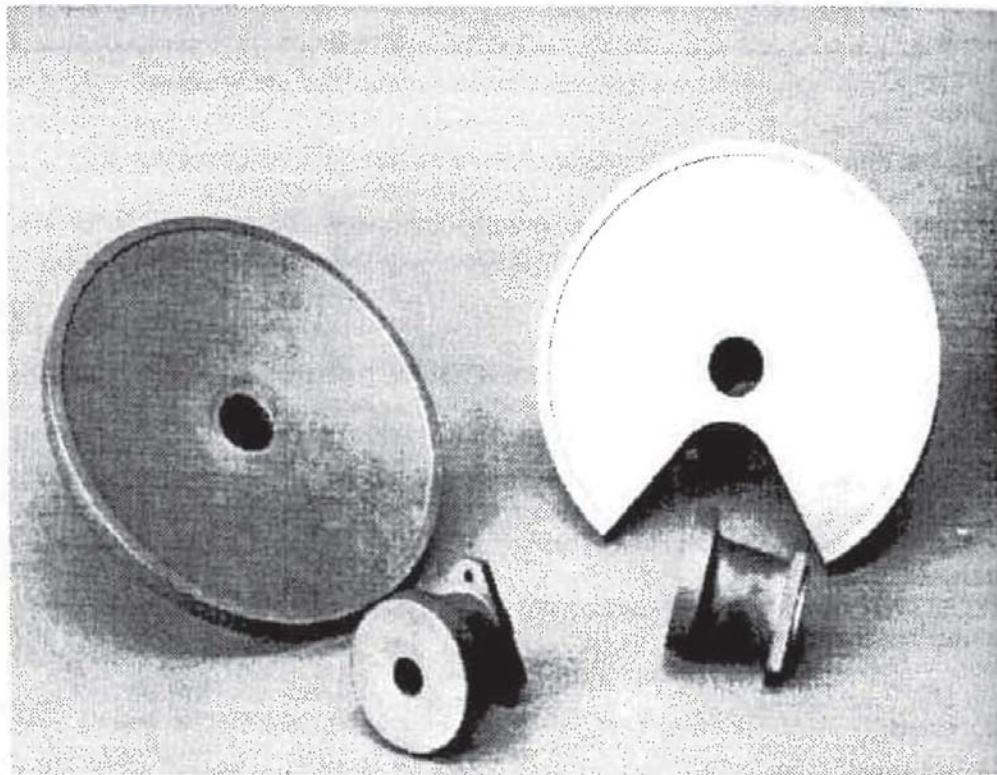


Fig. 10 Demonstrator sintered mirror blanks. A fully circular mirror ϕ 200 mm and one with a cut-out are developed to validate the whole process sequence.

Ultimate WFE performance has already been achieved on the T2 telescope after polishing. The measured value is $\lambda/40$ rms.

6.4 Assembly

From experience gained on the ESA FIRST project and the mast brazed on the baseplate, all aspects of this process are mastered. We have checked the mechanical behaviour through experiments on representative samples. Consequently, braze composition, thickness, temperature and other burning conditions are now mastered. The braze and the SiC material have the same coefficient of thermal expansion.

A SiC representative mock-up of the secondary mirror assembly has been designed and manufactured. The plane mirror (45x50 mm²) has been polished to a WFE of $\lambda/100$ rms. Optical tests have shown that deformation of optical surface under assembly strength is of the order $\lambda/60$ rms. Furthermore, a random test at 70 g rms on this mock-up shows the stability of the assembly.

6.5 Manufacture

As mirror manufacture has been discussed in the previous paragraph, we will pay attention to structure manufacture.

The realisation of the baseplate is a significant example of what can be done for lightened plates or bars. The mast is also a good example of a piece with thin areas connecting with thicker ones.

In particular, the minimum thickness, the shrinkage and deformation during sintering, are now well mastered. The manufacturing of complex shapes is demonstrated.

Many surfaces can be obtained directly from the blank, in that way the manufacturing costs are minimised. The realisations of accurate and well-fitted adjustment thanks to grinded cylinders and planes have also been demonstrated.

6.6 Adjustment & Alignment

Thanks to SiC adjustment shims, the alignment of the two telescopes is simple. This leads to save time during integration.

Furthermore, for the alignment of telescope T1, the radial adjustment of the primary mirror is done thanks to an external ground system equipment. Thus, this leads to integration time savings because the alignment process is simplified.

7. CONCLUSION

All these activities places SiCSPACE as a major player in the field of Space based telescopes, not only in Europe but also all over the world. SiCSPACE now masters all the technics necessary for the sound development of optical assemblies using the C&C SiC-100 sintered silicon carbide, and this for all the structural and optical parts of telescopes. This goes from the elaboration of the raw material to the design of optical and structural parts, their assembly by various technics, the polishing of mirrors, up to the alignment and tests of telescopes. This will be further consolidated by the environmental testing of the demonstrator beginning of 1998. These activities are also complemented by the development of coating technics necessary for polishing and by the development of a 1.4 meter mirror breadboard for the ESA FIRST project.

Thus, the complete mastering of SiC telescopes development is ensured, from commercial contacts, design, manufacture, to integration and opto-mechanical tests, thanks to the MMS/C&C winning association, through SiCSPACE.