From HERSCHEL to GAIA, 3-meter class SiC space optics

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ABSTRACT

HERSCHEL and GAIA are two cornerstone missions of ESA which embark 3-meter class optics. These instruments require so high thermal and mechanical stability than the SiC technology turned out to be indispensable.
The BOOSTEC SiC material has been selected first for its high specific stiffness and thermal stability. But it also shows a perfect isotropy of all its physical properties and it is remarkably more stable than the glass-ceramics in time and also against space radiations. This SiC material has furthermore been fully qualified for application at cryogenic temperature (HERSCHEL and also JWST NIRSpec).
The BOOSTEC manufacturing technology of very large size SiC components includes i) manufacturing 1.5 - meter class monolithic sintered parts and then ii) assembly based on a brazing process. The former one is a near net shaping process which allows manufacturing at reasonable costs and within short time.

HERSCHEL has been successfully operating at Lagrange L2 point since mid of 2009, giving amazing information to astronomers. It includes a 3.5 m primary mirror, a secondary mirror and a hexapod. It weighs only 315 kg and its WFE is kept below 6 µm rms despite an operating temperature of 80 K.
GAIA is made of more than 280 SiC parts of 80 different types. The most challenging of them is undoubtedly its highly stable structure, the 3 meters torus. This quasi octagonal and hollow shaped ring is made of 19 SiC elements brazed together. It weighs only 200 kg. All the GAIA hardware has been successfully manufactured and it is now being integrated and tested at ASTRIUM facilities.

Keywords: silicon carbide, space telescope, HERSCHEL, GAIA, mirror, stable structure, manufacturing process

1. INTRODUCTION

The BOOSTEC SiC technology has turned out to be indispensable for manufacturing the highly stable 3 – meter class optics of HERSCHEL and GAIA, two cornerstone missions of ESA [1] [2]. These both instruments have been designed by ASTRIUM France with all in SiC concept; the mirrors are made of SiC but also the stable structure and the focal plane hardware as well. Their SiC parts have been manufactured at BOOSTEC premises in the fisrt half of 2000-2010 decade for HERSCHEL and in the second one for GAIA.

HERSCHEL is one of the six telescopes entirely made of BOOSTEC SiC which are now successfully operating in space [3]. With a photons collecting surface more than twice as large as the one of Hubble, it is by far the largest space telescope. The 280 flight SiC parts of GAIA have now been fully achieved at BOOSTEC premises. The GAIA Structural Model (SM) has recently passed its vibration tests with success, at instrument qualification levels. ASTRIUM is now pursuing the integration of the Flight Model (FM) in view of further thermal and mechanical tests in 2012 and a launch towards L2 point in 2013.

The SiC material properties are reviewed in the present paper and the manufacturing technology is further described. It includes i) manufacturing 1.5 meter class monolithic SiC parts and ii) assembly of larger parts, based on a brazing process. The challenging SiC parts of HERSCHEL and GAIA instruments are presented in this paper.

2. BOOSTEC SILICON CARBIDE MATERIAL

BOOSTEC manufactures **sintered silicon carbide**. In comparison with the even most recently developed reaction bonded SiC including short chopped carbon fibers [4], it features 24% higher thermal conductivity, 25% higher bending

strength, 20% higher stiffness and similar toughness. Thanks to its isotropic microstructure, the physical properties of this alpha type SiC are perfectly isotropic and reproducible inside a same large part or from batch to batch. In particular, no CTE mismatch has been measurable, with accuracy in the range of 0.001 ppm/K.
The BOOSTEC SiC can be easily polished as it is single phased. Thanks to its high purity, its coefficient of thermal expansion (CTE) fits very well with the one of the extremely pure CVD SiC; this last one is obtained from chemical vapor deposition and it is commonly applied on the optical faces of SiC mirrors, in the aim to mask the few remaining porosities, when necessary.

Table 1. Basic properties of BOOSTEC SiC.

Properties	**Typical Values @ 293 K**
Density	3.15 g/cm^3
Young's modulus	420 GPa
Bending strength / Weibull modulus (coaxial double ring bending test)	400 MPa / 11
Poisson's ratio	0.17
Toughness (K_{1C})	3.5 MPa.m$^{1/2}$
Coefficient of Thermal Expansion (CTE)	2.2 . 10^{-6}/K
Thermal Conductivity	180 W.m/K
Electrical conductivity	10^5 Ω.m

The sintered SiC of BOOSTEC shows no mechanical fatigue, no degradation by space radiations, no outgassing and no moisture absorption nor release. It has been fully qualified for space applications at cryogenic temperature such as HERSCHEL but also NIRSpec instrument, which will be operated at 30K and embarked on the NASA James Webb Space Telescope [5] [6].
Its CTE is decreased from 2.2 ppm/K at room temperature down to 0.1 ppm/K at 20 K.

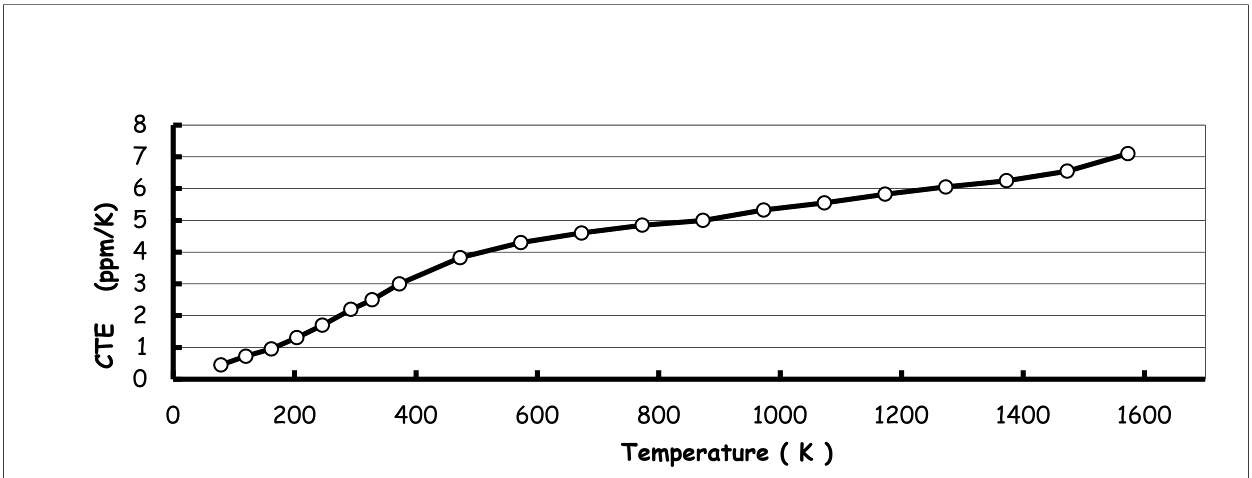


Figure 1. Coefficient of Thermal Expansion (CTE) of BOOSTEC SiC, versus temperature

3. BOOSTEC SILICON CARBIDE TECHNOLOGY

3.1 Manufacturing monolithic SiC parts

Commonly, BOOSTEC manufactures monolithic SiC parts of up to 1.7m x 1.2m x 0.6m (or Φ1.25 m). The flight models are manufactured with the sequence of steps shown in Figure 2.
The parts are machined very close to the final shape at the green stage i.e. when the material is still very soft (similar to chalk). This is high speed machining; typically, green parts of 1 meter are machined within 1 week while lightweighting such a glass-ceramic blank should take several months. Furthermore, in BOOSTEC process, the collected chips are

reused for producing new raw material. During the last ten years, the reliability and also the speed of this process have been continuously improved. New software has been invested for programming the CNC milling machines and also to verify the machining programs, thus allowing the green machining of very complex 3D shapes with a high reliability. These are some of the reasons why BOOSTEC process is so cost effective, reliable and quick.
These shaped parts are then heated-up to around 2100°C under a protective atmosphere, thus transforming the compacted powder blank into a hard and stiff ceramic material; it is the sintering. The "as-sintered" surfaces look highly smooth (typically Ra 0.4 µm) ; they can be used as is, without any sand blasting or other rework.
The mirrors optical faces and all parts interfaces are then generally ground in order to obtain accurate shape (from 1 µm up to 50 µm) and location; they are optionally further lapped or polished for a better accuracy and a smaller roughness.
The mechanically loaded parts are generally proof-tested in order to avoid defects which could be hidden in the material; even if unlikely; this is above all an easy way to really prove that the relevant SiC part is able to withstand with the predicted most critical loads. The parts are checked crack-free with help of UV fluorescent dye penetrant, before and after such a proof-test. They are measured with a large size accurate CMM or a laser tracker.

After having SiC CVD coated the mirrors optical face, they are re-shaped by grinding in BOOSTEC thus recovering their former < 50 µm shape defect; all GAIA mirrors have been successfully re-ground by this way, including the large off-axis ones.

1. Isostatically pressing large blanks from fine SiC powder premix
2. Green machining the pressed blank with help of high speed CNC milling machine
3. Sintering above 2000°C under protective atmosphere
4. Grinding and optionally lapping or polishing the optical faces or the interfaces
5. Mechanical proof-testing
6. Final check and cleaning

Figure 2. Manufacturing process of monolithic SiC parts

Figure 3. One of the 19 GAIA torus segments *left*) during green machining, *right*) ready for brazing assembly

3.2 Manufacturing 3-meter class SiC parts

The SiC parts the size of which exceeds 1.7m x 1.2m are obtained by **brazing** the assembly of previously sintered and ground pieces. The joint is made of a silicon alloy and it is generally less than 0.05 mm thick. The SiC parts are all joined together in a single run; their relative location is kept better than +/- 0.1 mm from the prediction to the final measurement, at the end of the brazing process.

The Φ 3.5 m HERSCHEL primary mirror has been obtained by brazing 12 segments, each of them forming a 30° angle [7] (Figure 4). Its optical face has been finally shaped parabolic by grinding, after the brazing assembly step.

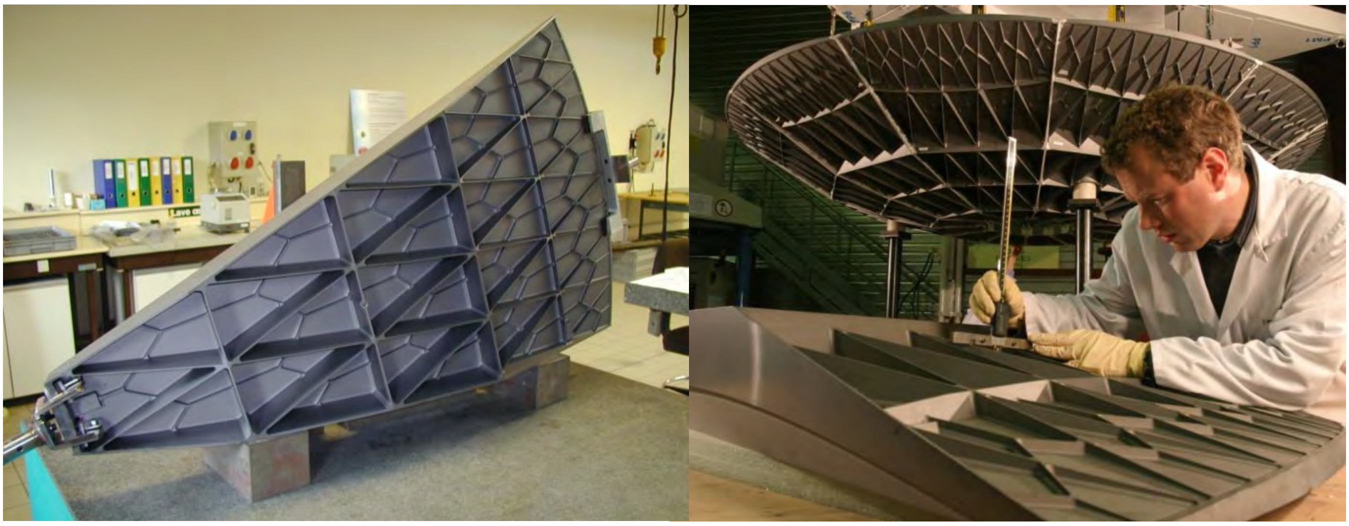


Figure 4. The HERSCHEL M1 is made of 12 SiC segments brazed together

The GAIA bench, the torus, is made of 19 SiC segments which have been brazed together, in a single run. Similarly as for HERSCHEL M1, the brazed joints are flat on flat.

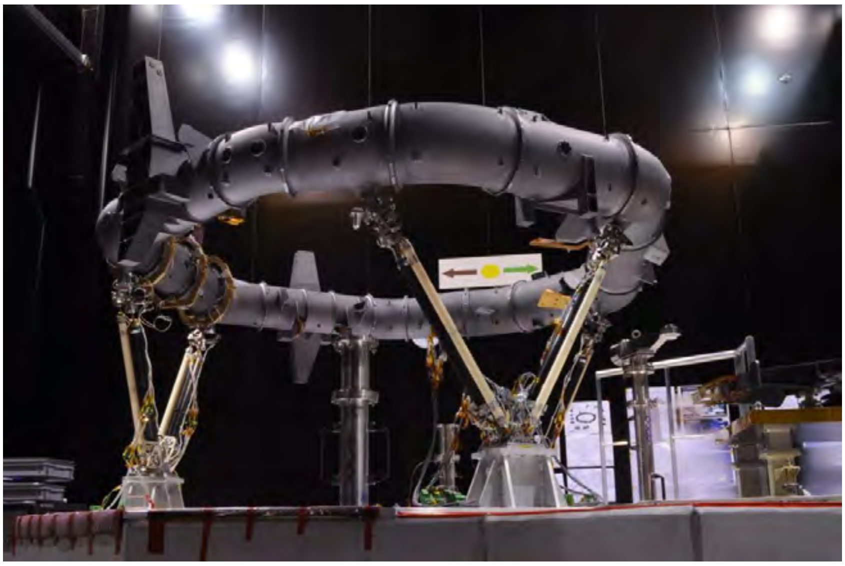


Figure 5. The GAIA bench is made of 19 SiC segments brazed together

4. HERSCHEL TELESCOPE

4.1 Description of the telescope

HERSCHEL telescope [1] is a Cassegrain type which is passively cooled down to 80K. Its WFE budget is < 6 µm rms at nominal focus for the complete 0.25° FOV, in the 60µm to 670µm working range. All its major components are made of BOOSTEC SiC: the primary and the secondary mirrors and also the hexapod that supports the M2. The SiC technology allowed ASTRIUM to reduce the telescope weight down to 315 kg instead of 1500 kg that would have resulted from using conventional materials. In addition to these substantial mass savings, silicon carbide also offers the excellent structural stability and thermal properties needed to maintain a mirror location accuracy of better than 10 µm.

Figure 6. HERSCHEL all-in-SiC telescope

4.2 SiC parts

As introduced in § 3.2, the primary mirror has been obtained from 12 SiC segments brazed together; 3 of them included an interface ready to be bolted with bipods (Figure 7). The M1 optical face sheet is stiffened by a network of 4 to 8 mm thick main ribs and 1.5 to 2.0 mm thick sub-ribs. Its aerial density is only 25kg/m². After brazing, the parabola (3.49 m RoC) has been ground down to a shape defect of 150 µm PTV. It has then been polished by Opteon (Finland) down to 3 µm rms WFE and coated with aluminum and a protective Plasil at Calar Alto (Spain).
No SiC CVD was required here as this M1 reflects far-infrared to sub-millimetric wavelengths.

Figure 7. Detailed view of the rear face of HERSCHEL Φ 3.5 m primary mirror, including an interface

The SiC secondary mirror is a convex hyperbola, 308 mm in diameter. An anti-narcissus cone has been implemented at the center of its face sheet. The M2 is bolted on the barrel through a rear central fixture and additional SiC tilt and focus adjustment shims.

The hexapod includes i) the hexagonal SiC barrel (Φ 850 mm size), ii) 6 "U shaped" SiC legs of 1.58 m length and iii) invar fittings. The upper end of each leg is glued on the barrel side while the other end of a pair of legs is glued on a single invar fitting. Each invar fitting is then bolted to the M1 interface.

Figure 8. Top view of the hexapod, the bolted M2 and their distorted image in M1

4.3 Current status

After having fully integrated the SiC telescope, ASTRIUM team has implemented a lot of successful qualifications i) 3 axis Sine sweep vibration tests on a shaker, ii) acoustic tests, iii) wave front error performance at room temperature and then at 70K [7]. Some telescope defocus has been measured at operational temperature and, after analysis, attributed to an inadequate knowledge of the materials CTE at cryogenic temperature [8]. It has been easily corrected by shimming the flight model.
The HERSCHEL telescope has been successfully launched towards its orbit around L2 point on 14 May 2009, with Ariane 5 ECA launcher [9]. A little bit more than one month later, the scientists gave the conclusion that the optical performance of the telescope was perfectly meeting their expectations. Since that time, the HERSCHEL observatory has been continuously unlocking the secrets of galaxy formation and evolution.

5. GAIA

5.1 GAIA payload module (PLM)

6^{th} cornerstone of the ESA scientific program, GAIA will provide positional, photometric and radial velocity measurements of about one billion star of our galaxy, with an unprecedented accuracy. The large payload has been designed by ASTRIUM [10][11]. It includes three science instruments:

i. **The Astro** which is devoted to the star angular position measurements (astrometry),
ii. **The Blue & Red Photometers which** provide continuous star spectra on 60 pixels in the band 330-1000 nm for astrophysics and Astro chromaticity calibration,
iii. **The Radial Velocity Spectrometer (RVS)** which provides high resolution spectra on 1260 pixels in the narrow band 847-874 nm and radial velocity measurements by Doppler effect.

Two 1.5 m TMAs point towards two directions forming a "Basic Angle" of 106.5°. The beams are then recombined with help of two folding mirrors, thus allowing them sharing a single large focal plane [12]. The astrometric accuracy (10-25 µarcsec at magnitude 15) relies on the very high stability of this "Basic Angle" (7 µarcsec over 6 hours). The SiC material appeared essential for obtaining the required **mechanically and thermally ultra-stable payload**.

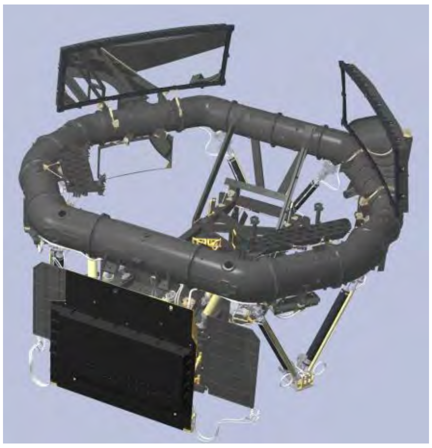
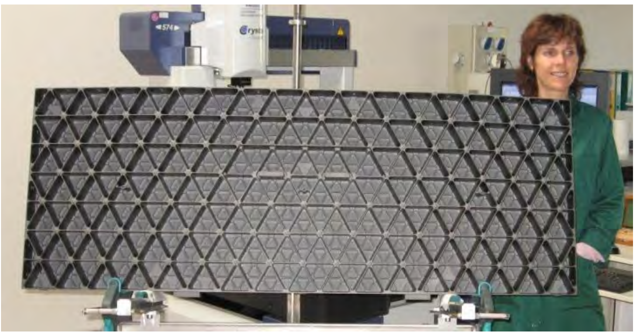


Figure 9. The GAIA payload module features “all SiC” architecture

5.2 SiC parts

The SiC is used all over the GAIA PLM.
The instrument includes 2 large Astro TMAs and then 2 times M1, M2 & M3 made of SiC. The following folding mirrors M4, M’4, M5 and M6 are also made of SiC; the optical face of all of them is SiC CVD coated.
The main bench comprises a 3m hollow shaped ring named the torus and a central base-plate. They are joined together with help of glued SiC struts.
The 106 flight models of CCDs have been mounted on individual SiC packages by their manufacturer, E2V UK. They are bolted on a large SiC baseplate, the CCD supporting structure. This base-plate is then bolted on the Cold Radiator for stiffening and cooling purpose. Three additional SiC panels allow to increasing the radiating area of the focal plane.
The “Basic Angle” formed between the pointing directions of the 2 ASTRO TMAs is extremely accurately monitored with help of interferometry. For that purpose, the GAIA payload embarks 2 optical benches which are also equipped with small SiC mirrors.
The optical hardware forming the Radial Velocity Spectrometer (RVS) is mounted inside a stiff structure made of SiC.
A lot of these SiC parts are quite challenging, due to their large size and also their highly complex shape. They are reviewed here after through a few examples.

The Astro M1 mirror blanks



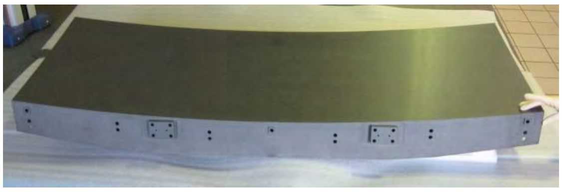


Figure 10. Views of a lightweight M1 mirror blank, ready for CVD coating (38 kg)

The primary mirrors of the Astro TMAs are aspheric and off-axis. They are quite challenging due to their large size (1.50 m x 0.56 m) and their huge number of back side cells which form a network of thin ribs and sub-ribs. The process for manufacturing the blank (in BOOSTEC) and the one for polishing (in SAGEM-REOSC) have been validated through a scale one M1 demonstrator, ahead on the project.

The Torus

The highly stiff and stable main bench of the GAIA instrument is hollow and quasi octagonal shaped, 3 m in diameter. It is made of 17 segments forming the large ring plus 2 additional brackets for M1 mirrors attachments; all of them have been joined by brazing, thus giving the required stiffness and stability. Individually, all torus segments were very challenging parts, due to their quite large size (0.5 - 1 m) and above all to the very complex shapes to be machined. Furthermore, they provide a lot of interfaces for setting-up on the satellite but also for mounting all optics and the focal plane as well. Before the assembly, they have been grinded and lapped very accurately. All individual torus segments have also been mechanically proof-tested.

The brazing assembly was undoubtedly a **key challenge** of the project. The 19 SiC parts had to be located accurately until the end of the brazing run (a single one!) which is performed around 1500°C. An ultrasound based technique has been developed specifically with the CEA (the French Nuclear Agency) for checking all the brazed joints. It allowed the detection and the cartography of possible voids down to a few mm². No significant defects were found in the brazed joints.

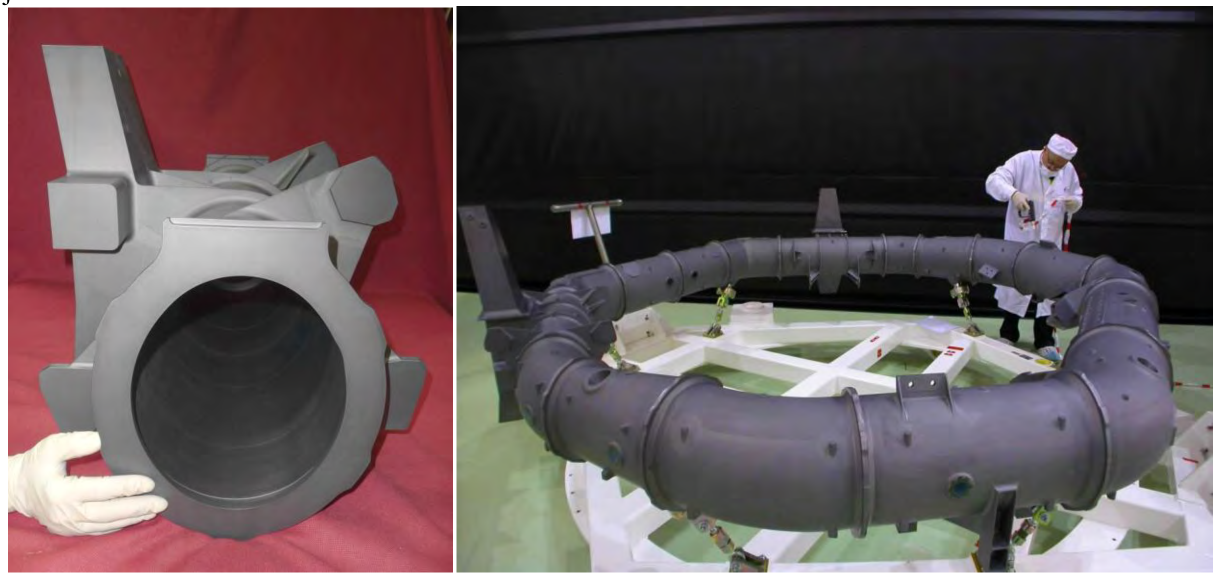


Figure 11. Torus *Left)* Torus segment before brazing *Right)* Reception of the torus assembly in ASTRIUM (< 200 kg)

The focal plane

Figure 12. Focal Plane *Left)* The CCD supporting structure (1.15 m x 0.53 m - 11 kg) *Right)* The Cold Radiator (1.17 m x 0.62 m x 0.41 m - 38 kg)

Beside the main Astro CCD plane, the CCD supporting structure features 3 other planes which are tilted with different angles. This base-plate is then bolted on the Cold Radiator. All the useful areas of these both large SiC parts have been polished to a local flatness of 1 µm by the company WINLIGHT. The Cold Radiator is very large in its 3 dimensions (Figure 12). It includes 6 accurately located interfaces areas which allow to hanging it under the torus, with help of thermally insulated bars.

The Basic Angle Monitoring (BAM)

The main SiC parts of the BAMs are 2 **very lightweight base-plates.** They include a lot of brackets, accurately finished for mounting all the optics on the front face. The rear face is stiffened by very thin ribs, only 1 mm thick.

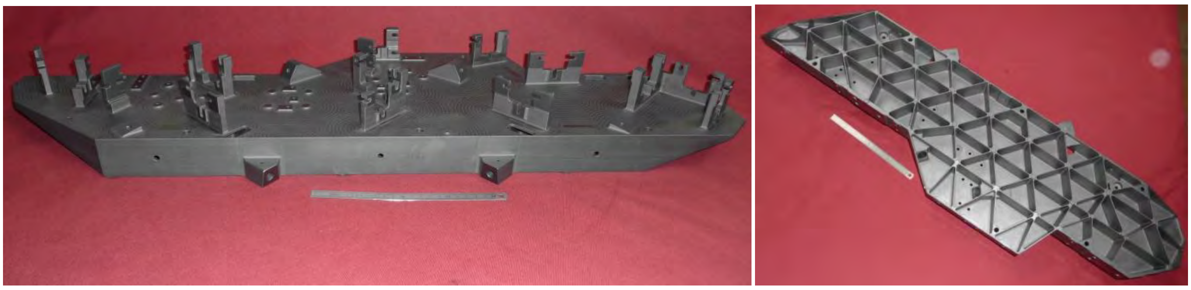


Figure 13. Views of the largest BAM base-plate (0.92 m x 0.28 m - only 5.6 kg)

5.3 Present status

The 106 CCDs flight models have been successfully mounted on the SiC CCD supporting structure (Figure 14).
The PLM structural model has been integrated (Figure 15), including a complete Astro flight line and a dummy one (7 of the 10 flight mirrors), a dummy focal plane and a dummy RVS. This structural model has recently passed its vibration tests at instrument qualification level with success (8 g on vertical axis). The measured performances of the SM were in perfect agreement with the predictions (within +/- 1% of the expected frequencies), thanks to the perfect knowledge of the material and the quality of both the analysis and the SiC assembly.
The structural model of the focal plane has also been qualified separately, with success.
After having dismounted the dummies, ASTRIUM is now pursuing the integration of the complete flight hardware. Further qualification tests are planned in the first half of 2012. The flight model of the PLM should be delivered end of 2012. The GAIA launch is planned in Kourou in 2013, on a Soyuz launcher.

Figure 14. The CCD flight models integrated on the SiC CCD supporting structure

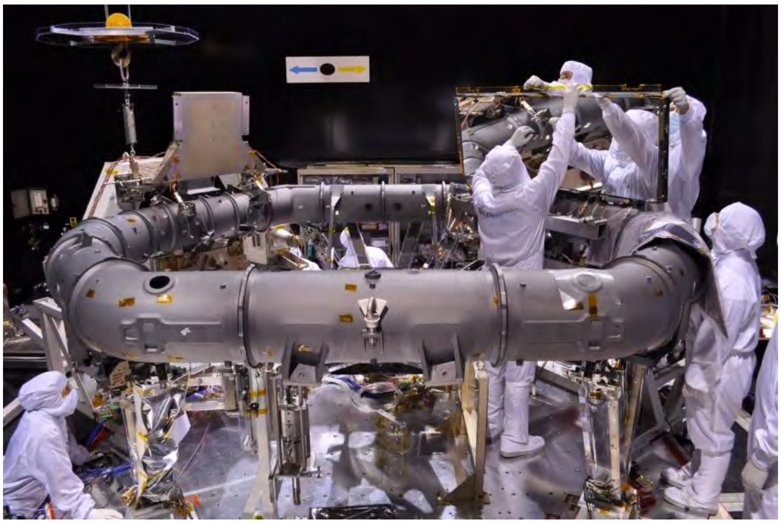


Figure 15. Integration of the GAIA structural model in view of its vibration tests

6. CONCLUSION

HERSCHEL and GAIA are two cornerstone missions of ESA which fully take profit of the BOOSTEC SiC technology. They both include a 3-meter class part but GAIA has also a lot of other challenging SiC components. HERSCHEL has been successfully operating in space since mid of 2009 while GAIA has now passed several critical qualification tests. These projects confirm BOOSTEC technology as the only one available in the world for manufacturing 3-meter class SiC optics. This technology is clearly available for future ESA large size instruments like EUCLID and SPICA.

ACKNOWLEDGEMENTS

We are extremely grateful to Göran Pilbratt and Thomas Passvogel for ESA side as well as Michel Duran and Yves Toulemont in ASTRIUM who have accepted to pioneer the use of our SiC technology for HERSCHEL project.
Rudolf Schmidt, Giuseppe Sarri and Philippe Gare (ESA) as well as Vincent Poinsignon and Philippe Charvet (ASTRIUM) have put their trust in BOOSTEC team for carrying out this very challenging GAIA project; we greatly appreciated.
We also express our warmest thanks to Didier Castel (ASTRIUM) for his very nice and fruitful collaboration of nearly every day, on both projects.

Images courtesy of ASTRIUM

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