

A Φ 3.5 M SiC telescope for HERSCHEL Mission

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Since ten years ASTRIUM has developed sintered Silicon Carbide (SiC) technology for space applications. Its unique thermo-mechanical properties, associated with its polishing capability, make SiC an ideal material for building ultra-stable lightweight space based telescopes or mirrors. SiC is a cost effective alternative to Beryllium and the ultra-lightweight ULE. In Complement to the material manufacturing process, ASTRIUM has developed several assembly techniques (bolting, brazing, bonding) for manufacturing large and complex SiC assemblies. This technology is now perfectly mature and mastered. SiC is baselined for most of the telescopes that are developed by ASTRIUM. SiC has been identified as the most suitable material for manufacturing very large cryogenic telescopes. In this paper we present the development of the Φ 3.5 m telescope for Herschel Mission. Herschel main goal is to study how the first stars and galaxies were formed and evolved. The Herschel Space telescope, using silicon carbide technology will be the largest space imagery telescope ever launched. The Herschel telescope will weight 300 kg rather than the 1.5 tons required with standard technology. The Herschel telescope is to be delivered in 2005 for a launch planned for 2007

Keywords: Large Telescope, Space Application, Lightweighted reflector, SiC

1 INTRODUCTION

Over the past ten years ASTRIUM have developed the SiC technology for Space Applications^{1,2} in collaboration with a ceramic company BOOSTEC Industries (Tarbes, France) The joint venture SiCSPACE gathers the expertise of both companies for supplying optics and telescopes for both space and ground applications. The technology is now fully mastered and ESA selected ASTRIUM in 2001 for manufacturing HERSCHEL large telescope. HERSCHEL satellite is part of HERSCHEL/PLANCK program of the European Space Agency (ESA) devoted to far infrared astronomy. Both satellites, HERSCHEL and PLANCK will be launched in 2007 by Ariane 5 in a dual launch and will operate at an orbit about Lagrange L2 point.

HERSCHEL telescope is of Cassegrain type with a parabolic primary reflector of diameter 3.5 meters. This unprecedented telescope will be mounted on the top of HERSCHEL helium cryostat vessel that contains three science instruments. The telescope operates at cryogenic temperature (~ 80 K) in the far infrared wavelength range (80 μm to 600 μm) and it will be the largest telescope in orbit in 2007. The overall telescope mass is below 300 kg and this puts in evidence the exceptional lightweighting capability of SiC technology: for comparison, Hubble Space Telescope primary mirror mass is about 900 kg for a diameter 2.4 m

During previous study phases (1995–2000), ESA conducted extensive trade-offs on the telescope material, supported by the development of breadboards of CFRP composite and lightweight aluminium mirrors. It was clearly established that ASTRIUM/BOOSTEC Silicon Carbide technology was the only viable solution for meeting mass and performance requirements.

After a brief review of the material properties, we present the development status of this telescope and the results of the HERSCHEL mirror demonstrator that was manufactured and tested two years ago.

2 PROPERTIES OF THE SINTERED SiC

Silicon Carbide is now a mature technology for space applications that presents a high growth potential. The material can be obtained by several processes, which can significantly affect either, its physical properties or its cost. We shall only consider here the sintered Silicon Carbide manufactured by BOOSTEC industries (located at Tarbes) according to a well-defined and cost efficient process.

2.1 Material Basic Properties

Some key figures measured by ASTRIUM are summarized in Table N°1.

Material Characteristics		Room Temp.	110 K
Density	ρ (Kg/m ³)	3160	3160
Young Modulus	E (Gpa)	420	120
Bending strength	σ_r (Mpa)	374	405
Toughness	K_{Ic} (Mpa.m ^{1/2})	2.75	2.83
Weibull Modulus	m	14	14
CTE	α (ppm/K)	2	0.65
Thermal conductivity	λ (W/m/K)	190	180
Specific Heat	C_p (J/kg/K)	700	135

Table N°1: Some basic properties of SiC (ASTRIUM measurements)

Two classical figures of merit have been added :

Thermal distortion ratio λ/α : The higher is the better. It physically reflects that thermal distortions are not only proportional to the CTE, but also to the thermal gradients, which, under given thermal environment, drop down when the thermal conductivity (λ) increases.

Specific stiffness E/ρ : The higher is this value, the better is the material lightweighting capability, for equal mechanical behaviour (e.g. equal first resonance frequency). However, a comparison only based on specific stiffness is rather theoretical, since it does not include manufacturing limitations such as the aspect ratio (rib thickness/ height). Actually, such limitations are not very constraining for SiC: an aspect ratio about 20-25 can easily be reached, and values as high as 80 with a rib thickness of 1 mm have been achieved.

2.2 Optical Properties

BOOSTEC Silicon Carbide is polishable (polishing convergence as good as for glass) and the surface roughness can be made as low as 1 nm. The material can therefore be used for optics in the visible range. It can be metal-coated by using the same process than for silica glass and with similar performances. Several types of reflecting coating have been space qualified on the sintered SiC (Al, Ag, Au) without any problem.

2.3 Joining Techniques For Manufacturing Large Sic Telescope

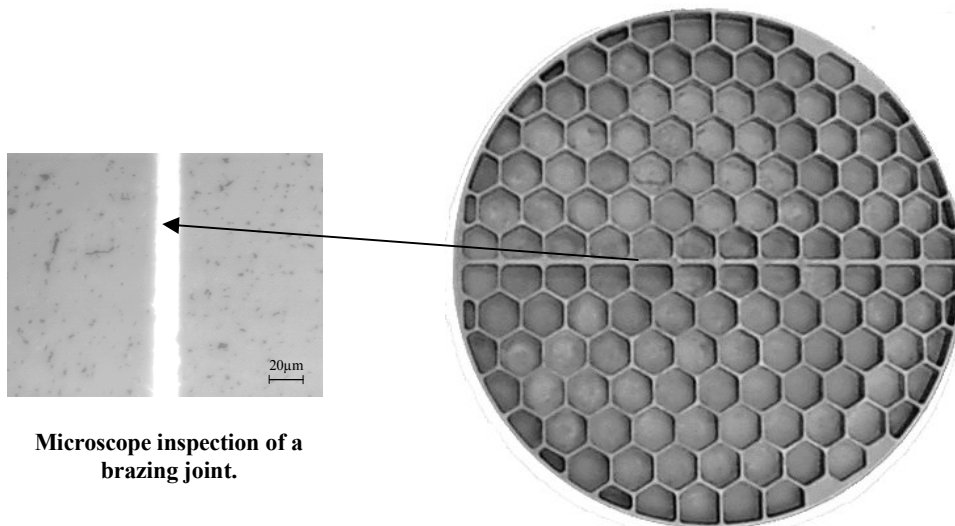
Available facilities allow manufacturing monolithic silicon carbide pieces of dimensions up to 1 m x 1.6 m. This covers practically most of the needs. Manufacturing larger monolithic pieces would require a significant industrial investment. Therefore, the cost effective and safe approach for the realisation of large pieces, such as HERSCHEL primary reflector, is to assemble together smaller pieces, which are well within manufacturing capabilities.

In addition such joining techniques are absolutely necessary for telescope manufacturing where we have to integrate SiC mirror onto SiC mechanical structure. Several techniques can be envisaged and have been investigated:

- i) Mechanical assembly of two SiC pieces, by bolting with shear pins (this type of assembly has been space qualified)
- ii) Epoxy bonding
- iii) High temperature brazing

Brazing technique consists of adding a material between two SiC pieces. ASTRIUM technique is a high temperature brazing that provides several remarkable properties:

- Its CTE can be matched to that of Silicon Carbide, say within 0.1 ppm/K or so,
- The brazing joint can be very thin : few μm to few tens of μm (Fig. 6). But thick joints of thickness as high as 300 μm 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 brazing strength is practically not affected at low temperatures.



Microscope inspection of a brazing joint.

Figure N°2: Φ 630 mm brazed mirror

(This mirror is composed of two identical semi-spherical lightweighted mirrors brazed on a diameter)

- The brazing is non-reactive, i.e. SiC is not attacked. Therefore, de-brazing is possible without any damage of the SiC parts.

3 THE Φ 3.5 M SiC HERSCHEL TELESCOPE

The main characteristics of this telescope are given in table N°16 .The telescope is a Cassegrainian telescope which elements (reflector and structure) will be manufactured in SiC.

Parameters	
Diameter	3.5 m
Mass of the telescope	<300 kg
Operating temperature	70 – 90 K
Operating wavelengths	80 μm to 600 μm
Telescope total WFE	< 6 μm rms
Transmission	> 0.95
Longitudinal frequency	> 60 Hz
Lateral frequency	> 45 Hz

Table N° 3. HERSCHEL Telescope Characteristics

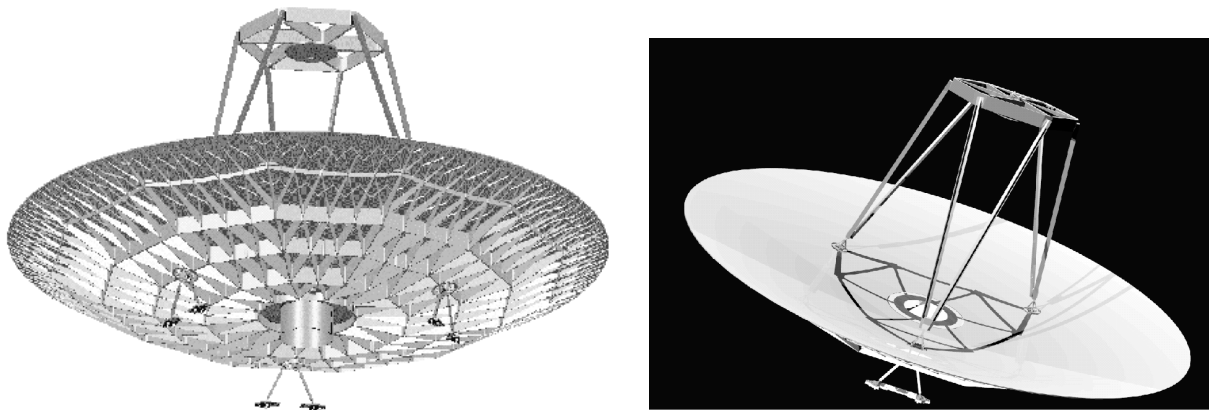


Figure N ° 4 : Herschel Telescope

3.1 Optical Design

The HERSCHEL telescope is a pure Cassegrain design composed of a parabolic primary and a hyperbolic secondary. The primary makes a perfect image of an on axis object point at infinity and the secondary re-images this point in a perfect manner in the focal plane. Standard Cassegrains can be improved by higher order aspherisation of the mirrors as in the Ritchey-Chretien design. In our case however, the difference between the

two designs is negligible and purely theoretical so that the simple Cassegrain design has been selected. The main optical characteristic is given in the following figure (Figure N° 5)

Herschel Telescope optical parameters	Cassegrain
Primary reflector	
Radius of curvature	3500 mm
Conic constant	-1
Distance to M2	1587.998 mm
Secondary reflector	
Radius of curvature	345.2 mm
Conic constant	-1.279
Diameter	308.12 mm
Image surface	
Radius of curvature	-165 mm
Conic constant	-1
Diameter	246 mm
Distance to M1	-1050 mm

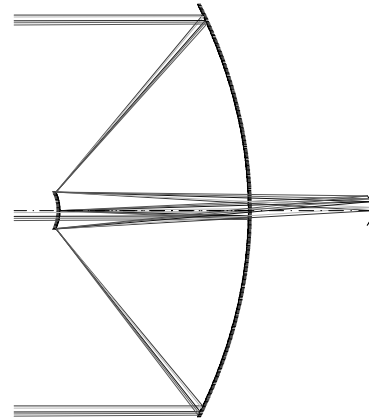


Figure N° 5: HERSHEL telescope optical design.

The coating is made of a first adhesive layer on NiCr (less than 10 nm thickness) and a 150 to 300 nm layer of aluminium. The coating will be performed at the CALAR ALTO Observatory facilities in Spain where a 4 m deposition vacuum chamber is available.

The telescope design has to be optimised in order to avoid narcissus effect and to restrict the impact of spurious source and self-emission of the structure below the background induced by the reflecting mirrors. Therefore a thermal foil or multi-layer blankets of low emissivity envelope all non-optical parts (un-coated). This naturally ensures a thermal decoupling of the telescope from the rest of the satellite. Heaters are also attached to the telescope parts for a contamination release of optical surfaces in-orbit. The contamination release phase is achieved at the beginning of life prior to the cryostat opening by heating up the telescope parts to ~ 45 °C. After contamination release phase, heaters are switched off and the thermal control of the telescope is purely passive.

3.2 Primary reflector design

The most complex element is obviously the Φ 3.5 m primary reflector that is composed of 12 SiC segments brazed together. The segment is open-back lightweighted with triangular cells of inner diameter ~ 120mm. The rib heights and thickness are optimised for minimising mass while meeting frequency requirement. As an illustrative example, the rib height varies from 110 mm in the centre of the segment to 10 mm at the edge. The thickness of the optical surface is 2.5 mm. For minimising manufacturing cost and schedule, the design has been constrained so as to include only two types of segments (figure 11) with minor differences between the two types: Three segments include interfaces for mounting the Secondary Mirror hexapod and the telescope isostatic mounts, while the nine other are “without interfaces”.

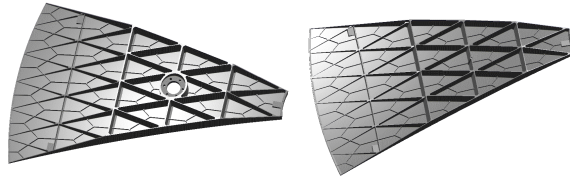


Figure N°6– HERSCHEL Primary Reflector design – segments with or without I/F



FigureN°7– HERSCHEL Primary Reflector

The main parameters of the primary reflector are detailed in the following table:

Diameter	3.5 m
Mass	210kg
Areal density	21.8 kg/m²
First Frequency	
Lateral	50 Hz
Axial	100Hz

Table N°8 – HERSCHEL Primary Reflector Main Characteristic

The primary reflector blank will be ground by BOOSTEC then polished by OPTEON (Turku, Finland). The lapping and polishing are efficiently performed with a technique specific to OPTEON where the polishing tool consists of several sub-tools disposed in a linear array across the mirror radius. The sub-tools are moved in a short radial stroke while the mirror is rotating during lapping/polishing. The sub-tool sucking produces the surface pressure by generating a partial vacuum to the reflector face-sheet. There are no unbalanced forces

acting perpendicularly to the surface and the quilting problem is minimised. The partial vacuum is varied under computer control to regulate the surface pressure and the local removal efficiency. It is necessary for the vacuum induced surfacing pressure that the three interface holes of the face-sheet are blocked with silicon carbide pieces. During lapping phase, the measurements of the mirror shape are made with a swing arm profilometer. Fine measurements of the polished mirror are achieved with a pentaprism test device.

OPTEON polishing technique using partial vacuum between the tool and the optical surface was demonstrated on the 1.35 m reflector in 1999 (see section 4)

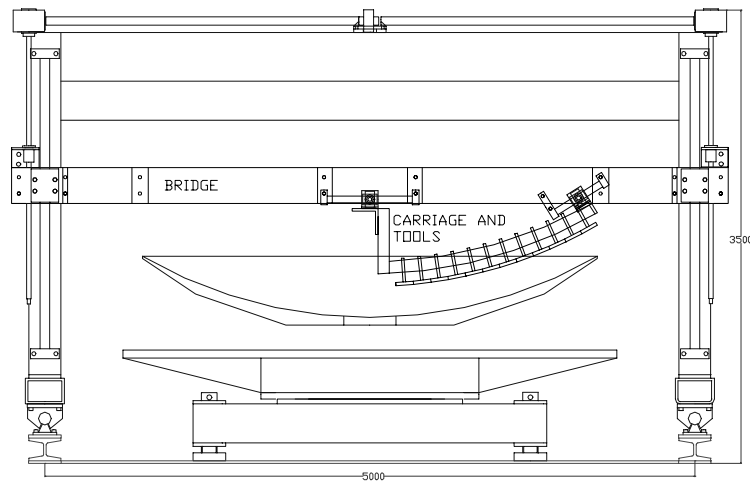


Figure N°9. Polishing machine showing the polishing tools and their carriage.

3.3 Secondary reflector design

The secondary reflector is a 308 mm diameter hyperbolic convex mirror.

Its dimensions are compatible with a simple central fixation concept integrated to the mirror. This kind of interface has been developed and validated by ASTRUM for various other instruments and features several advantages: simple mounting by bolting on the hexapod SiC barrel, no isostatic mounts, accurate and reproducible shimming during telescope alignment, cost effective design.

The optical face thickness 2.4 mm, leading to a weight below 2.1kg.

The mechanical sizing of this piece is not critical with regard to frequency as well as to strength.

For avoiding narcissus effect by reflection at the central area of the reflector, a special shaped SiC piece is added at the vertex. Herschel wavelength range is such that this cap piece is not required to be polished and may be only ground (roughness < 0.5 μm). Therefore the piece is simply fixed to the mirror after polishing.

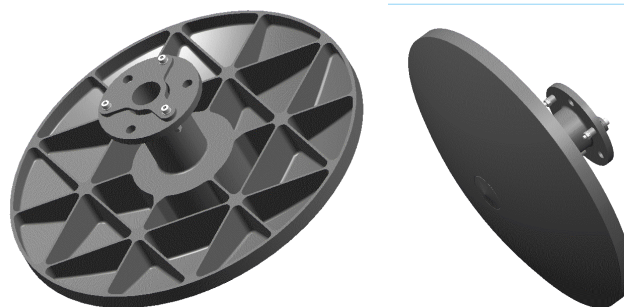


Figure N°10 – M2 design

3.4 Mechanical structure design

-The Hexapod

- The hexapod ensures the relative position of the primary and secondary mirrors, which has to be stable within less than 10 μm at operational temperature without any refocusing mechanism. The selection of hexapod configuration was driven by mass, stiffness and obscuration ratio constraints. The reflector material choice drives that of the hexapod and the use of a unique material for the whole telescope practically suppresses thermal stresses and distortions. The defocus error is then almost insensitive to average temperature variations of the telescope. Furthermore, the defocus error induced by residual thermal gradients at operational temperature is negligible, because silicon carbide material combines a low thermal expansion (CTE) with a high thermal conductivity.

The hexapod concept is based on:

- 6 SiC Legs .The legs are “U” shaped and slightly rotated by for straylight minimisation
- 1 SiC barrel glued to the 6 legs
- 3 flexible Invar fittings glued onto 2 legs each and bolted onto M1 upper inserts via an adjustment shim to minimize integration distortions

The legs and the barrel are covered by kapton foil for thermal and optical purposes. SiC/invar gluing was validated down to 50 K through a dedicated qualification plan.



Figure N°11– SiC HERSCHEL Hexapod with its interface fittings

-Isostatic Mount and Hexapod Fittings

The telescope isostatic mount function is to enable the telescope integration on the satellite cryostat structure with negligible optical distortions. The isostatic mounts consist of titanium bipods with a 49° optimal angle. They will be fixed through specific INVAR inserts bolted on the M1 reflector interfaces. The bipod rod section is designed so as to achieve a proper isostatic mounting while meeting frequency requirements.

The purpose of the Hexapod fittings is to isostatically link the hexapod onto the M1 reflector interfaces for minimising the primary reflector optical distortion during integration. The Hexapod fittings are made of invar for matching as close as possible the SiC CTE and minimizing the telescope defocus in cold related to SiC/invar CTE mismatch.



Figure N°12: Telescope bipods and Hexapod Fittings

3.5 WFE test set-up

The most challenging verification process will be the optical WFE measurement near operational temperature (110 K). The Herschel telescope will be tested in auto-collimation on a flat mirror in vacuum chamber with a Shack-Hartmann wavefront sensor. The test will be performed by ASTRIUM in the Centre Spatial de Liege (Belgium) test facility. The optical test is performed in autocollimation configuration and in cold environment ideally fully representative of operational conditions. Since the whole telescope is practically made of a single homogeneous material, residual elastic cool-down distortions are expected to be small with respect to the overall WFE budget, with a smooth dependence with temperature. The telescope behaviour at 80 K can safely be deduced from thermal cycling tests and sample tests. The auto collimation set-up is the major difficulty of the optical test. ASTRIUM excluded for obvious economical reasons the manufacturing of a 3.5 m flat mirror, which quality must be better than that of the telescope. It is proposed to replace the flat mirror by a set of distributed liquid mirrors that cover the entire telescope pupil. This set-up is compatible with a Shack-Hartmann measurement technique, which relies on ray slope measurements: actually the liquid mirror height can be arbitrary, while the gravitation field ensures its surface quality. The liquid mirror sub-assembly is made up of 48 identical mirrors of 100 mm diameter distributed on a square grid. The grid period is 440 mm. Each mirror is made up of a cell containing mercury sealed by a BK7 window and the test will be made in the visible range for simplicity and improved accuracy.

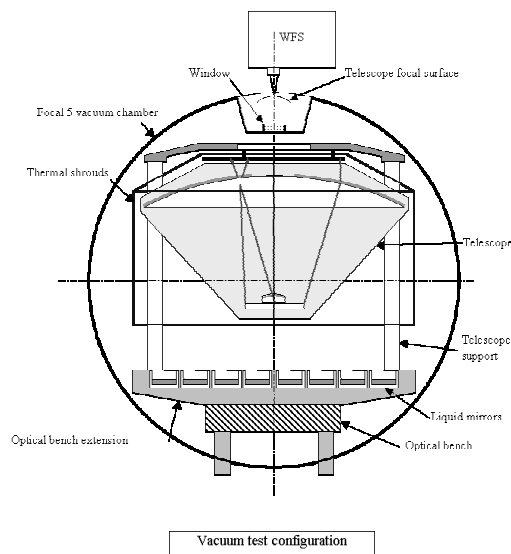


Figure N° 13: HERCHEL telescope Vacuum test configuration

4 HERSCHEL PRIMARY REFLECTOR DEMONSTRATOR

During the preliminary design phase several breadboard and mock-up were developed in order to demonstrate that a large cryogenic telescope could be manufactured in SiC.

4.1 Breadboard $\Phi 1.35\text{m}$

For validating the manufacturing process³ of the primary reflector we realised a $\Phi 1.35\text{m}$ diameter demonstrator. This demonstrator will be fully representative of the HERSCHEL manufacturing technology. The breadboard experience was funded in the frame of ESTEC contract.

The design was made of 9 SiC segments brazed together in order to realize a half scale demonstrator of the primary reflector. The reflector breadboard has sustained all the qualification tests planned for the Herschel Telescope showing not only the compliance of the proposed technology with the environmental requirements but also the mastery of the analysis and design process of Silicon Carbide pieces.



Figure N°14: $\Phi 1.35\text{ m}$ HERSCHEL demonstrator (before brazing and after, brazing, machining and polishing)

The vibration test was performed at ESTEC including low level frequency research survey and static tests at fixed frequency sustained up to 29g laterally and 27g axially. The resulting stress sustained by the Reflector is estimated to 100Mpa in SiC and 6Mpa in Braze joints. This test has also enabled the measurement of the amplification factor ($Q=110$ to 175 on mirror modes). Furthermore the measured natural frequencies were well correlated with the model predictions (<5%). This gives good confidence for the future Herschel vibration test predictions and proposed notching.

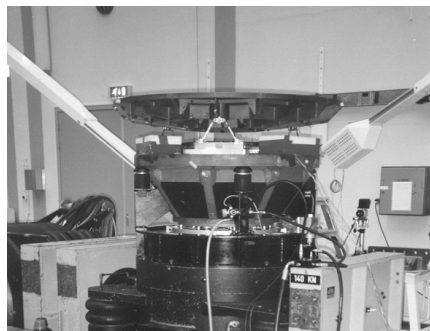


Figure N°15– HERSCHEL Breadboard during Vibration Test

The Breadboard has also sustained the acoustic Ariane5 proto-qualification spectrum in free-free boundary conditions, in ESTEC chamber. Once again the measurements were in good accordance with

the predictions. This test has shown that, despite the high acceleration measured on the external contour (56g at 3 sigma), this environment is less critical for the Reflector (stress level: < 11 MPa).

The proposed technology (SiC+brazing) has been also tested at 110°K, close to the Herschel operating temperature, without any damage on the SiC parts or brazed joints. In addition no distortion resulting from brazing or from CTE variation between segments has been measured. However a trefoil distortion of WFE = 2.6µm due to local effects on the 3 Invar fittings has been detected and is also recovered with the mechanical model. This has been avoided on the Herschel design by adapting the design of the fittings.

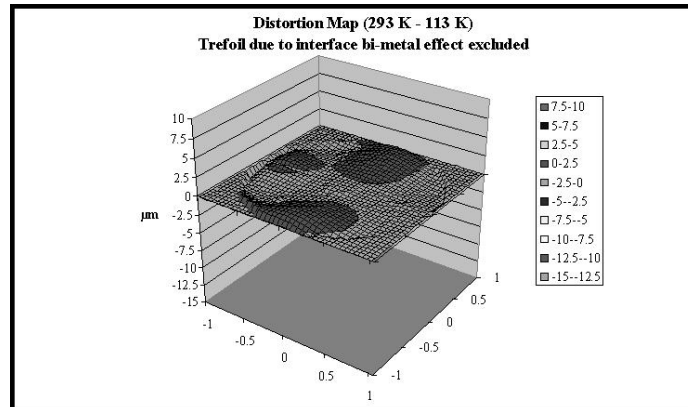


Figure N°16– WFE distortion Map between ambient and operational temperature

If the pure trefoil distortion is removed, the residual cool-down distortion is within the measurement noise of the interferometer (0.3 µm rms). Neither effect due to the reflector segmentation nor to the brazing was detectable, in accordance with the predictions and measurements on samples.

4.2 3.5m segment mock-up

During this phase we also design and manufacture a full size petal .The achieved design takes into account not only the HERSCHEL telescope specifications but also all the manufacturing requirements and the 1.35 m breadboard experience.

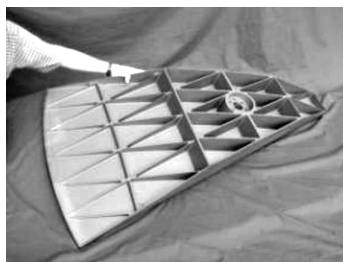


Figure N°17: HERSCHEL telescope full-scale petal. Size 1.5 m x 0.91m.

5 FUTURE TRENDS & CONCLUSION

The SiC technology developed by ASTRIUM and BOOSTEC is now fully mature. Space qualified telescope and mirrors are currently proposed for a wide range of applications. The Φ 3.5 m HERSCHEL telescope is currently under development .The critical design review has been successful .The primary reflector is expected to be completed on June 2003. The full telescope will be delivered to our customer on march 2005 after acceptance

test campaign. During this program, all the preliminary validation activities have demonstrated that SiC material is ideally suited the development for very large cryogenic telescope.

We are presently pushing up the technology for manufacturing ultra-lightweighted mirrors with areal density down to 9 kg/m² and very large instrument as GAIA (where the complete payload will be build in Sic), DARWIN telescopes. Further more, the sintered Sic manufacturing is really cost effective and it will a very attractive solution for future ground based telescope as the 100 m diameter telescope OWL planned by ESO

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