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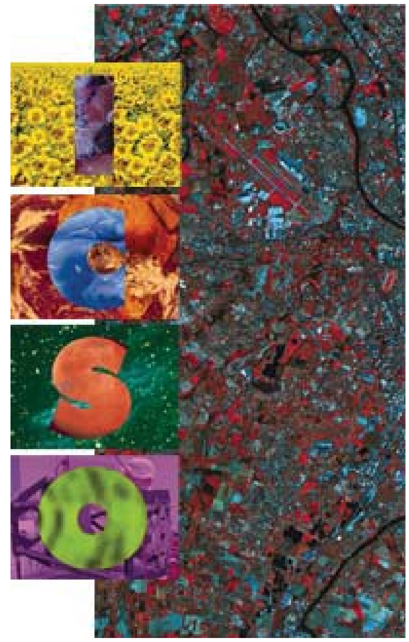

Development of silicon carbide mirrors: the example of the Sofia secondary mirror

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DEVELOPMENT OF SILICON CARBIDE MIRRORS
THE EXAMPLE OF THE SOFIA SECONDARY MIRROR

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RÉSUMÉ - Le miroir Secondaire SOFIA (ϕ 352 mm) a été développé par le GIE SiCSPACE (ASTRIUM/BOOTEC), en tirant bénéfice des propriétés intrinsèques du Carbure de Silicium fritté S-SiC de BOOSTEC, en association avec des procédés qualifiés spécialement développées pour l'optique spatiale par ASTRIUM SAS. Les performances atteintes incluent une faible masse de 1.7 kg, une très grande raideur conduisant à un premier mode de fréquence propre supérieur à 1300 Hz et une précision de la surface optique correspondant à un défaut maximum de surface d'onde de 50 nm rms.
Ce miroir est l'un des composants du projet conjoint NASA-DLR de télescope stratosphérique aéroporté pour l'astronomie dans l'InfraRouge lointain SOFIA.

ABSTRACT - *The ϕ352 mm tip-tilt SOFIA Secondary Mirror has been developed by the ASTRIUM / BOOSTEC joint venture SiCSPACE, taking full benefit of the intrinsic properties of the BOOSTEC S-SiC sintered material, associated to qualified processes specifically developed for space borne mirrors by ASTRIUM SAS. Achieved performances include a low mass of 1.7 kg, a very high stiffness with a first resonant frequency higher than 2000 Hz and an optical surface accuracy corresponding to a maximum WFE of 50 nm rms.*
This mirror is part of the joint NASA-DLR project for a 2.5 m airborne Stratospheric Observatory For Infrared Astronomy (SOFIA).

1. PRESENTATION

The SOFIA telescope is a joint NASA-DLR project for a 2.5 m airborne Stratospheric Observatory For Infrared Astronomy to be flown in a specially adapted Boeing 747 SP plane.
The ϕ 352 mm Secondary Mirror is mounted on a chopping mechanism to allow for alignment, focusing and avoidance of background noise during infrared observations. Stiffness associated to lightness is a major demand for such a mirror to achieve high frequency chopping.
Its development has been run by the ASTRIUM SAS / BOOSTEC joint venture SiCSPACE, taking full benefit of the intrinsic properties of the BOOSTEC S-SiC sintered material, associated to qualified processes specifically developed for space borne mirrors by ASTRIUM SAS. Achieved performances include a low design mass of 1.7 kg (corresponding to 17 kg/m²), a very high stiffness with a first resonant frequency higher than 1300 Hz and an optical surface accuracy corresponding to a maximum WFE of 80 nm rms.
After a short description of the SOFIA project, the major design features of the SOFIA Secondary Mirror are presented, highlighting the main advantages of using Silicon Carbide, the main steps of its development and the achieved optomechanical performances of the developed mirror.

2. THE SOFIA PROJECT

The Stratospheric Observatory For Infrared Astronomy (SOFIA) is NASA's and DLR's premier observatory for infrared and submillimeter astronomy into the next century. A Boeing 747-SP aircraft will carry the 2.5-meter telescope designed to make sensitive infrared measurements of a wide range of astronomical objects. It will fly at and above 12.5 km, where the telescope collects radiation in the wavelength range from 0.3 micrometers to 1.6 millimeters region of the electromagnetic spectrum (fig.2/1).

The SOFIA telescope is developed in Europe under the responsibility of DLR. During operation, German scientists will utilise 20 percent of the flying observatory's telescope time. The aircraft modifications and the observatory operations are carried out under NASA responsability.

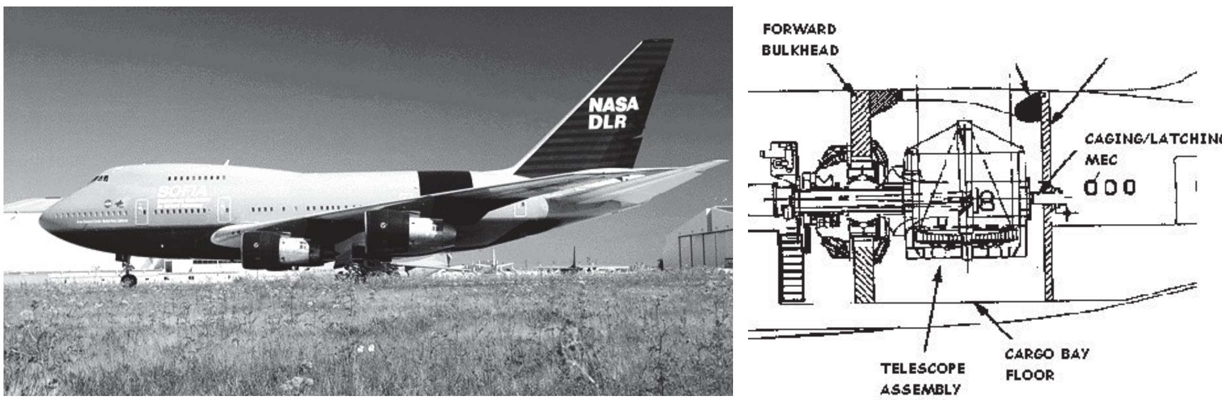


Figure 2/1: *The 18 tons telescope assembly is located in an openable cabinet at the rear of the Boeing 747 SP. Coarse pointing over 10° to 70° in elevation and ± 3.5° in azimuth is achieved thanks to a 1.2 m spherical bearing at the forward bulkhead level.*

The spectral range will extend from the near UV up to the far infrared (0.3 µm to 1.6 mm overall wavelength range / 15 µm to 0.3 µm prime range). Silicon Carbide has been selected for the SOFIA Secondary mirror to provide the lower mass and the higher stiffness. The final image quality corresponds to a point spread image of 1.5 arcseconds (80% energy) at 0.6 µm.
The Secondary Mirror itself will interface with a 6-axis mechanism developed by CSEM, in Switzerland, providing a chopping capability of ± 5 arcmin at frequencies of 1 to 20 Hz 2-point square wave.

Figure 2.2: *The core part of the Secondary mirror chopping mechanism is shown here. It provides a 3 points mounting interface to the mirror through isostatic decoupling devices.*

3. SiCSPACE SINTERED SILICON CARBIDE COMPARED CHARACTERISTICS

Silicon Carbide is recognised world-wide as a highly performing candidate for most of the space based telescopes. This covers in particular:
- earth observation applications, with sizes running from 100 mm up to 1000 mm
- scientific instruments, covering a wavelength range from the extreme UV, and even X-ray radiation to the sub-millimeter waves, with sizes which may reach, as planned for the ESA FIRST project, 3.5 m.

Whatever the instrument, silicon carbide, and more precisely the sintered S-SiC from SiCSPACE, appears to be the ideal candidate to develop these applications,

3.1 Comparison to potential candidate materials

Silicon carbide has been identified since many years as a candidate 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 as given in the Fig.3.1/1

	C&C S-SiC	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.3.1/1: *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.*

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

- The sintered S-SiC
- The pyrolised SiC (or C-SiC)
- The reaction bonded SiC (RB SiC or Si-SiC)
- The vacuum deposited SiC (SiC CVD)

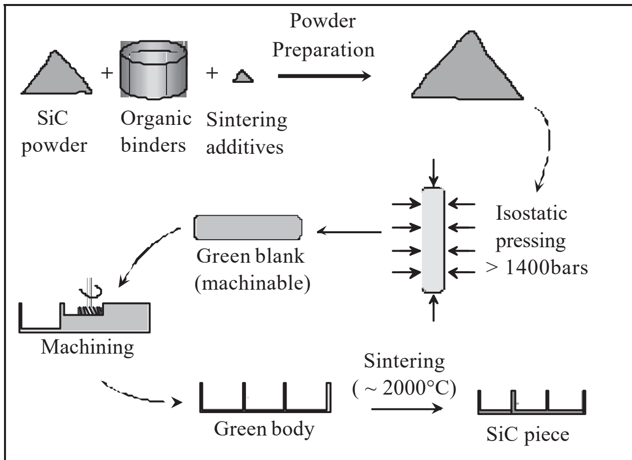
Compared properties of these different types of materials (non-exhaustive list) is given in the Fig.3.1/2.

	SiCSPACE S-SiC	**Pyrolised 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	$SiCl_4 + C_2H_2$ 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>40µm	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 / good*	impossible	medium	Good
Cost	Low	quite low	low	Very high

*after CVD SiC gladding

Fig.3.1/2: *The superior characteristics of the sintered S-SiC, close to pure SiC, associated to a very low production cost, puts this material as the ideal one for space based assemblies*

Among these 4 types of SiC, the sintered SiC, S-SiC as elaborated by SiCSPACE, gives the material which is the closest to pure SiC at the most economical conditions. The process, as described in figure 3.1/3, is well controlled and insures a very high constancy of the characteristics.

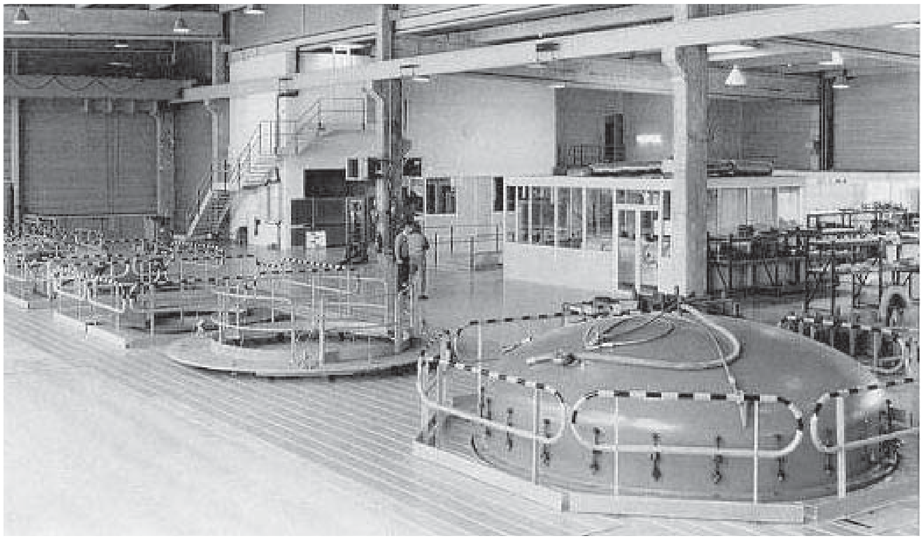


- SiC powder preparation : *Silicon Carbide fine powder is mixed with organic binders and added elements*
- Isostatic compression : *The powder is isostatically pressed at a high pressure (> 1400 bars) at room temperature, giving birth to an intermediate material called « green body ».*
- Green body machining : *The green body is easily machined to the desired shape. For reflectors and structural elements , the lightweight shape is performed on the green body.*
- Sintering : *The machined green body is pressureless sintered at high temperature, about 2000°C*

Figure 3.1/3: *The sintering process induces a shrinkage of about 17 % in all dimensions. It is controlled to better than 0.4%, thus, all non-critical dimensions are machined at green body level.*

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.

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 with SNECMA through the mastering of the coating of bare SiC grinded surfaces with a thin layer of SiC CVD.



The SiC CVD process is run by SNECMA on an industrial basis, using large diameter chambers, thus allowing confidence in the repeatability and uniformity of the deposited layer characteristics

After polishing, the coated surface displays scattering characteristics identical to glass.
BDRF characteristics of polished SiC CVD overcoated mirror is shown Fig. 3.2/2.

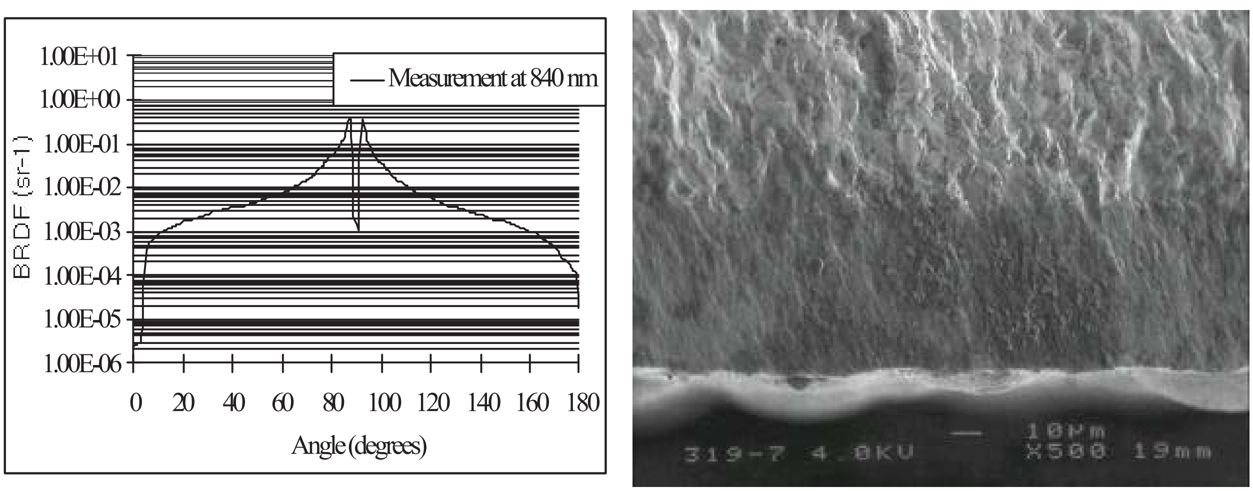
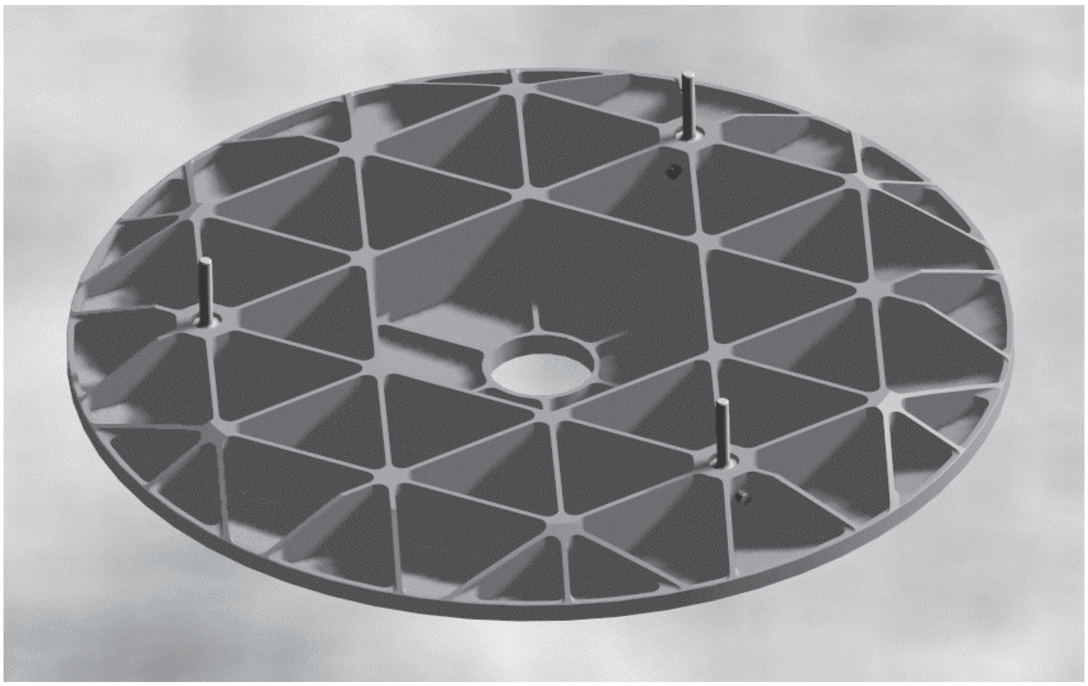


***Fig. 3.2/2**: The BRDF of polished SiC mirror with SiC CVD coating is equivalent or better to the one obtained with glass mirrors. Electronic Microscope section view of the CVI coated S-SiC sample shows the high adherence of the deposited layer to the bulk mirror blank*

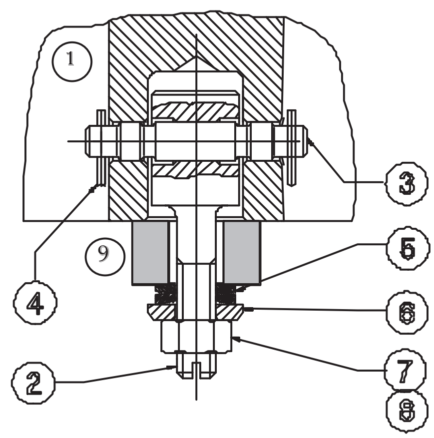
4. THE SOFIA SECONDARY MIRROR

4.1 Mirror mechanical design and performances

The secondary mirror is a ϕ 352 mm hyperbolic convex mirror. The rear side lightweighting is optimised as an open back structure , which is the easiest lightweighting for the sintered SiC blank. This mechanical design is optimised for minimum deformation under gravity, under grinding and polishing efforts and for eigen frequency requirements. Critical dimensions and interface areas are mechanically lapped after sintering. The optical surface is mechanically lapped and then optically ground to a the best fitted spherical shape , CVD coated and polished by Stigma-Optique to the final aspherical shape before the final Al coating. The central hole -maximum size ϕ40 mm- allows the reference mounting of an autocollimation alignment mirror.



The mirror (1) is clamped to the three isostatic interface mounts (9) by three threaded axes (2). The ϕ5 pin (3), associated to elastic shims (5), gives the required preload in a controlled way when tightening the M5 nut (7). This design has been first validated on a dummy as shown in figure 4.1/1.



dummy of the SSM interface design

Figure 4.1/1 *Detail of the joint design between isostatic mount head and mirror*

The detailed mechanical design of the mirror has been optimised through finite element modeling to achieve low mass, low inertia and high resonant frequency. Lightweighting geometry and attachment points location have been optimized to minimise wavefront distortions under polishing and gravity variation impacts. Thanks to a low walls and skin thickness of 2 mm only, the achieved design mass is as low as 1.7 kg, the inertia of only 0.015 kg/m² (0.03kg/m² around the optical axis) while achieving a first frequency of 1360 Hz.

Fracture analysis has also been run. Thanks to the high strength and the insensitivity of the S-SiC material to fatigue, the failure probability is lower than 10^{-10} for potential crash loads up to 9g.

4.2 Mirror optical design and performances

The mirror is an aspherical convex secondary. Its radius of curvature is of 954.1 ± 1mm and its conic constant equal to -1.280, leading to a maximum departure from the best fitted sphere of 45 µm.

The optical figuring of the aspherical profile is performed after the 110 µm thick SiC CVI coating of the mirror blank which has been previously optically ground spherical to the best fitted sphere.

After polishing, the mirror receives a non-protected 0.3µm pure Aluminium reflective coating to achieve a minimum reflectivity of 88%.in the visible and 95% in the IR.

The WFE error budget given in figure 4.2/1 leads to a maximum wavefront distortion of 80 nm RMS.

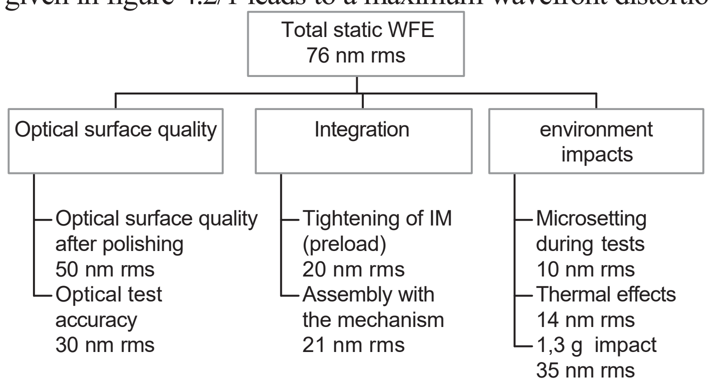


Figure 4.2/1: *The achieved wavefront of the SOFIA mirror is dominated by the achieved wavefront performance of 50 nm RMS during polishing, associated to the 30 nm rms interferometer accuracy*

The mirror scattering will be driven by the achieved microroughness after polishing. Thanks to the SiC CVD coating, the BRDF of the mirror will easily meet the required performances described by the Harvey model with a pivot value of 0.2 and an exponent of -1.5, corresponding to an equivalent microroughness of 25 Å RMS.

The mirror is in final polishing stage at STIGMA-Optique as show in figure 4.2/2.

Figure 4.2/2: *Figuring / polishing of the mirror is run using classical processes at Stigma-Optique*

4.3 Mirror testing

All along its development, the SOFIA secondary mirror is subjected to a series of tests which allow to verify its compliance to the requirements. This includes both mechanical and optical testing as shown hereafter.

The machined blank at delivery from BOOSTEC is first subjected to a stringent static load proof test to check the good health of the sintered and grinded piece. as shown in figure 4.3/1.

Figure 4.3/1 a *The mirror is loaded with about 48 kg while resting on its interface points. The induced deflection is monitoring to check no permanent deformation appears after the test*

The first eigen frequencies are measured after SiC CVI coating to account for the additional mass and stiffnes of the SiC CVD layer. The mirror, resting on decoupling blocks of foam, is subjected to a modal survey test in free-free conditions. The blank resonant modes are excited with a hammer and the response measured by 3 axis accelerometers, as shown in figure 4.3/2. The measured first mode in free-free conditions is at 1865 Hz corresponding to a first resonant frequency of 1490 Hz on perfect isostatic mounts for the actual mirror.

Figure 4.3/2 *The modal survey test is a convenient and simple approach for determining accurately the first modes of equipments and assemblies*

The WFE testing of convex aspherics is commonly performed in the so called Hindle test configuration, as shown in figure 4.3/3.

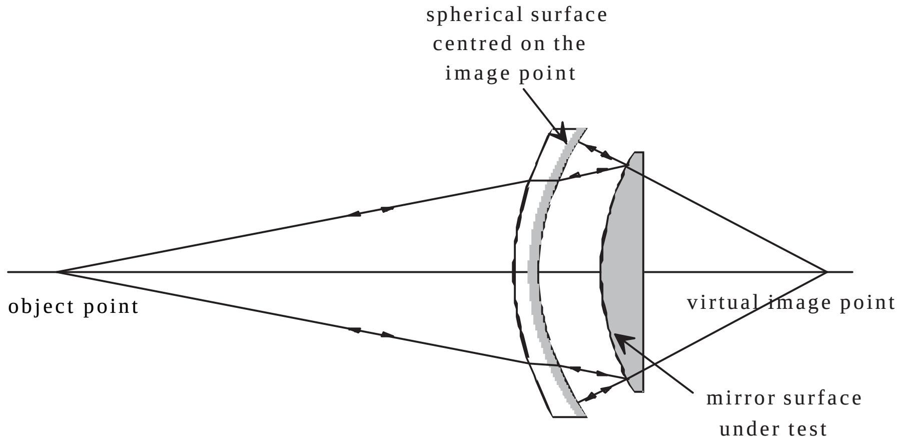


Figure 4.3/3 *the Hindle test configuration principally performs a null testing at the two focii of the aspherical convex mirror surface*

An interferometer is generating an object point. The rays go through a meniscus lens, they are reflected by the secondary mirror and retroreflected by the rear spherical surface of the meniscus which has a partially reflecting coating. The curvature of the front surface of the meniscus is chosen so that the spherical aberration of the set up is minimised. The test set up performance has been computed using CODE V. The theoretical wavefront error is 4 nm rms on axis and still below 14 nm rms at 30 mm from axis which leaves some room for the alignment tolerances.

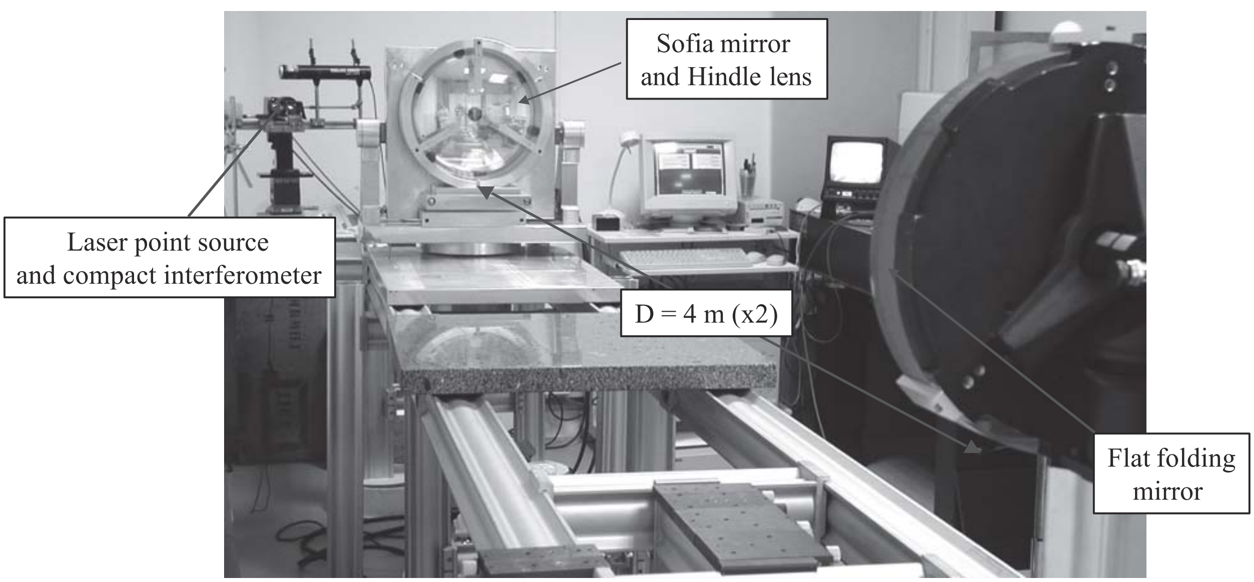


Figure 4.3/4 *A flat folding mirror is used to fold the 8 meters distance between the interferometer and the lens-mirror assembly. The exactness of this distance is verified thanks to a reference spherical mirror which can be fitted against the apex of the lens front surface.*

After polishing, the mirror behaviour under thermal environment is checked through thermal cycling at ambiant pressure between -65°C and +85°C. Mirror wavefront is measured before and after this test, to verify no permanent distortion is induced by such a temperature excursion.

5. CONCLUSION

The development of the SOFIA secondary mirror is one example of the developments of Space optical equipments successfully run today by the ASTRIUM / BOOSTEC joint venture SiCSPACE.

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 S-SiC 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.

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Many thanks also to STIGMA-Optique, and in particular Bernard FILLOL and Gerard ANCOURT, for their valuable involvement in the polishing and optical testing of this mirror.

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