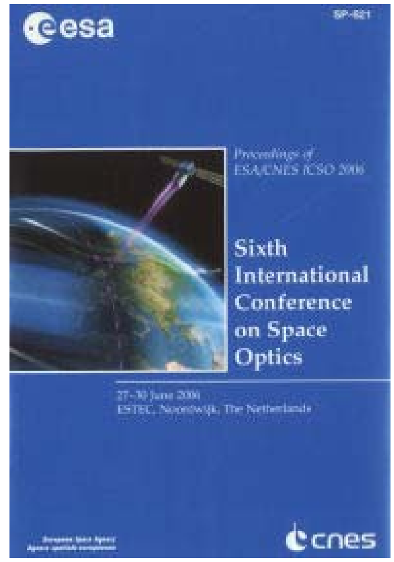
International Conference on Space Optics—ICSO 2006

Noordwijk, Netherlands

27–30 June 2006

Edited by Errico Armandillo, Josiane Costeraste, and Nikos Karafolas



The HSOB GAIA: a cryogenic high stability cesic optical bench for missions requiring sub-nanometric optical stability

Pascal Courteau, Anne Poupinet, Mathias Kroedel, Giuseppe Sarri

International Conference on Space Optics — ICSO 2006, edited by Errico Armandillo, Josiane Costeraste,
Nikos Karafolas, Proc. of SPIE Vol. 10567, 105670O · © 2006 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2308157

THE HSOB GAIA : A CRYOGENIC HIGH STABILITY CESIC OPTICAL BENCH FOR MISSIONS REQUIRING SUB-NANOMETRIC OPTICAL STABILITY

Pascal Courteau[(1)], Anne Poupinet[(2)], Mathias Kroedel[(3)], Giuseppe Sarri[(4)]

[(1)] Alcatel Alenia SPace – 100 bd. du midi 06156 Cannes la Bocca France – Tel : +33 (0)4 92 92 66 25
Fax : +33 (0)4 92 92 71 60 – @mail : pascal.courteau@alcatelaleniaspace.com
[(2)] SAGEIS CSO – 70 avenue des Martryrs 38000 Grenoble France – Tel : +33 (0)4 76 47 85 88
Fax : +33 (0)4 76 46 84 56 – @mail : a.poupinet@wanadoo.fr
[(3)] ECM – AM Bleichbach 10 85452 Moosinning Germany – Tel : +49 (0)8123 4045
Fax : +49 (0)8123 4044 – @mail : KroedelM@ec-muenchen.de
[(4)] ESA – postbus 299, 2200 Noordwijk Netherlands – Tel : +31 71 565 49 66
Fax : +31 71 565 52 44 – @mail : giuseppe.sarri@esa.int

ABSTRACT

Global astrometry, very demanding in term of stability, requires extremely stable material for optical bench. CeSiC developed by ECM and Alcatel Alenia Space for mirrors and high stability structures, offers the best compromise in term of structural strength, stability and very high lightweight capability, with characteristics leading to be insensitive to thermo-elastic at cryogenic T°. The HSOB GAIA study realised by Alcatel Alenia Space under ESA contract aimed to design, develop and test a full scale representative High Stability Optical Bench in CeSiC. The bench has been equipped with SAGEIS-CSO laser metrology system MOUSE1, Michelson interferometer composed of integrated optics with a nm resolution. The HSOB bench has been submitted to an homogeneous T° step under vacuum to characterise the homothetic behaviour of its two arms. The quite negligible inter-arms differential measured with a nm range reproducibility, demonstrates that a complete 3D structure in CeSiC has the same CTE homogeneity as characterisation samples, fully in line with the GAIA need (1pm at 120K). This participates to the demonstration that CeSiC properties at cryogenic T° is fully appropriate to the manufacturing of complex highly stable optical structures. This successful study confirms ECM and Alcatel Alenia Space ability to define and manufacture monolithic lightweight highly stable optical structures, based on inner cells triangular design made only possible by the unique CeSiC manufacturing process.

1. SCOPE OF THE HSOB STUDY

1.1 GAIA ASTRO Basic Angle stability

The GAIA astrometric performance is driven by the “Basic Angle” stability of few picoradians during consecutive 6 hours of acquisition duration. The “Basic Angle” is twice the angle between the two lines of sight of the ASTRO telescope, defined by the angle between the two entrance flat mirrors.

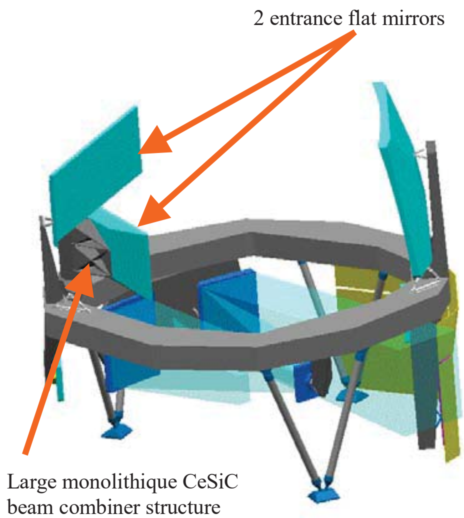


Fig. 1. View of Alcatel Alenia Space GAIA instrument

To achieve this high stability, Alcatel Alenia Space proposed to mount theses mirrors on a monolithic large CeSiC support, CeSiC offering a quasi-null thermal expansion coefficient at GAIA temperature (120K).

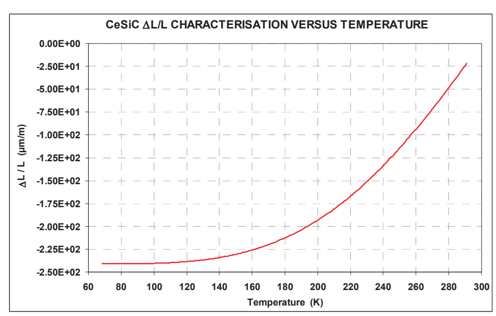


Fig. 2. CeSiC CTE is quasi-null at cryogenic T°

Proc. ‘6th Internat. Conf. on Space Optics’, ESTEC, Noordwijk, The Netherlands, 27-30 June 2006 (ESA SP-621, June 2006)

1.2 CeSiC homogeneity demonstration

The Alcatel Alenia Space ASTRO line of sight stability has been demonstrated through detailed stability analyses performed in the frame of the GAIA proposal. The HSOB study has validated one of the major hypothesis of these analyses : the adequacy of a complete 3 dimensional CeSiC structure in term of CTE homogeneity performance to the respect of global GAIA beam combiner structure LOS stability.
For that purpose, Alcatel Alenia Space has built the HSOB CeSiC optical bench, representative of the GAIA flight beam combiner structure, issued from the same manufacturing process, same material, similar way of assembly between CC blocks, similar final refine machining technique and overall dimensions close to the flight mirror interface ones. A measurement of the relative stability in tilt of the two I/F plane of the entrance plane mirrors under a uniform thermal change at ambient temperature has been performed.

2. HSOB CeSiC BENCH DESIGN

2.1 HSOB scale one representative

The main design driver of the HSOB structure is to be closely representative of the GAIA flight beam combiner structure. The HSOB bench is then issued from the same manufacturing process, same material, similar way of assembly between Carbon/Carbon blocks, similar final refine machining technique and overall dimensions close to the flight mirror interface ones.

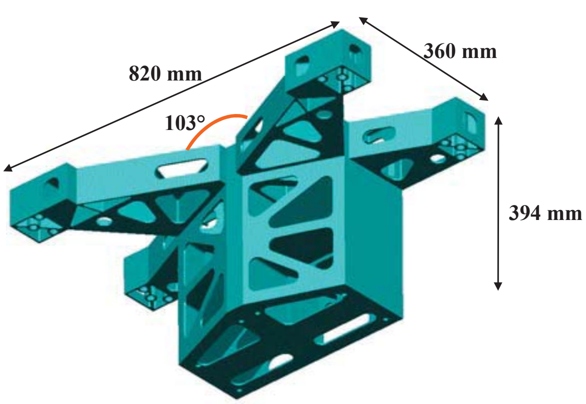


Fig. 3. HSOB scale one representative

CeSiC material developed by ECM and Alcatel Alenia Space offers a unique manufacturing technique based on greenbody blocs machining prior to infiltration, associated to post infiltration Electro Discharged Machining (EDM), described in next paragraph. This allows to manufacture complex but monolithic 3D structures with inner cells and ribs, allowing to reach very lightweight structure.

Fig. 4. HSOB : complex 3D with inner cells & ribs

Such complex cells and ribs cannot be achieved with classical metallic materials or other non electrically conductive SiC that cannot be machined by EDM.

2.2 Laser measurement device accommodation

The second design driver of the HSOB structure is to accommodate a laser metrology line dedicated to measure the bench inter-arm distance variation during the stability test under vacuum. The top plate-form of the HSOB is adapted to the SAGEIS-CSO laser metrology system mounting.

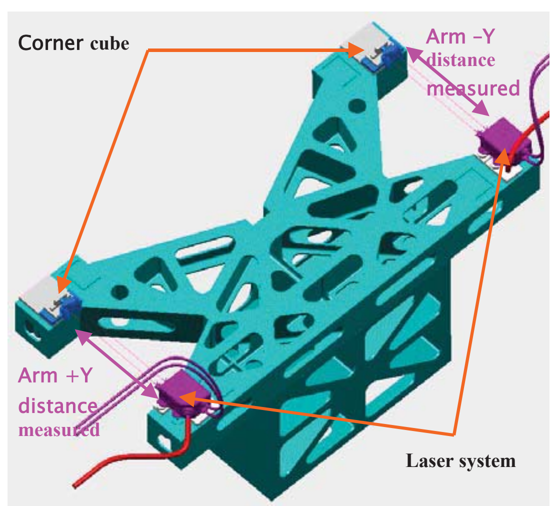


Fig. 5. Laser metrology system on HSOB arms

The nanometric accuracy foreseen during the HSOB tests implicates to precisely locate the laser measurement system and its corner cube. The HSOB interfaces are then very accurately machined by EDM. Bosses reference planes have a co-planarity of 50µm and H7 reference holes a locating quality of 50µm. It is noticeable that EDM machining could have reach a 10µm accuracy if this had been necessary.

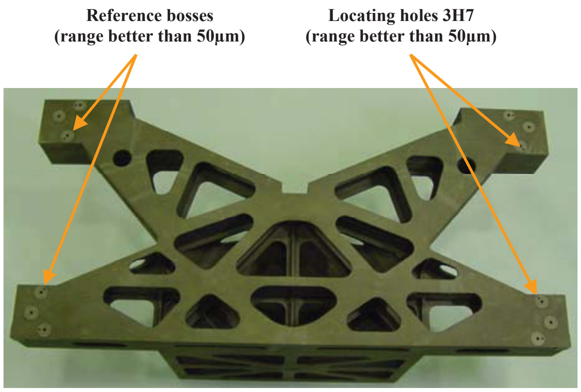


Fig. 6. Very accurate bosses & reference holes

3. HSOB CeSiC MANUFACTURING

CeSiC is a composite ceramic material composed of SiC (55%), Si (25%), C (<20%) and is manufactured following the hereafter simplified process schematized on the following figure. The CeSiC development status and manufacturing process is detailed in [1].

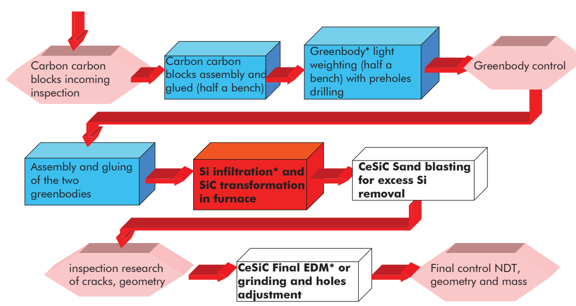


Fig. 7. CeSiC manufacturing simplified scheme

3.1 From raw material to greenbody

SGL, a world-wide known producer of C/C, manufactures C/C blocks from short cellulose carbon fibber felt. Isotropic layers with fibber being randomly oriented are first constituted. The layers are then impregnated with phenolic resin, then stacked together and then polymerised under high pressure. After what, the CFRP blocks are pyrolised and graphited at very high temperature in a furnace.
The obtained C/C block is a relatively dense material (d=0,75) with open porosity, with relative strength, and is not fragile, allowing the machining of cells and ribs prior to be assembled and infiltrated.

C/C blocks are then delivered to ECM which manufacture the CeSiC, on the form of big plate of 1mx1m on 80 mm thickness.

Fig. 8. View of a C/C block after cut

These blocks are then cut, joined and machined to realise the final shape of the piece before its infiltration.
The greenbody manufacturing is one of the key technologies of the CeSiC process. Performed on the greenbody before Si infiltration, it offers the capability to create very complex stiff and lightweight structures.
ECM has the capability to manufacture large greenbodies (ECM is able to join four 1mx1m C/C blocks) and machine them with its large CNC controlled milling machine of 2.5 x 1.75 m. This allows to manufacture one thick 300 mm piece, before the milling of the final greenbody shape.

Fig. 9. HSOB plate-form greenbody during milling

Due to the specific joining technology, which has been developed by ECM, it is possible to manufacture very easily and fast C/C parts with conventional tools and join them prior to the silicon infiltration process. Such process allows to obtain in one part a monolithic structure with very great geometrical inertia like structure in “I” shape, but also “complex” 3 dimensional structures like HSOB bench (819 x 360 x 394 mm). Indeed, a design like HSOB bench one includes lots of inner lightweight cells stiffened by transversal ribs and closed by external skins. This allows to optimise the structural stiffness on one hand and the mass saving on the other hand.

Fig. 10. HSOB inner cells due to ribs & skins

Such a structural network would be impossible to machine in once into a global deep carbon bloc. Thus, ECM CeSiC joining technology is the solution. Through the infiltration process the joined structure will become afterwards a monolithic piece without discontinuities and differences of thermal and mechanical properties.

Other big interest of the CeSiC manufacturing process : this is a direct to shape process. Greenbody structure will be manufactured very close to the final CeSiC structure in shape and in size. In fact, during the following infiltration process the material has a very low shrinkage. Shrinkage value has been characterised on previous programs at 0.20 +/- 0.05%.
On top of that, the transformation from C/C to SiC is a transformation solid to solid with all the time a high structural capability ensuring no deformation due to gravity or others effect.
Due to this very low shrinkage, the greenbody manufacturing is very close to the final dimensions. This allows the manufacturing and preparation of high accurate interface areas for big and large structures or mirrors. This small dimension change is an important advantage of CeSiC compared to other silicon carbide materials.

The C/C raw material being not fragile, the panel lightweighting on CNC machine is easy and fast with quasi no risk of greenbody failure. Large ribs with less than 1.5 mm thickness are easily shaped, and the machining time for a full reinforced panel is less than 15 days for 1 m^2.

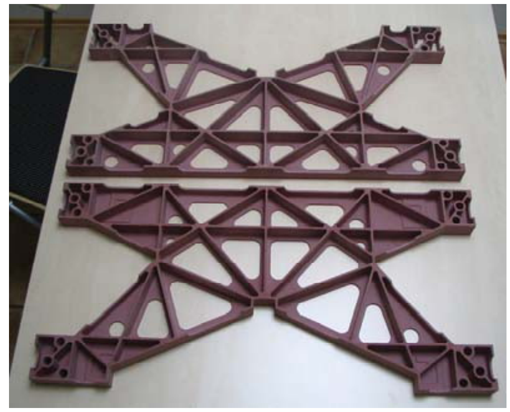


Fig. 11. View of HSOB machined plate-form panels

After the machining of independent panels, the C/C joining technology allows to assemble together upper and lower panels to constitute a very stiff monolithic structure.

Fig. 12. Assembly of the two HSOB plate-form panels

After assembly greenbody part is machined to obtain the final monolithic bench shape with its I/F area

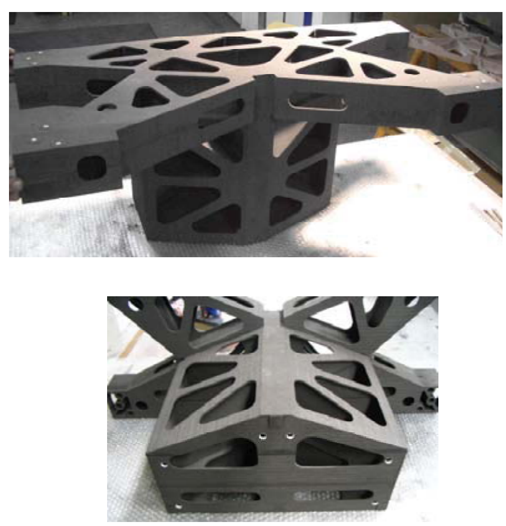


Fig. 13. View of HSOB greenbody once assembled

3.2 From greenbody to final HSOB bench

Then the greenbody is infiltrated at high temperature with liquid Silicon what penetrates inside the C/C through the open porosity and then react with the C to form the SiC, the porosity being filled by Si.
The current existing ECM XL furnace has a useful diameter of 2.4 m. This furnace enables ECM to infiltrate the whole HSOB and even biggest pieces, without equipment size increase, up to 2.3 m diameter.

Fig. 14. View of the XL furnace of ECM

After infiltration the structure is cleaned by sandblasting to remove the remaining silicon from the structure surfaces.

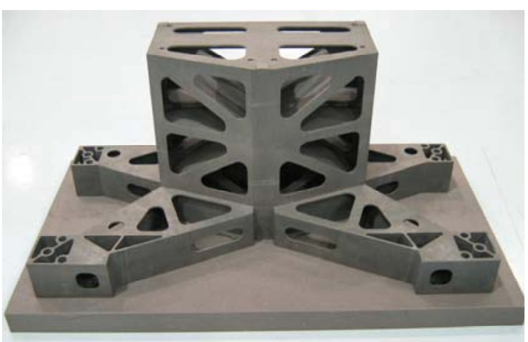


Fig. 15. HSOB after sand blasting

According to the properties of CeSiC it is possible to use different methods for final machining for the I/F preparation or other functional areas. The different possibilities are:

- Grinding with diamond tools
- EDM machining and wire erosion machining, the one chosen for HSOB accurate I/F.

Especially the possibilities of EDM machining and wire erosion (pure sintered SiC being not compatible of this technology) gives the unique opportunity to have a very precise method with low risk and to realise very good surface qualities.
Therefore the very low dimensional change during infiltration process combined with the possibility of EDM machining is a significant advantage of Cesic compared to other ceramic materials. This is all the more interesting since EDM offers the possibility to machine accurately very complex shapes and low accessible areas, the machined surface being the counter shape of the EDM electrode (possibility to machine bosses inside holes for example).
At greenbody level, precise interface with respect to surface flatness and also location of the interface, are machined with slight over thickness for the I/F planes and smaller diameter for the holes.
I/F surface are finalised by EDM after infiltration, with precise pad, giving the flatness and the location of the I/F planes (flatness of less than 10µm with a position of +/-20µm are achievable).
The holes will be increased after infiltration to the final diameter and precisely located by EDM machining through cost effective wire erosion process and without any risk for the piece (typical accuracy are H7 on hole with a locating +/- 10 µm).
The final HSOB monolithic CeSiC bench, accurately machined by EDM, is presented at delivery to Alcatel Alenia Space on the following figure.

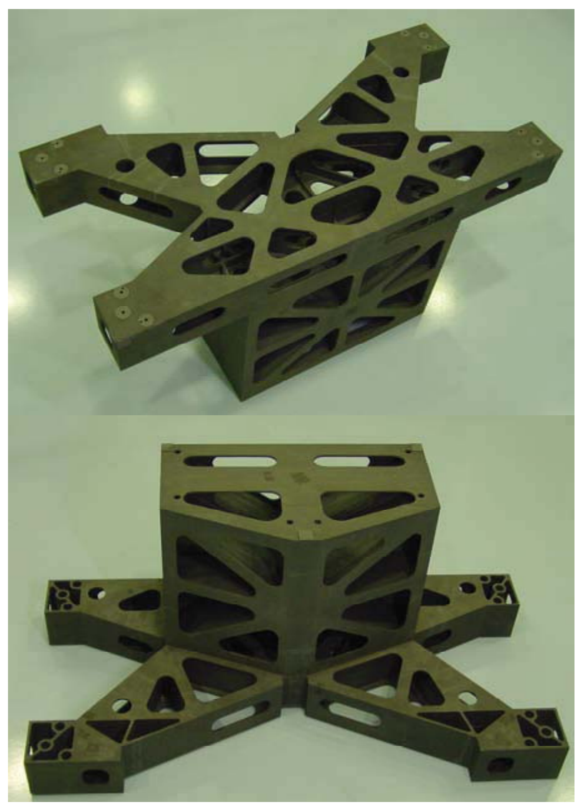


Fig. 16. Final HSOB at delivery from ECM

4. HSOB TEST

The HSOB is equipped with a laser metrology line to measure its inter arms distance stability. The line is composed of a MOUSE I (Metrologic Optical Unit for Space Environment generation I) system and a Corner Cube. The MOUSE line is mounted on the HSOB plate-form arms to measure its distance variation in Z direction (see figure 5).

4.1 MOUSE I laser system description

The principle of the measurement is to inject a highly stable laser of 1.55 µm wavelength via the optical system called "MOUSE I" toward a Corner Cube in Pyrex. The laser beam returns inside the MOUSE I creating an interference between the in and out beams. Once laser has been locked, the interference fringe pattern shifting is measured. The distance variation between corner cube and MOUSE I is directly connected to this interference pattern shifting.

The MOUSE I technology has been developed in 2001 under CNES contract. It is based on a Michelson interferometer, fully realised with single mode optical guides included in a glass substrate.

Fig. 17. MOUSE I system design overview

The MOUSE I system includes the optical circuit, the interferometric fringe detection system (photodiode) and data pre-treatment.

The laser source feeds the MOUSE I via an optical fibre. The pre-treated data are then transferred to an external electronic acquisition and treatment system via classical wires. (see details in [2]).

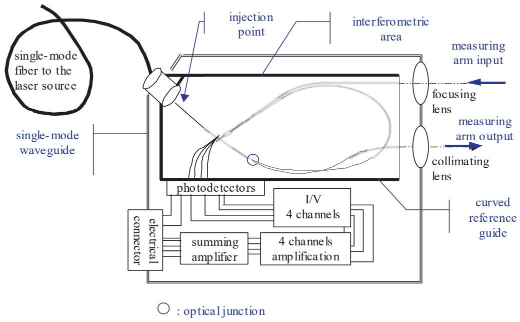


Fig. 18. MOUSE I system principle overview

The MOUSE I system performance has been established through calibration tests prior to the HSOB campaign. These measurement have demonstrated the ability of the MOUSE I system to reach a very high resolution of 10 pm at a 10kHz rate, compliant with HSOB needs that is in the range of nanometer.

4.2 HSOB tests configuration

The test has been performed into the ALCATEL Cannes V01 South vacuum chamber. This chamber is a large one (5 m diameter and 16 m long) chosen because it is the most efficient in term of chamber bench suspension. So, external mechanical vibrations are dynamically filtered, reducing at lowest as possible the vibrations induced on the HSOB specimen during the tests. This vacuum chamber is located into the class 100 area of the clean room, but this level of cleanliness is not requested for HSOB tests. Following figure gives an overview of this huge test installation.

Fig. 19. Alcatel Cannes huge test facility class 100

A double thermal cavity with MLI between, has been mounted inside the vacuum chamber, on insulating permaglass cubes. The HSOB has been laid on permaglass disks to insulate it from the chamber bench.

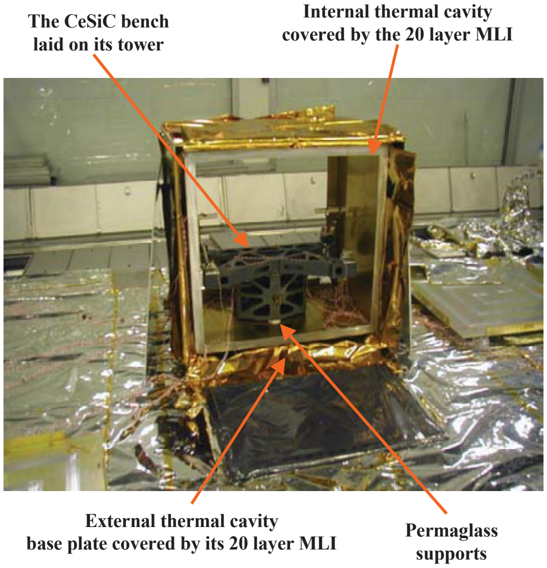


Fig. 20. HSOB test configuration cavities opened

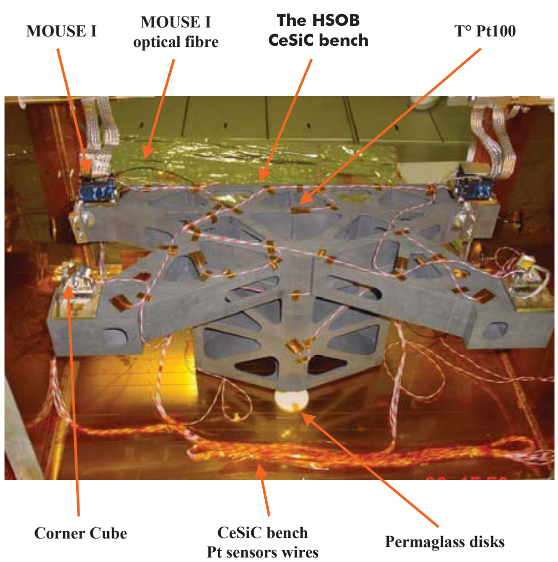


Fig. 21. HSOB zoom on the equipped bench

4.3 HSOB tests sequence

The principle is to submit the HSOB bench to a 1°C temperature increase under vacuum, while measuring the inter-arms distance variation with the MOUSE I system. The temperature step shall be as smooth as possible in order to limit to the minimum the parasitic effects of thermal gradient created by the test configuration along the bench. Three consecutive vacuum runs are performed in order to mount the laser system alternatively on one arm of the bench and on the other one, to achieve the following measurements :

- Run 1 : distance variation of arm -Y
- Run 2 : distance variation of arm +Y
- Run 3 : distance variation of arm –Y.

A typical thermal vacuum sequence is presented into the following figure, associated to the distance measurement plot.

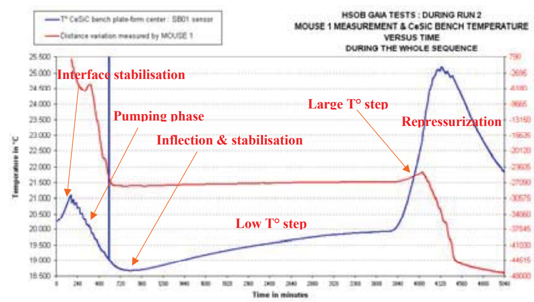


Fig. 22. HSOB test run 2 sequence measurements

A lot of care has been paid to perform these three vacuum cycles in strictly the same configuration, with same component mounting (shims, torque …), same sequence (chaining and duration of steps), same temperature levels, same temperature variation speed, same gradients inside the bench. The combined analysis of these three runs allows to measure the following parameters :

- Run 2 w.r.t run 1 and run 2 w.r.t. run 3 : CeSiC HSOB bench homogeneous behaviour in term of distance elongation of its two arms
- Run 1 w.r.t run 3 : reproducibility quality.

The thermal behaviour of the test configuration components is monitored with a very high accuracy via Pt100 sensors. The temperature resolution on the HSOB bench sensors is very good (below 0.001°C). These data allow to determine the best period for distance variation exploitation : the smooth +1°C temperature step of 24 h during which thermal gradients through the HSOB bench remain very low.

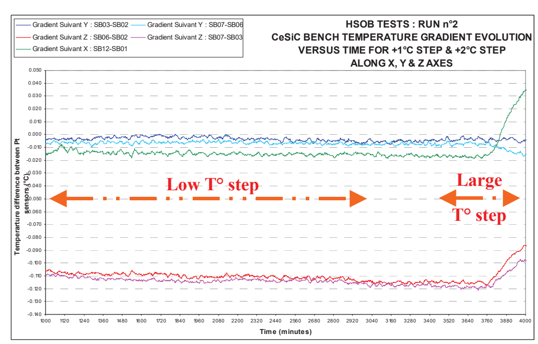


Fig. 23. Pt100 sensors resolution & HSOB gradients

4.4 HSOB tests results

Each of the three runs are compared in the same conditions :

- Same temperature sensor taken as a reference in the centre of the bench
- Same temperature evolution range : from 18.9°C to 19.9°C.

For each run, the temperature slope of the distance variation measurement is computed in nm/°C by linear regression over the whole +1°C temperature step.
The following figure presents the comparison between runs 2 and 3 of the distance variation measured versus the bench temperature increase (distance variation in nm, temperature in °C). The inter arms CeSiC bench homogeneity is measured equal to 21nm/°C.

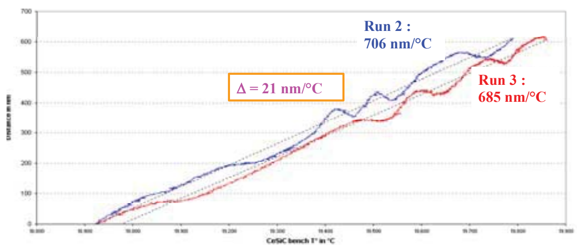


Fig. 24. HSOB CeSiC bench homogeneity measured

The test reproducibility is characterised in the range of few nanometers, as illustrated by the following figure presentsing the comparison between runs 1 and 3 of the distance variation. This results consolidates the previously announced homogeneity factor.

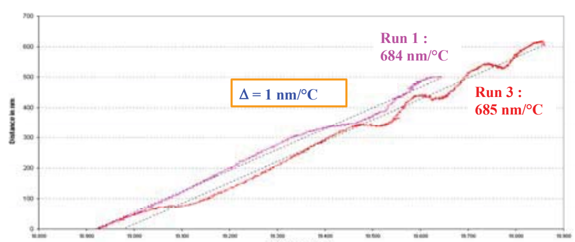


Fig. 25. HSOB CeSiC bench reproducibility measured

5. CONCLUSION

The delta of elongation measured between the arms of the HSOB represents 3.5% of the arms elongation due to CTE. This result is fully consistent with CTE homogeneity of 3.4% measured on numerous samples on previous programs and presented in next figure.

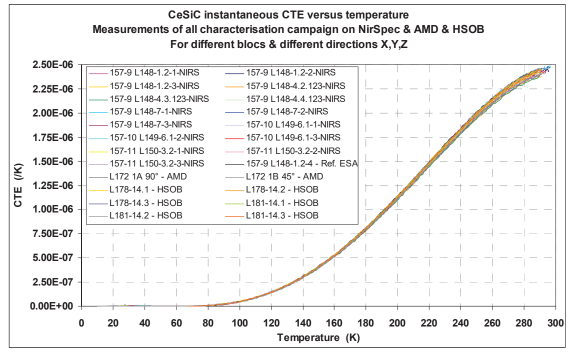


Fig. 26. CeSiC CTE homogeneity measured

The HSOB study has demonstrated that at ambient T°, a complete and complex lightweight monolithic 3D structure in CeSiC has the same CTE homogeneity as the samples already characterized. This leads CeSiC structure to be very attractive for high stability space instrument.
This is all the more true for cryogenic applications, CeSiC CTE homogeneity being even better than at ambient and associated to a quasi null CTE.

The HSOB study has evidenced ECM and ALCATEL ability to define and manufacture lightweight but monolithic and highly stable structures, based on an inner cells triangular design, realisation made possible due to the unique CeSiC manufacturing technique. This is very promising in the frame of ultra-stable and large structures for next generation of space telescopes

1. C. Devilliers, *A new technology for lightweight and cost effective space instruments structures and mirrors,* paper 303031 of the sixth International Conference on Space Optics, ESTEC Netherlands, 2006.

2. A. Poupinet, *Laser metrology for High Stability Optical Bench characterization,* paper 297677 of the sixth International Conference on Space Optics, ESTEC Netherlands, 2006.