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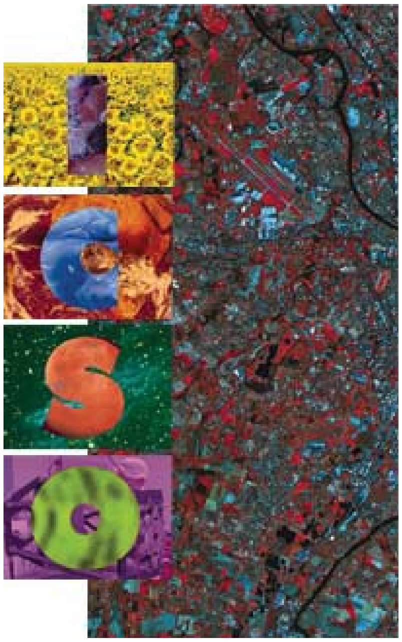

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DEVELOPMENT AND TEST OF A 1.35 m SILICON CARBIDE REFLECTOR

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Résumé

Astrium propose de réaliser le télescope FIRST de diamètre 3.5 m en carbure de silicium (SiC). Compte tenu des limitations des moyens industriels actuels et pour éviter des investissements lourds, le « blank » du miroir primaire est constitué de douze segments assemblés par brasage. L'ébauche est ensuite rectifiée et polie jusqu'à la performance souhaitée (de l'ordre de 2 µm rms). Pour démontrer la validité du procédé de fabrication proposé, Astrium a réalisé sous contrat ESA un miroir sphérique de diamètre 1.35 m constitué de neuf segments brasés suivant le même procédé. Cet article décrit les principales étapes de la fabrication ainsi que les résultats d'essais. Le démonstrateur 1.35 m a été réalisé avec succès en 1999, puis optiquement mesuré à froid (jusqu'à 110 K) au moyen d'un interféromètre dans l'infrarouge à 10.6 µm. Enfin, le réflecteur a été soumis à des essais de vibrations sinus et acoustiques. Les résultats d'essais démontrent sans ambiguïté que la technologie proposée est parfaitement adaptée au télescope de FIRST.

Abstract

Silicon Carbide technology is proposed by Astrium SAS (France) for building FIRST 3.5 meter telescope. Due to available facilities limitations, the primary reflector blank is made of twelve brazed segments, in pie segmentation. The blank is then ground and polished to the desired surface error performance (about 2 µm rms). For demonstrating the proposed technology, Astrium has built and tested a spherical reflector of diameter 1.35 meter under an ESA contract, by deliberately and strictly following the manufacturing process which is proposed for FIRST primary reflector. The paper describes the major manufacturing steps of the reflector and the test results. The 1.35 meter reflector is made of nine brazed segment. The blank has been successfully manufactured, then ground and polished in 1999. The reflector distortion was optically measured at 110 K by using an infrared interferometer working at 10.6 µm wavelength. The reflector was then submitted to vibration tests and to an acoustic test. All tests are successful and the results demonstrate the suitability of the proposed technology for FIRST.

1- INTRODUCTION

The Far InfraRed and Submillimetre Telescope (FIRST) mission is the fourth cornerstone of the ESA long-term space science programme. This unprecedented European astronomical spaceborne observatory will explore a wavelength observation window in the far infrared/submillimetre range (λ = 80 µm - 670 µm), where ground-based telescopes are inefficient because of the poor atmospheric transmission in this wavelength range. The operational orbit is around the second Lagrange point L_2 of the sun-earth system, at about 1.5 million kilometres from the earth.

FIRST telescope major requirements are recalled in the table below. The telescope is of Cassegrain type of diameter 3.5 m: it consists of a large very fast parabolic reflector (diameter 3.5 m, f/0.5) and an hyperbolic secondary reflector connected to the primary reflector by the mean of a tripod structure. The whole telescope is isostatically mounted on the cryostat structure, inside which the science instruments are located.

Primary reflector diameter	3.5 m, f/0.5
Telescope focal length	27 m
Operating wavelength	80 µm to 670 µm
Operating temperature	70 K to 90 K
Eigenfrequency	> 45 Hz lateral > 60 Hz axial
Overall height	< 1.7 m
Overall mass	< 260 kg
WFE requirement	< 10 µm rms Goal : < 6 µm rms

FIRST telescope major requirements

The telescope is a critical and crucial technological item of FIRST, not only because of its large size (unusual for space-borne telescopes) and of the resulting mass constraints: the primary reflector is very fast (f/0.5), the overall wavefront error is difficult to achieve with a fully passive design and the telescope optical quality must be mastered and reached at very low temperatures. The discussion of FIRST telescope needs and the interest of using SiC technology for FIRST will be found in [Safa 97].

By the end of 1996, Astrium (previously MMS-F) proposed to build the telescope with a specific Silicon Carbide technology in collaboration with BOOSTEC (Tarbes, France). Both companies were co-operating for developing and promoting this technology since many years for space applications, and it clearly appeared in 1996 that the technology was sufficiently mature for making FIRST telescope. The basic idea is to manufacture the primary reflector in twelve segments brazed together at high temperature: the manufacturing of each individual segment is well within available facilities capabilities and can be achieved with low development risk.

Following this proposal, ESTEC has placed a contract with Astrium for demonstrating that the proposed technology is suitable for FIRST telescope: the purpose of the contract was to design, manufacture and test at cold temperature a spherical reflector of diameter 1.35 m, and radius of curvature 3 m, by using exactly the manufacturing process that Astrium/Boostec proposed for FIRST telescope. A significant financial investment was made by Astrium and Boostec in complement to ESTEC funding.

The demonstration model was defined for being representative for critical aspects. In principle, since our material is homogeneous, the demonstrator size is of lower importance. However, since one purpose of the demonstration was precisely to demonstrate the material homogeneity versus temperature, the demonstrator diameter was fixed to an appreciable value (1.35 m). For practical and budget reasons the number of segments was reduced to nine, but the segmentation geometry is similar to that of FIRST. The major stiffener heights was deliberately increased for being equal to the maximum height foreseen for the 3.5 m FIRST reflector stiffeners. The purpose was to have a brazing area height fully representative of FIRST. As a result, the demonstrator model mass (38 kg) and mass per unit area are not representative of FIRST reflector, but this point is not critical and does not need a demonstration, because the proposed lightweighting design of FIRST petals is well within available and demonstrated capabilities.

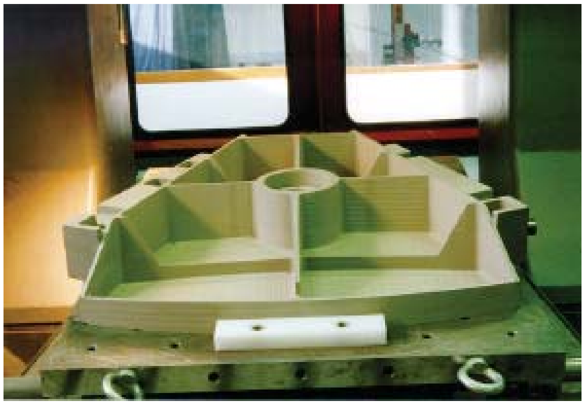
The work was performed in 1998-1999 and involved several European companies. The reflector demonstration model was successfully brazed in ABMT oven (Annecy, France) by the end of 1998, then ground by Boostec, polished by Opteon (Turku, Finland), optically measured in cold by CSL (Liège, Belgium) and vibrated at ESTEC. All tests are successful.

2- REFLECTOR MANUFACTURING

The various manufacturing steps are briefly described and illustrated below.

- **Petal manufacturing**

The nine petals have been manufactured with no particular problem within about 4 months only, demonstrating the efficiency of the manufacturing process. One petal manufacturing consists of three steps: green blank pressing, green machining and finally sintering. As for the 3.5 meter reflector, there are two types of petals: three of the petals exhibits interface areas for the reflector isostatic mount fixation, the others are without interface. For the sake of efficiency, the green body machining verification was directly made on representative SiC blanks for both types of petals.



Green body machining

View of a petal as sintered. Note that the rear side lightweighting is performed and completed directly on the green body

- **Reflector blank brazing**

Once all the petals are manufactured, they are mechanically assembled and brazed at high temperature. Because of thermocouple failures, the first brazing attempt was not fully satisfactory. The reflector did not exactly reached the required temperature and was only partly brazed. This problem was nevertheless very instructive in the sense that it allowed to demonstrate the possibility of repair in case of accident during the brazing procedure. The reflector segments were de-brazed by a specific acid attack process, and a new brazing was done in October 98 with an improved oven instrumentation. The brazing was then a total success : the brazed areas were filled to better than 99.7%, while the acceptance level is about 25%. The brazing strength was verified by strength tests on witness samples brazed in the same oven run.

View of all the petals prior to brazing

- **Blank grinding and polishing**

Once the blank was brazed, the whole following work was performed within less than 6 months, namely: grinding of the optical face (Boostec, Tarbes), integration of isostatic mounts (Astrium), polishing (Opteon, Finland), optical cold test at CSL (Liège) and vibration tests at ESTEC. The optical face was ground within ~ 3 weeks on a vertical lathe and the surface error was reduced down to ~ 30 µm PTV. Binocular inspection of the surface after grinding allowed to measure the brazing joint thickness: the typical thickness is about 15-20 µm and the maximum joint width was found below 30 µm. Brazing lines are hardly visible with naked eyes.

The reflector has been polished by Opteon (Finland), by using an innovative vacuum polishing technique: the polishing pressure is introduced by generating a partial vacuum between the tool and the reflector. This technique allows to somehow reduce classical quilting effects, although the reflector design was made compatible with conventional polishing techniques with regard to quilting. The maximum quilting obtained is below 1 µm PTV. The reflector shape was controlled at Opteon in the visible with a Hartmann test. The achieved surface error was 2.5 µm rms.

Optical face grinding at Boostec

View of the reflector after grinding

Polishing at Opteon (Finland). The reflector surface was made specular in the visible for allowing a Hartmann test. The surface error was reduced down to 2.5 µm rms (FIRST need).

3- REFLECTOR TESTS

- **Optical cold test**

The wavefront error was measured in cold by the Centre Spatial de Liège in focal 2 vacuum chamber. The optical cold test was the ultimate crucial test for demonstrating the reflector optical performance. It has clearly confirmed the analyses and sample test results by demonstrating the homogeneity of the material. The cold test also confirmed that the brazing effect on the optical quality is negligible, despite the large temperature variation of the reflector, in full accordance with the predictions.

The temperature was lowered down to 110 K by the mean of shrouds cooled with liquid nitrogen. The optical surface was continuously measured during the whole temperature cycle (see figure) with an optical interferometer located at the centre of curvature of the reflector and working at 10.6 µm wavelength. The overall measurement accuracy was 0.3 µm rms (surface error). Each surface error map was then expanded over the 35 first Zernike polynomials providing a spectral analysis of the measured distortions. Such spectral analysis allows to identify the origin and the amplitude of the individual potential contributors to the observed distortion. As an illustrative example, thermal torques/forces at the interface points due to the (small) ΔCTE between invar clamps and SiC produces a trefoil distortion, while brazing effect (if any) would produce spherical aberration because of the pie-shape segmentation.

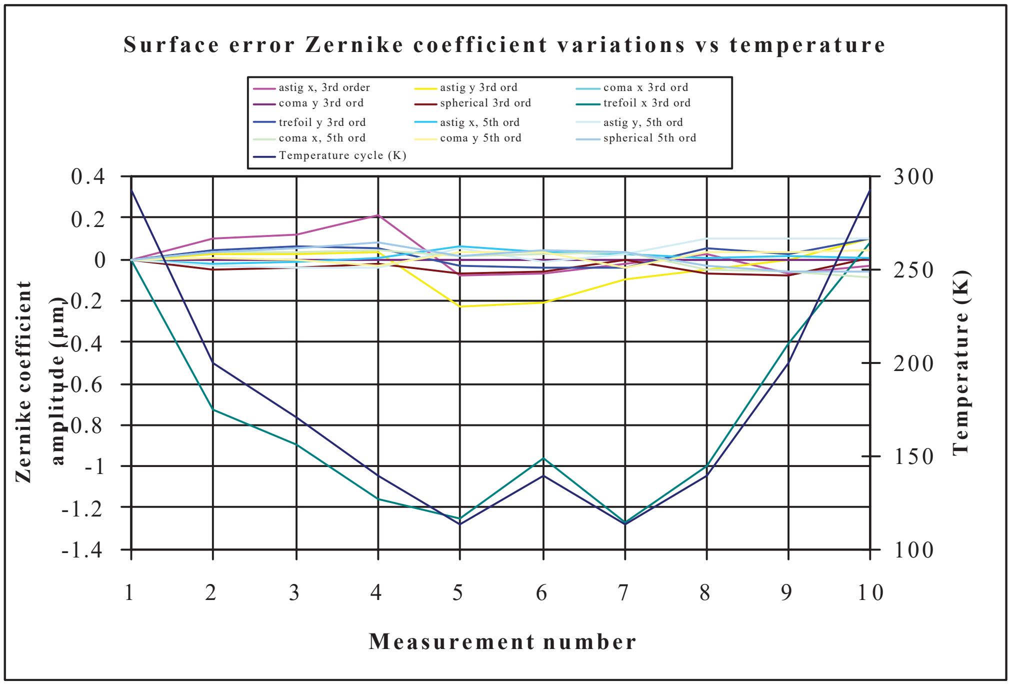
The cold test results are quite impressive and can be summarised as following:

i) A cool-down distortion of 1.31 µm rms was observed. It consists of a pure trefoil distortion perfectly connected to the interface points. This distortion is predictable and due to a bi-metal thermal distortion induced by the ΔCTE between invar and Silicon Carbide. It does not scale up with the reflector diameter and the distortion amplitude is compatible with FIRST telescope WFE budget goal (WFE < 6 µm rms). However, it can be suppressed for the 3.5 meter reflector for increasing the WFE budget margins, by improving the interface design.

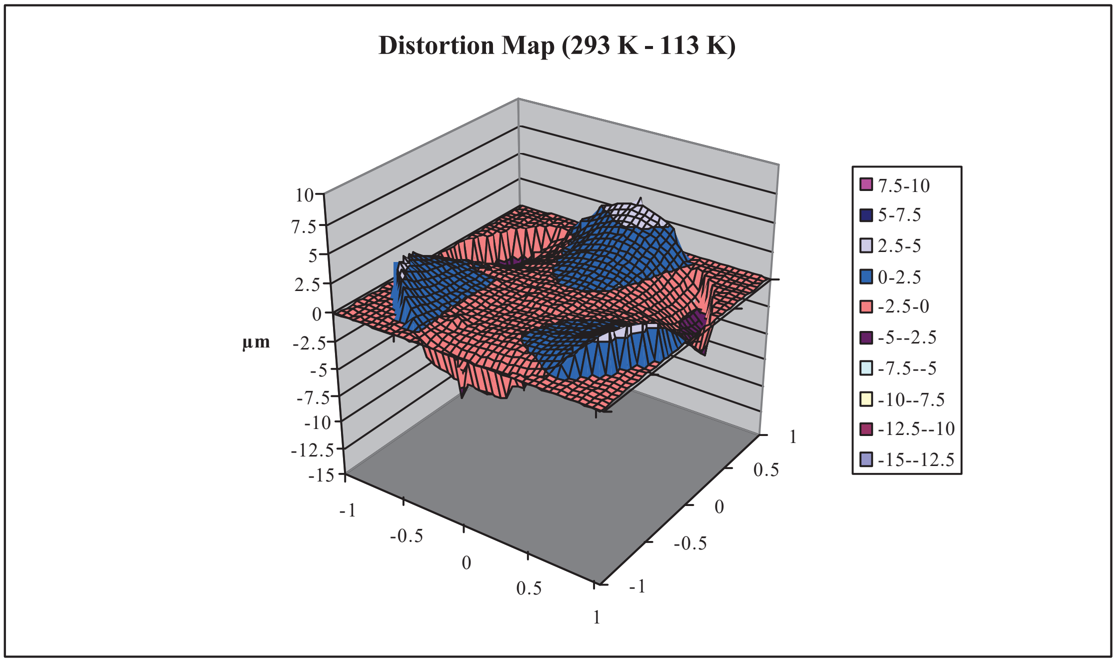
ii) The observed distortion is elastic: the reflector came back in its original shape, within the measurement noise (0.3 µm rms). Therefore, no stress-release effect nor hysteresis of the material was detected.

iii) Aside from trefoil, *all the other Zernike coefficient variations are within the measurement noise, during the whole temperature cycle*. This clearly demonstrates the homogeneity of the material in terms of CTE (in accordance with sample tests) and that the impact of brazing is negligible (in accordance with the FEM analyses).

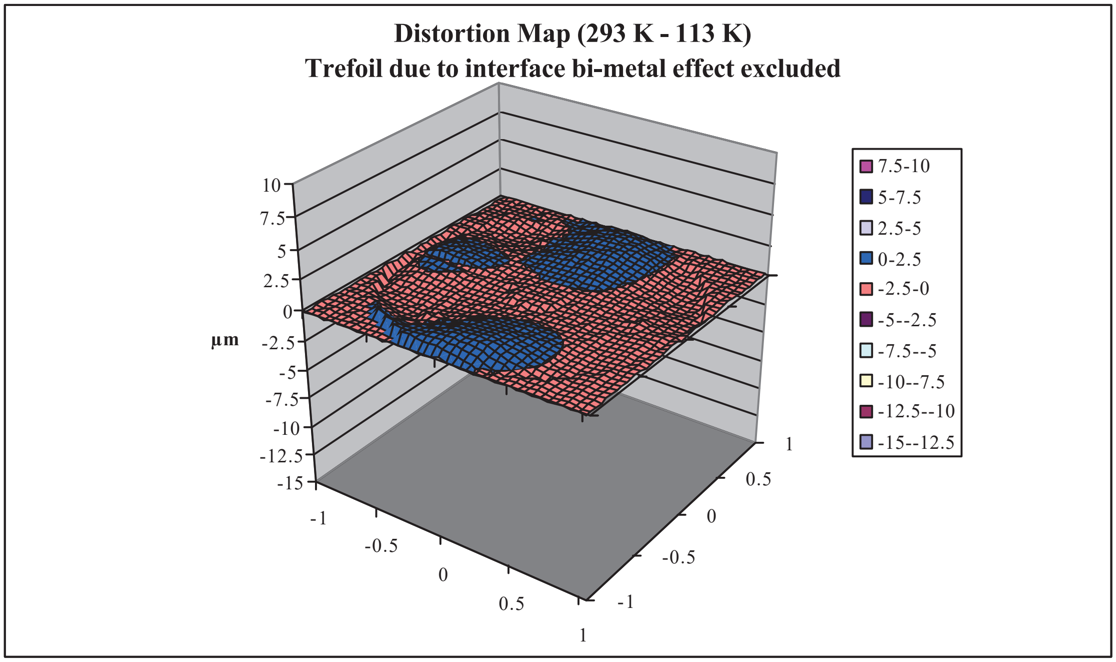
View of the reflector in Focal 2 chamber at the Centre Spatial de Liège. The reflector temperature was lowered down to about 110 K by the mean of LN2 cold shrouds. The reflector optical performance was continuously measured during the temperature cycle with an infrared interferometer working at 10.6 µm wavelength.



This plot represents the cold test temperature cycle (right scale) and the variations of the first Zernike coefficients of the surface error (left scale). Aside from the trefoil coefficient (elastic thermal distortion due to residual bi-metal effect between SiC and invar at the interfaces), all the other coefficient variations are within the interferometer measurement noise, which is quite remarkable and unambiguously demonstrates the material homogeneity as well as the fact that brazing effects, if any, are negligible in comparison to FIRST needs..



The observed cool-down distortion is a pure trefoil distortion (1.3 µm rms), related to a bi-metal effect at the reflector interfaces. The distortion is elastic, predictable and within the cool-down budget allocation. It can be made negligible with an appropriate design of the fixations.



If the pure trefoil distortion is removed, the residual cool-down distortion is within the measurement noise of the interferometer (0.3 µm rms). No effect due to the reflector segmentation nor to the brazing was detectable, in accordance with the predictions and measurements on samples.

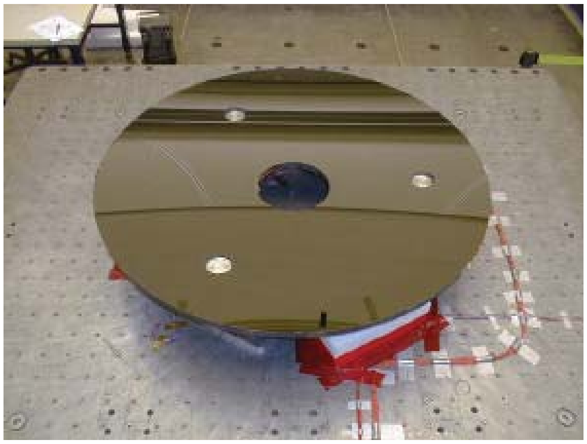
- **Vibration and acoustic tests**

Following the cold test at CSL, the reflector was successfully submitted to vibration tests at ESTEC over the 3 axes, with acceleration amplitudes as high as 27 g. The optical quality was controlled with a spherometer before and after each run and no optical degradation was observed. The reflector eigenfrequencies were in good accordance with predictions obtained from the Finite Element Model.

	First modes (Hz)	Second modes (Hz)
X-axis (lateral)	111 Hz, 113 Hz (*106 Hz*, *106 Hz*)	146 Hz, 148 Hz (*143 Hz, 141 Hz*)
Y-axis (lateral)	111 Hz, 113 Hz (*106 Hz*, *106 Hz*)	146 Hz, 148 Hz (*143 Hz, 141 Hz*)
Z-axis (axial)	236 Hz (*225 Hz*)	330 Hz (*333 Hz*)

The measured eigenfrequencies are in good accordance with FEM prediction (predicted values are in italic in parenthesis).

The reflector was also submitted to an acoustic test at ESTEC, with an acoustic load corresponding to Ariane V specifications. The controls performed during and after the test (visual, ultrasonic tests on brazed joints, final low level) show no degradation. The highest accelerations were measured at the external edge of the mirror (18.6 g rms). Here also, the measurements are in good accordance with the predictions performed with RAYON software.



View of the reflector on ESTEC shaker

View of the reflector in the LEAF acoustic chamber at ESTEC

4- CONCLUSION

The 1.35 meter Silicon Carbide demonstration model development is definitely a success. All the assigned objectives have been met:

1- The manufacturing process proposed for FIRST 3.5 meter reflector is fully demonstrated,

2- The optical performance of the 3.5 meter telescope at operational temperature using SiC technology is fully secured. The optical cold test performed on the 1.35 m reflector demonstrates that the telescope performance will be basically driven by the polishing accuracy of the reflector (which can be specified to some extent to be as good as desired) and by residual distortions induced at the telescope interfaces. No distortion effect due either to the material or to the brazing was detected. The overall telescope WFE design goal of 6 µm rms can therefore be met and is well mastered.

3- The 1.35 meter reflector have been submitted to vibration and acoustic tests. Both tests were successful.

The work performed and the test results clearly demonstrate the maturity and the suitability of the proposed technology for FIRST telescope, regarding both feasibility and performance.

Acknowledgements :

We would like to thank ESTEC FIRST project team, MM B. Guillaume, M. von Hoegen, T. Passvogel for the interesting and exciting work performed so far on FIRST.

References:

[Safa 97] F. Safa, F. Levallois, M. Bougoin, D. Castel: "Silicon Carbide Technology for Submillimetre Space Based Telescopes", 48th International Astronautical Congress, Turin, October 97.

[Safa 97] F. Safa, F. Levallois, M. Bougoin, D. Castel : "Silicon Carbide Technology for Large Submillimetre Space Based Telescopes", ICSO 97.