Gaia Basic Angle Monitoring system

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ABSTRACT

The Gaia mission[1] will create an extraordinarily precise three-dimensional map of more than one billion stars in our Galaxy. The Gaia spacecraft[2], built by EADS Astrium, is part of ESA's Cosmic Vision programme and scheduled for launch in 2013. Gaia measures the position, distance and motion of stars with an accuracy of 24 micro-arcsec using two telescopes at a fixed mutual angle of 106.5°, named the 'Basic Angle', at an operational temperature of 100 K. This accuracy requires ultra-high stability at cryogenic conditions, which can only be achieved by using Silicon Carbide for both the optical bench and the telescopes. TNO has developed, built and space qualified the Silicon carbide Basic Angle Monitoring (BAM) on-board metrology system[3] for this mission, measuring the relative motion of Gaia's telescopes with accuracies in the range of 0.5 micro-arcsec. This is achieved by a system of two laser interferometers able to detect Optical Path Differences (OPD) as small as 1.5 picometer rms. Following a general introduction on Gaia and the use of Silicon Carbide as base material this paper addresses the specific challenges towards the cryogenic application of the Gaia BAM including design, integration and verification/qualification by testing.

Keywords: Gaia, Opto-mechanics, picometer, metrology, stability, Silicon Carbide, cryogenics, space qualification

1. INTRODUCTION

1.1 Gaia mission

Gaia[4] is a global space astrometry mission, part of ESA's Cosmic Vision program. The Gaia spacecraft (see Figure 1) is being built by EADS Astrium France and is scheduled for launch with a Soyuz launcher from Kourou in 2013. At a distance of 1.5 million kilometres from Earth at Lagrangian point L2, slowly spinning around its axis, Gaia will monitor each target star about 100 times over a five-year period, precisely measuring its distance, movement, and change in brightness. Through comprehensive spectrophotometric classification, it will provide the detailed physical properties of each star observed: characterizing their luminosity, temperature, gravity, and elemental composition. This massive stellar census, will provide the basic observational data to tackle an enormous range of important questions related to the origin, structure, and evolutionary history of our Galaxy.

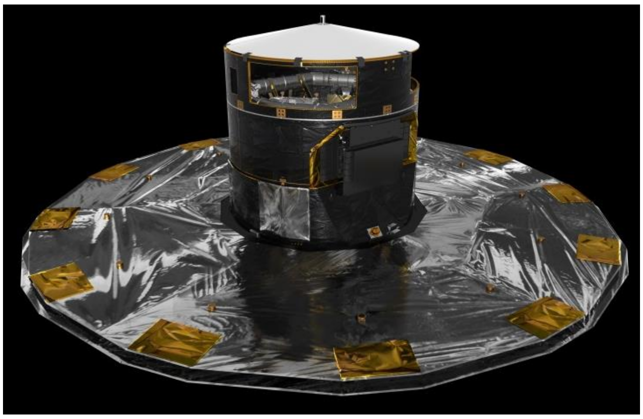

Figure 1: Artists impression of the Gaia satellite (credits: ESA)

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The astronomical measurements performed with Gaia will be accurate to 24 microarcsec, about 100 times more accurate than its predecessor Hipparcos launched in 1989, comparable to measuring the diameter of a human hair at a distance of 1000 kilometres. To achieve this extreme accuracy at a minimum operational temperature of 100K, the entire Gaia Payload Module is made out of Silicon Carbide (SiC); the first time ever in space history.

1.2 Gaia Payload Module

Figure 2 shows the Gaia Payload Module (PLM) consisting of two telescopes with a focal length of 35 m that re-image the stars on a common focal plane by means of a beam combiner. The two large telescope mirrors (1.45 m x 0.5 m) are fixed on the torus at a mutual angle of 106.5°, named the 'Basic Angle'. The payload structure and mirrors are made entirely out of Silicon Carbide (SiC), for reasons of dimensional stability. Although the payload itself is designed to be a-thermal, gradient fluctuations within the payload can still cause remaining small Line Of Sight (LOS) fluctuations of maximum 7 micro-arcsec. Without compensating for these small LOS fluctuations, the targeted accuracy of Gaia will not be met. Therefore Gaia is equipped with a metrology system that monitors the Basic Angle and enables the correction of the fluctuations by calculation: the Basic Angle Monitoring (BAM) system.

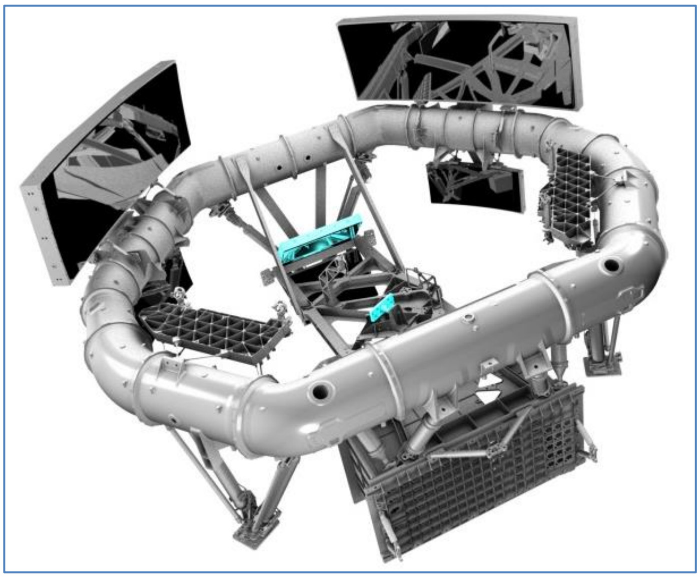


Figure 2: The Gaia Payload Module (PLM) with the two large telescope mirrors on top (credits: ESA)

1.3 The Basic Angle Monitoring (BAM) system

The BAM measures the Basic Angle in flight with an accuracy of about 0.5 micro-arc second rms at 5 minutes intervals of scientific operation. Considering a telescope base length of 0.6 m, this variation corresponds to an optical path difference (OPD) of 1.5 pico-meter rms.

The BAM principle, shown in Figure 3, is based on the measurement of the relative position of two interferometric patterns, each one being generated from a common laser diode source. The common beam is split by optics into two pairs that are sent towards the two M1 telescopes Astro 1 and Astro 2 via two 'bars' (BAM OMA 1 and BAM OMA 2) positioned opposite the M1 mirrors. Both beam pairs are projected on the same CCD in the focal plane of the telescope mirrors, resulting in two interference patterns on the BAM CCD. Rotation of a telescope mirror induces differential fringe motion providing information about the differential variation of the line-of-sight of each telescope and hence basic angle variations. For purposes of reliability, the BAM system is redundant resulting in a nominal (N) and redundant (R) laser diode source, light path and CCD, projecting two fringe patterns on each CCD.

The BAM bars are open-structured base plates (see Figure 4) supporting optics to create and direct the optical beams. The base plates, periscopes, folding mirrors, and collimator optics are all made of Sintered Silicon Carbide (SSiC). Some components are necessarily made of glass; these are the transmission optics such as the beam splitters, attenuator filters and polarizers. Each bar is mounted via INVAR iso-static mounts on the Gaia payload main SSiC structure (torus).

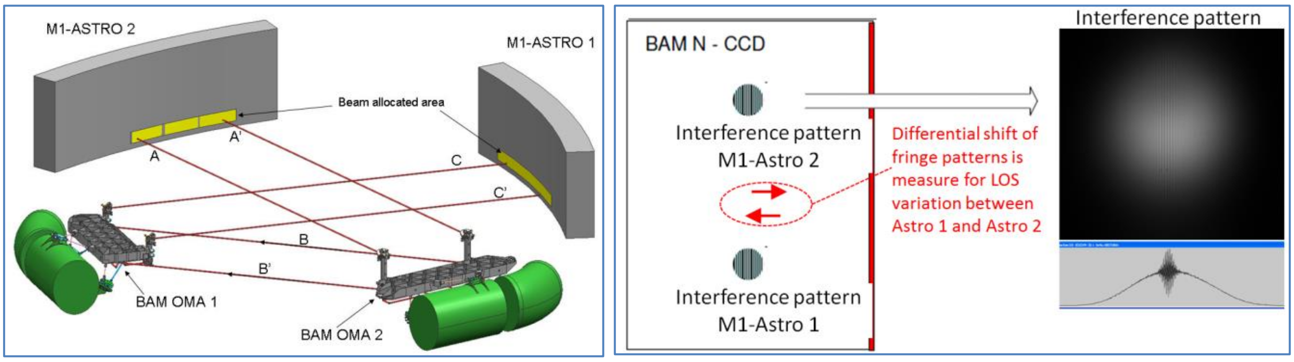


Figure 3: Schematic of Basic Angle Monitoring system with optical beams (left) and principle of fringe patterns on CCD (right).

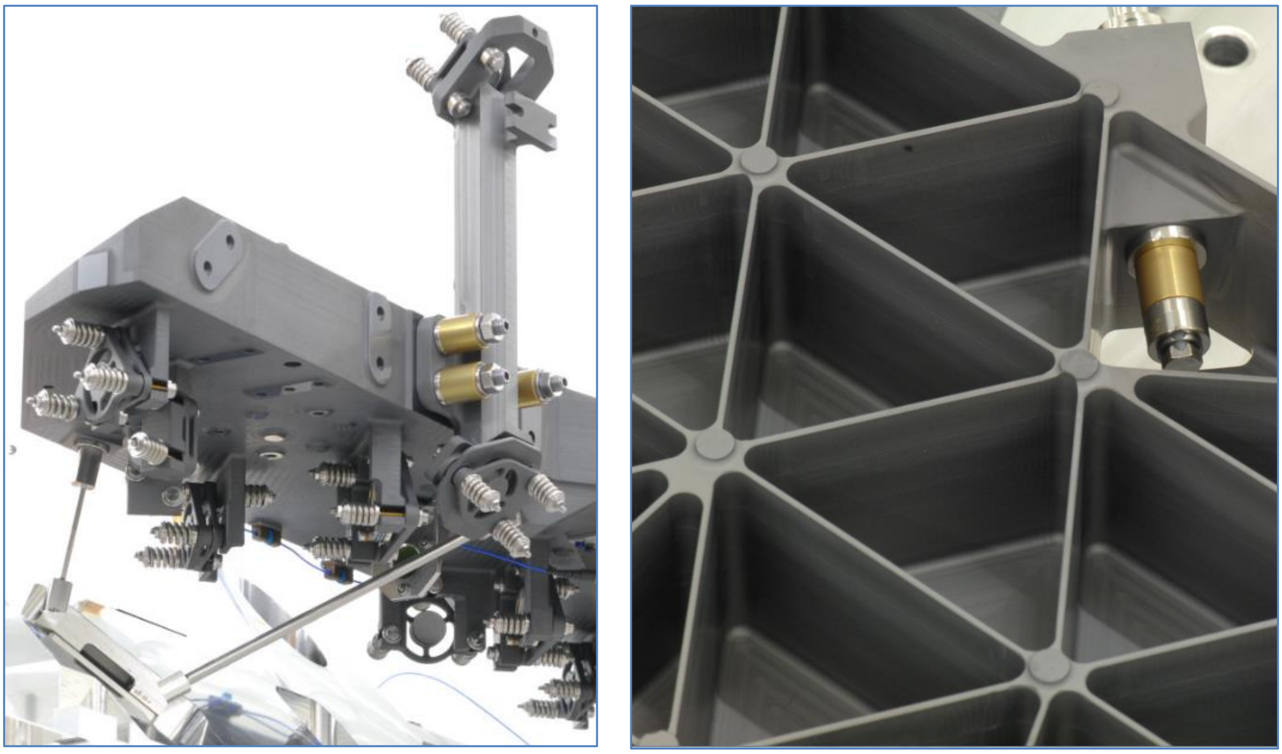


Figure 4: Details of SSiC BAM bar 2 with optics, periscope and Invar iso-static mount (left) and open backside structure of SSiC baseplate (right). Credits: TNO/Fred Kamphues

1.4 Sintered Silicon Carbide (SSiC)

To achieve the level of high accuracy and extreme stability at cryogenic temperatures, required for the Gaia mission, the use of exotic materials like Sintered Silicon Carbide (SSiC) or Beryllium has some major benefits (see Figure 5). Unlike Beryllium, SSiC has no toxicity issues during manufacturing and machining and is therefore preferred. The SSiC material used for the Gaia mission was supplied by Boostec, nowadays part of the Mersen group.

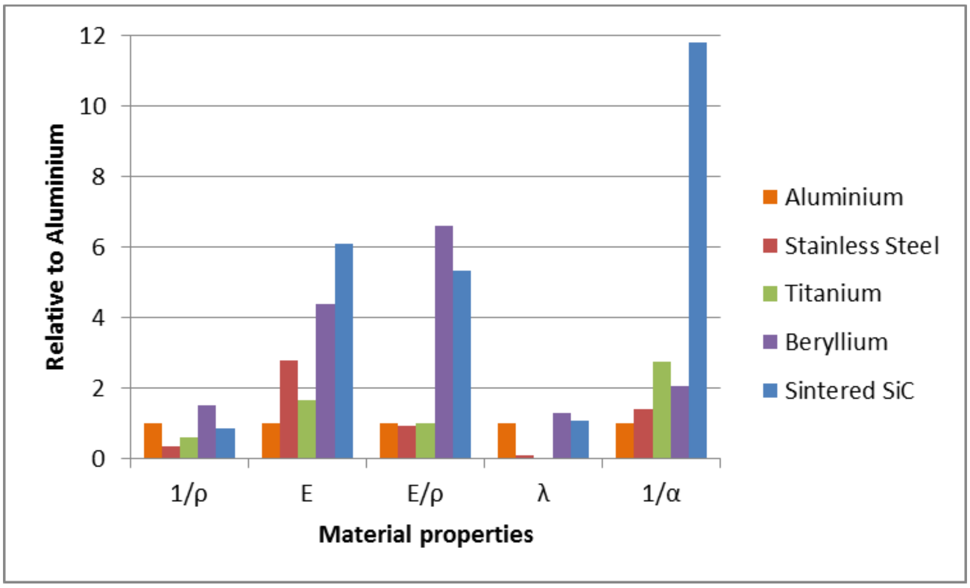
SSiC is a relative lightweight material (ρ = 3160 kg/m^3) with a high stiffness (E = 420 GPa) resulting in a very high specific stiffness (E/ρ = 135 x 10^6 Nm/kg), about 5 times the value of the usual materials used in space: Aluminum, Titanium and Steel. As a result, structures of SSiC can be made 5 times lighter to achieve the same stiffness. This is an important criterion for applications where every kilogram is expensive (due to launch costs).

Another advantage, especially of interest to Gaia, is the dimensional stability of SSiC due to the combination of:

- low thermal expansion ($\alpha = 2 \cdot 10\text{-}6$ /K); this results in low deformation due to temperature changes
- a relative high thermal conductivity ($\lambda = 180$ W/m/K); low thermal gradient distribution
- a high degree of isotropy; homogeneous in all directions.

Moreover SSiC is a chemically stable material and can be polished to optical qualities which makes it a suitable material for manufacturing mirrors.

Figure 5: Characteristic properties of SSiC, Beryllium and some other materials commonly used in space relative to Aluminium. The benefits of Beryllium and SSiC on weight and (specific) stiffness are evident. On low CTE, SSIC is far out the big winner.



Obviously, the use of SSiC for manufacturing complex opto-mechanical instruments also has some drawbacks. The material in its final state (after sintering) is highly brittle and extremely hard. This significantly limits the opportunity for machining the material; the available methods are expensive and time consuming (and most of the time still experimental). Handling and applying SSiC parts requires special attention to prevent fracture due to mechanical impacts or stress concentrations.

The properties of SSiC have a major impact on its application both in design solutions, manufacturing, handling and operation.

2. GAIA BAM PERFORMANCE REQUIREMENTS

The main performance requirements of the BAM system are derived from the following functional needs:

- The BAM shall generate two beam sets that, through reflection by the Gaia telescope system, shall be projected in the focal plane of the BAM CCD; this applies for both telescopes ASTRO-1 and ASTRO-2 and for both the nominal light source/path and the redundant light source/path.
- The beams of each set shall have sufficient overlap in order to create a fringe pattern with sufficient resolution; the white light fringe (or zero path difference fringe) shall be included in each fringe pattern
- The fringe patterns created by the beams shall have sufficient contrast

Table 1 gives an overview of the resulting opto-mechanical requirements applicable at BAM subsystem level; it also shows the performance results achieved at the completion of the full verification and space qualification testing campaign.

Table 1: Main performance requirements derived for the BAM system. The final (worst case) results achieved after verification and qualification testing are also presented; non-compliant values (red) are accepted at system level by waiver.

BAM system performance requirements and results:		
Requirement	**Required value**	**Achieved result**
Baseline angle *(angle between beam sets A/A' – C/C')*	106,5° ± 50 µrad	A/A'- C/C': 106,5° ± 23 µrad
Base length (difference) *(distance between A and A' & C and C')*	600 ± 60 mm; Δ between beam sets A and C: ± 1mm	A-A': 540.0 mm C-C': 540.7 mm
Beam pointing *(deviation from nominal angle)*	<100 µrad	**A/A': 120 µrad** **C/C': 110 µrad**
Differential beam tilt *(angle between A and A' or C and C')*	<50 µrad	A-A': 38 µrad C-C': 42 µrad
OPD *(path diff. between A and A' or C and C')*	<8.5 µm	A-A': 8.2 µm C-C': 4.4 µm
WFE *(wave front quality of beams)*	25 nm rms	Beam set A: 24 nm rms Beam set C: 20 nm rms
Transmission *(optical throughput of beams)*	>0.15	Beam set A: 0.182 – 0.215 **Beam set C: 0.073 – 0.132**

Note that the BAM performance need to be achieved after alignment and remain within allowable positive margins after qualification testing and unit delivery, storage, satellite integration and transport, launch (vibration), PLM bi-pod release (shock) and at L2 conditions (zero g, vacuum, 120K, radiation) for a minimum in-orbit lifetime of 5,5 years. In combination with other requirements and budget limitations that need to be satisfied such as mass, envelope and thermal behaviour it will be obvious that the design, development and realization of the BAM system is more than challenging.

3. GAIA BAM CRYOGENIC DESIGN AND DEVELOPMENT CHALLENGES

Designing a complex cryogenic opto-mechanical space interferometer that is mainly built of Silicon Carbide requires an entirely different approach than what is custom for e.g. Aluminum instruments.

One of the specific features to be taken into account, particularly for the SSiC type of silicon carbide, is the shrinkage in the order of 16% that occurs after the sintering at high temperature. Normally, the machining of SiC products is performed in the so-called green phase, prior to sintering. In case the manufacturing drawings are properly scaled to guarantee that the final product after sintering has the correct dimensions, this 16% shrinkage is not of special concern. However, the variation in shrinking between separate sintering batches can amount up to 0.4%. This can be a major concern in a case as for Gaia BAM, where the larger structures like baseplates cannot be manufactured in the same sintering batch and where interchange-ability of spare baseplates from different batches needs to be guaranteed. On a length of a BAM baseplate of typical 1 m, a variation of 0.4% results in a potential difference of 4 mm; for a system where a maximum base length difference between beam sets A and C of 1 mm is required and that needs to be aligned at micro-meter level this is unacceptable and necessitates additional tuning opportunities. More tuning requires more optical components and as a result higher mass, lower opto-mechanical budgets (tilt stability, WFE, roughness, optical throughput) for each single component and more complex and expensive alignment of the complete system.

Ultra-stable mounting of optical components is required to achieve the severe beam pointing, beam tilt, OPD and WFE requirements shown in Table 1, both after vibration loads and over a wide temperature range from ambient down to 100K. The worst case number of optical surfaces that are passed by one of the BAM beams amounts up to 18, each surface adding to the total beam tilt and wave front error.

Reflection of the beams is accomplished by flat SSiC mirrors, polished down to <2 nm rms WFE, coated with protective Silver and mechanically spring-mounted to monolithic brackets on the SSiC baseplate. Due to the SSiC-SSiC interface with the BAM structure these mirrors are intrinsic less sensitive to temperature changes and the required tilt stability of less than 2 micro-rad is mainly influenced by mechanical vibration and shock loads during launch and PLM bi-pod release.

Splitting of the collimated beam, originated from a common laser diode light source, is achieved by means of reflecting/transmitting beam splitters. In total three beam splitters are used in the BAM system to generate two beam sets (A-A' and B-B') both nominal and redundant. As beams need to be transmitted, these beam splitters are necessarily made of glass. Fused Silica is selected to match the low CTE of SSIC. Having the same tilt stability requirement of 2 micro-rad, another design approach needed to be developed as the glass-SSiC interface is not only susceptible to mechanical loads but also to temperature changes.

For both the SSiC mirror and Fused Silica beam splitter mounting configurations, extensive technology development test campaigns at component level have been performed in the early design phase to arrive at the final design solution (see Figure 6). With these test campaigns, including several design iterations, finally tilt stabilities in the required range of 2 micro-rad were demonstrated. Emphasizing the cryogenic application of BAM, especially the design of the glass Beam Splitter experienced a significant number of evolutions. Early design solutions did result in unacceptable form (WFE) and tilt deviation during cool down to 100K as the initial concept of adhesive bonding, selected for lateral fixation, lead to unpredictable stresses and subsequent deformation. To solve this problem, a split-up of function between lateral fixation at room temperature (launch) and stress free mounting at cryogenic (performance at L2) has been implemented. In the final design the adhesive interface was substituted by a thermal compensation mechanism of thermoplastic PEEK having low out-gassing properties and a relative high CTE value compared to the SSIC mounting interface.

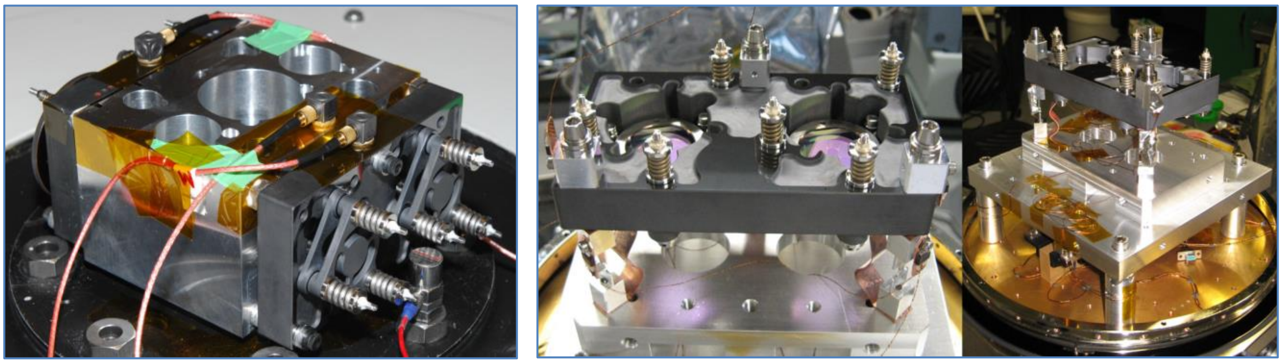


Figure 6: Test specimen for component level testing of stable mounting. Vibration testing of SSiC mirrors (left) and cryogenic testing of Fused Silica beam splitters (right). Credits: TNO/Fred Kamphues

Another extensive technology development program was allocated to the fibre collimator because at start of the Gaia BAM program, cryogenic stable fibre collimators did not exist at all.

With the main challenge to stay within the budgeted requirements of WFE and beam pointing stability allocated to the fibre collimator, both under mechanical vibration loads and a wide thermal range of 190K, the development was dominated by two components:

- The stable interface between the customer supplied laser source, a space qualified polarization maintaining fibre with standard AVIM connector, and the SSiC bar structure of the BAM system. The development is mainly driven by the cool-down from ambient to 100 K (ΔT of 190K) that needs to be taken into account for the different coefficients of thermal expansion of materials applied (ZrO_2 fibre ferrule, Titanium fibre tip, Steel connector body, SSiC BAM structure); in the final design configuration, applying an Invar bracket interfacing with the SSiC structure and a special designed thermally compensating Titanium ferrule clamp in between the Zirconium ferrule and Invar bracket, stabilities of less than 750 nm axial and 250 nm radial were established by design (where <2 µm axial and <1 µm radial were required). Environmental testing at BAM-level (and later on Gaia Payload Module level) demonstrated the high stability of the fiber collimator.

- A strongly curved off-axis parabolic SSiC mirror to make a perfect collimated beam from the diverging light emitted by the fibre light source. The main difficulty of this collimator mirror, beside that it is made of silicon carbide, is it small radius of curvature (R = 50.17 mm) over an effective aperture of only 10 mm, maintaining a surface shape error of ≤12.5 nm rms and a surface roughness of Rq ≤6 nm. With this unique combination of requirements, worldwide no suppliers could be found that could guarantee the delivery of such a state-of-the-art component in time. In close cooperation with the Leibniz Institute of Surface Modification (IOM), a manufacturing process of iterative robot machine polishing and Plasma Jet Machining was developed by TNO in-house, which resulted in the realization of flight mirrors with a surface error in the range of 4.4 – 7.2 nm rms and surface roughness better than 6 nm rms.

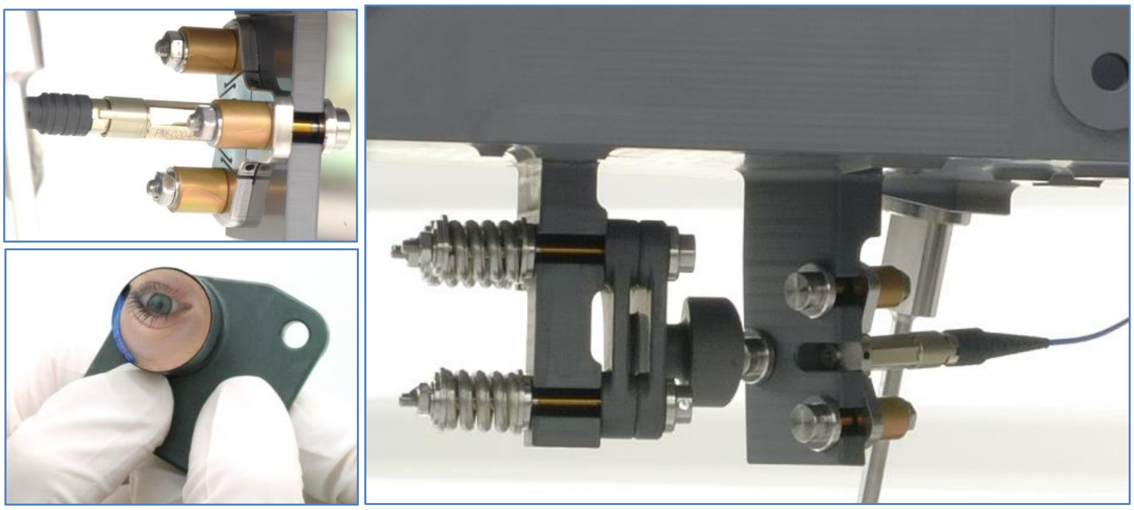


Figure 7: The cryogenic fiber collimator (right; Credits: TNO/Fred Kamphues) with the two dominating parts: fiber connector interface to SSiC BAM structure (upper left; Credits: TNO/Fred Kamphues) and the strongly curved off-axis parabolic SSiC mirror (lower left; Credits: TNO/Leo Ploeg).

Other constraints that are involved with the design and implementation of the SSiC opto-mechanical BAM system although less relevant to the cryogenic application are the stiffness of SSiC-SSiC interfaces (lower allowance tolerances for spread in pre-loads), the required manufacturing flatness of SSiC interface surfaces (fracture sensitivity), the behaviour of other materials in contact with SSiC, the friction behaviour specific to SSiC surfaces and the impact of the porosity of SSiC, if not CVD coated, on optical properties (reflection and stray light of SSiC mirrors).

4. GAIA BAM REALIZATION AND INTEGRATION

Based on the design definition of TNO, manufacturing of the SSiC parts for Gaia BAM, as for all Gaia SSiC part, has been performed by Boostec (nowadays Mersen) under control of Astrium. The most complex parts to be manufactured were the periscopes and the monolithic 1 meter length baseplates with all brackets for optical components included and the open backside structure (see Figure 4 right). For the design of the baseplates the main constraint was with the location and direction of mirror and beam splitter brackets such that all contact surfaces can be grinded to achieve the minimum needed flatness (5 µm). Sufficient flat and reflective reference surfaces for alignment purposes were polished by TNO directly on the baseplates after delivery.

The SSiC mirrors were delivered as semi-finished blanks; polishing to high-quality optical components was developed and completed by TNO in-house (see Figure 8 left), using conventional diamond paste polishing for the flat folding mirrors and the iterative process of robot polishing by TNO and Plasma Jet Machining of IOM for the off-axis parabolic collimator mirrors. Tuning of the thickness and tilt angle of alignment shims is executed as part of the alignment process.

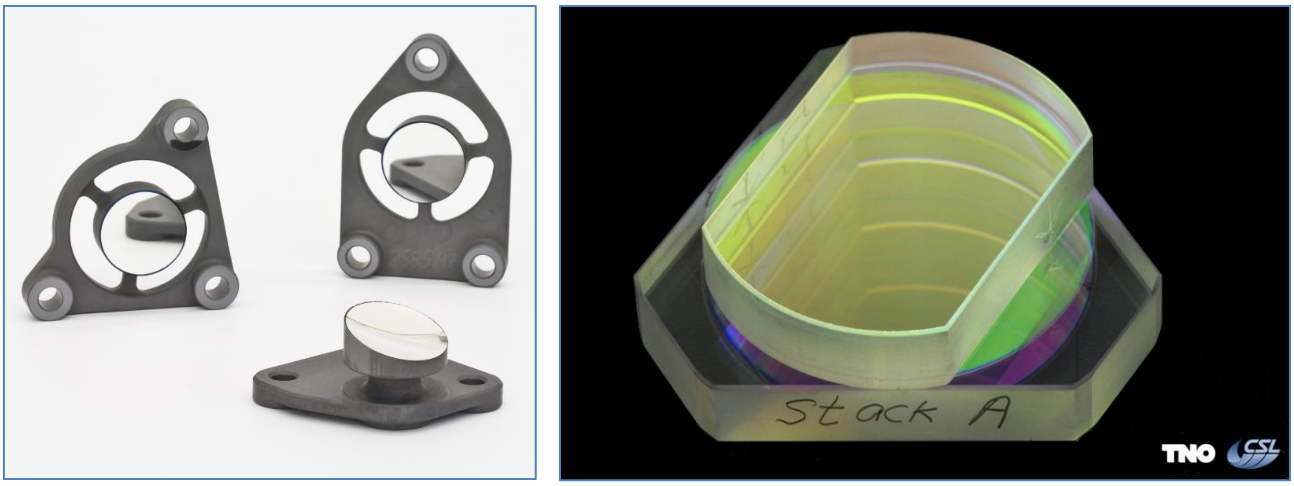


Figure 8: Polished and coated SSiC flat folding and off-axis parabolic mirrors (left; Credits: TNO/Leo Ploeg) and optical contacted fused silica beam splitter (right; Credits: TNO/Fred Kamphues)

For the glass beam splitters (Figure 8 right), also manufactured by TNO in-house, optical contacting of Fused Silica plates with a beam splitter coating in between is applied. The attenuator filters and polarizers are commercially procured.

All optical coatings were designed, qualified and manufactured by Centre Spatial de Liège (CSL): protected Silver on SSiC mirrors, filter coating on beam splitters and AR coatings on beam splitters and polarizers.

Integration of all parts, SSIC and non-SSiC, to a working BAM system has been a complex and delicate task involving specially developed tools and operations by specially trained workforces. Apart from working in ISO class 6 cleanroom environments and applying all rules and procedures custom for building space hardware, the specifically fragile properties of SSiC dictate the pace and sequence of steps. The amount of pre-load applied on bolted interfaces is one of the issues of concern; due to the mechanical surface properties of SSiC and to maintain the required alignment stability of the BAM, the allowable spread in pre-load is limited to prevent gapping on one hand and fracture due to highs stresses on the other hand. For each unique fastener interface therefore the torque-preload ratio needed to be calibrated.

Figure 9: Gaia BAM periscope bolt installation with PMTS (left) and Titanium fasteners equipped with PMTS structure (right). Credits: TNO/Fred Kamphues

For the large fasteners, e.g. the Titanium M8 bolts used to mount the SSiC periscopes to the SSiC baseplates with high pre-load, even this calibration was not considered safe enough. To enable in-situ preload measurement, special ultrasonic transducers have been used, the so-called Permanent Mounted Transducer System (PMTS) developed by Intellifast GmbH (see Figure 9). With these transducers and the proper procedure, a repeatable accuracy of better than +/- 3% pre-load, independent of the operator skill has been demonstrated by TNO before application. This demonstration also included a thermal cycling qualification test of unloaded and pre-loaded fasteners (5 cycles in gN_2 between 400K and 100K, $\Delta T \leq 25K/min$).

Following positioning and alignment of the BAM bars with the Iso-static Mounts to the defined interface with the Gaia PLM torus, by far the major task during integration of the BAM system was allocated to optical fine alignment of the collimators and flat folding mirrors by tuning of shims. Methods, tools and procedures for measurement and alignment to the required values have been developed making optimum use of the current state-of-the-art accuracies for optical test equipment and dedicated set-ups. A special SSiC flat reference mirror with very accurate polished reference surfaces (specified for surface form, flatness and parallelism) at the base length difference of 540 mm was procured to facilitate accurate alignment. Especially in the final stage, to arrive at the required low values for beam pointing, differential beam tilt and OPD for each of the beam sets A-A' and C-C' (see Table 1), new techniques, procedures and tooling for iterative polishing and measurement of alignment shims needed to be developed. Various measurement methods involving interferometry and the TNO in-house developed NANOMEFOS non-contact measurement machine for freeform optics were applied (Figure 10 left). In the final stage of the program, a large 700 mm collimator (the COL70), kindly provided on loan by EADS Astrium, was used to arrive at the required accuracy level for final OPD verification (Figure 10 right).

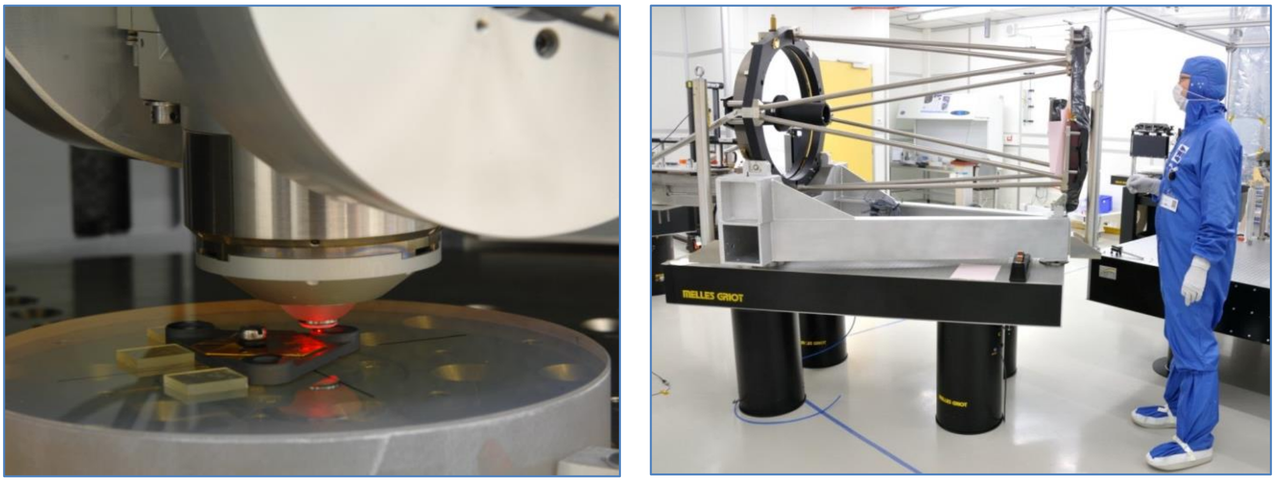


Figure 10: Non-contact measurement of SSiC alignment shim on TNO NANOMEFOS (left) and the Astrium COL70 collimator used for final OPD verification (right). Credits: TNO/Fred Kamphues

5. GAIA BAM VERIFICATION & QUALIFICATION TESTING

After completion of integration and alignment and prior to environmental qualification testing, the performance of the BAM system has been verified by a set of measurements at ambient conditions. The alignment parameters such as baseline angle, base length difference, beam pointing, differential beam tilt and OPD were already included in the final alignment verification. Additionally the WFE, transmission and polarization (extinction ratio) were determined. All requirements were fulfilled except for transmission of beam set C-C', the channel with the most optical surfaces in the light path, but this out-of-spec performance could be waivered at PLM system level without loss of performance.

Next step in the verification program was to demonstrate, through an environmental qualification test campaign, that the BAM system survives and still meets all performance requirements after exposure to vibration (launch) and after transient to low temperature (L2 conditions).

Vibration testing of the BAM system was performed at an external facility of CSL Belgium (see Figure 11); both BAM bars 1 and 2 were individually subjected to pre-defined sine and random vibration spectra derived from Soyuz launch loads. Before testing the BAM PFM, a mechanically representative Structural Model (SM) of BAM bar 1 was tested to demonstrate that models and prediction were within acceptable range, to exclude any risk of damage during the flight model testing. Testing is performed in each of the three perpendicular axes X, Y and Z; notching of the input spectra, where needed, was agreed prior to test and iteratively tuned with customer Astrium along the test. Following the vibration test campaign, the key performance parameters (pointing and beam tilt alignment stability and OPD) were measured again at TNO, providing evidence that the alignment did not change more than the predicted settling effects and that the performance requirements are still met.

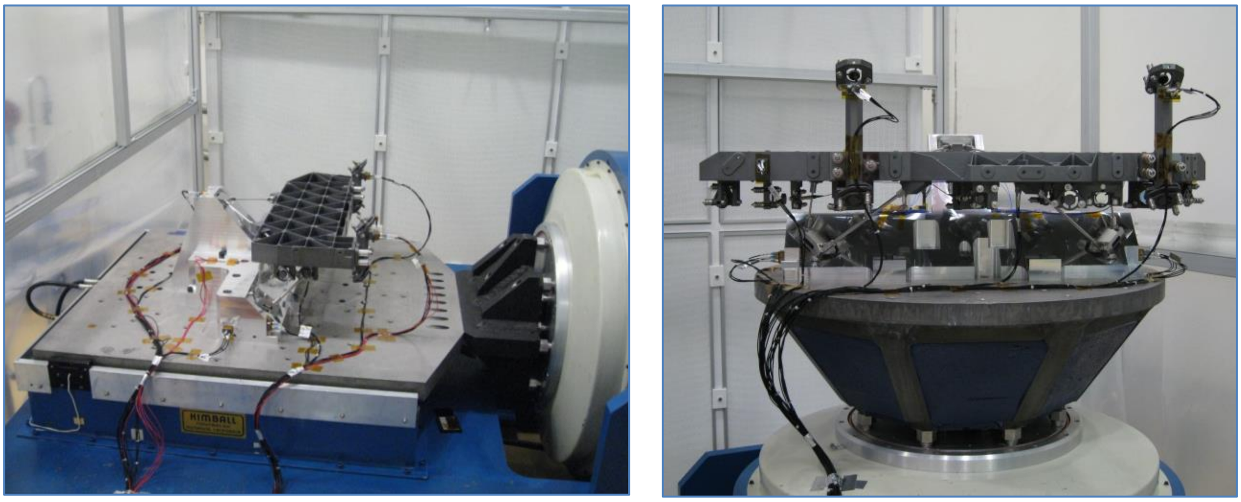


Figure 11: Vibration testing at CSL (cleanliness protective foil temporarily removed). SM bar 1 Z-axis vibration on slip table (left) and PFM bar 2 X-axis vibration on head expander (right). Credits: TNO/Jeroen Mekking)

Thermal cycling of the BAM PFM bars was performed in the VCF Thermal Vacuum chamber of TNO (Figure 12, right); 4 thermal cycles, covering a temperature range from 323K to 100K, have been applied of which 1 cycle down to the minimum qualification temperature of 93K. Performance measurements of the BAM system at operational conditions were accomplished at a temperature of 110K.

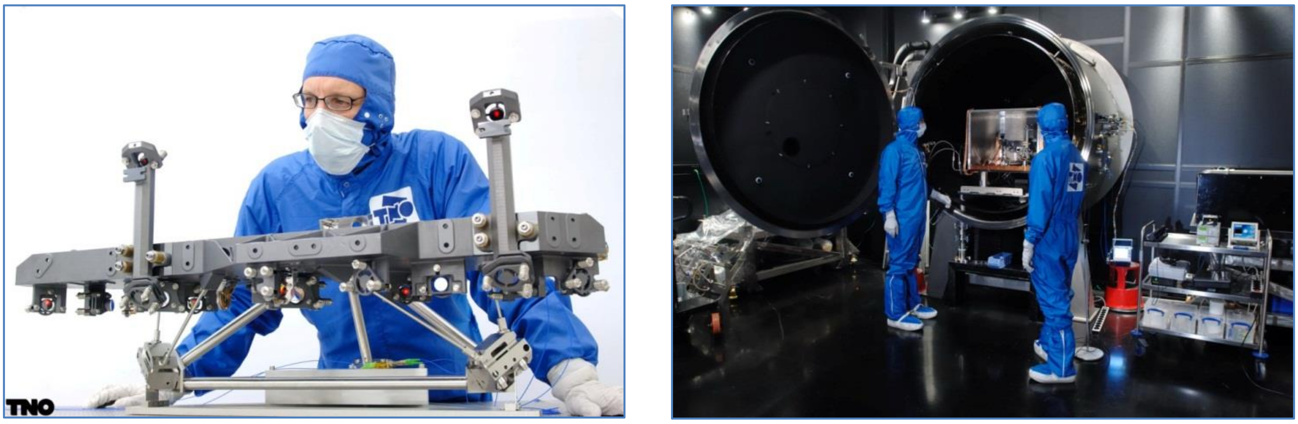


Figure 12: Thermal testing of BAM PFM: bar 2 on Invar set-up (left) and BAM in TNO VCF Thermal Vacuum chamber (right). Credits: TNO/Fred Kamphues

A dedicated thermal-mechanical balanced set-up of Invar (Figure 12, left) was developed and applied to achieve the necessary stability for the interface between the test chamber and the SSiC BAM structure and to secure the required stability for accurate alignment performance verification. Despite this set-up and all other precautions, serious difficulties were encountered in the stability of measuring the beam pointing performance. Initially this instability could not be solved within the program constraints of the BAM verification campaign. A separate failure investigation was performed to close-out that deformation of the Gaia BAM due to thermal effects is the root cause. For demonstrating the impact of the Invar set-up, an additional stand-alone cryogenic testing and measuring sequence of this set-up was defined and executed (see Figure 13). During cooling down in vacuum from ambient to 140K, the orientation of the surfaces at 7 different locations of interest of the Invar structure was monitored by means of special thermally de-coupled adjustable test mirrors installed on the set-up (Figure 13 left). This test was successful in that it showed deformations in the order of magnitude and in the same tilt direction as experienced during cryogenic testing of Gaia BAM. With the outcome, the findings of the Gaia BAM beam pointing at cryogenic could be corrected for.

The slightly out-of-spec beam pointing values shown in Table 1 with achieved BAM system performance results present the worst case situation at 110K including the linearly added uncertainties caused by the experienced testing constraint.

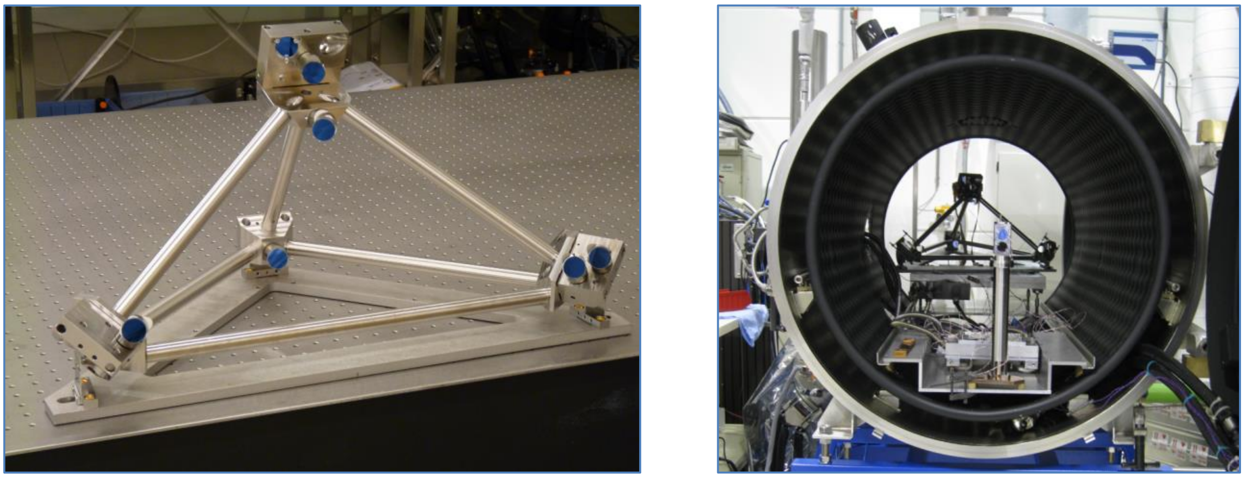


Figure 13: Stand-alone cryogenic test on Invar set-up: Left: Invar set-up with thermally de-coupled adjustable mirrors (7x). Right: Set-up in Thermal Vacuum chamber (right). Credits: TNO/Teun van den Dool.

The final BAM system performance results achieved at the completion of the entire verification and space qualification testing campaign are presented in Table 1. The values shown include the performance at operational temperature (measured at 110 K) and shows the worst case combination of individual test data and measurement uncertainties. For beam pointing and transmission of beam set C-C', the non-compliances have been waivered at Gaia system level.

Concluding verification of the mechanical and cryogenic stability of Gaia BAM system was performed during environmental testing by EADS Astrium SAS at Gaia PLM level (see Figure 14), positively confirming the excellent performance of BAM in accordance with the TNO test results.

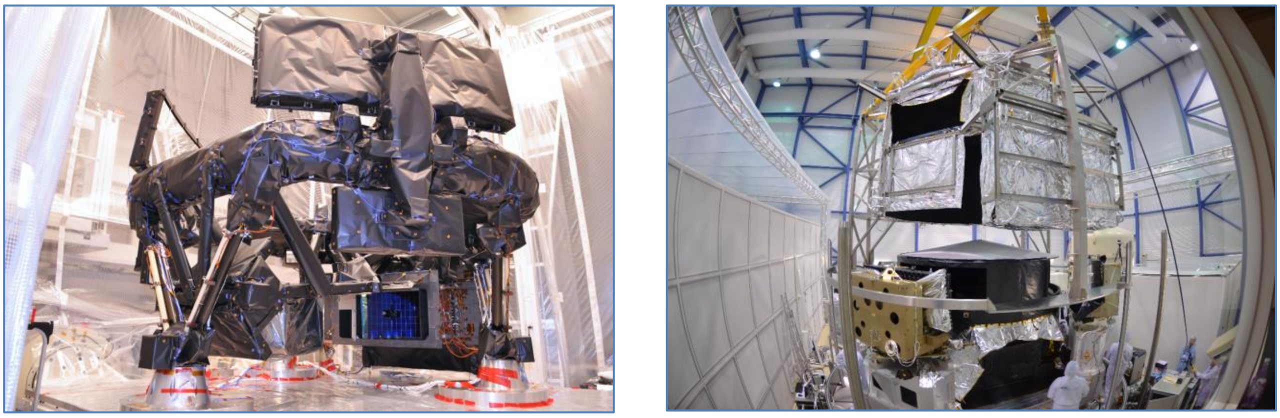


Figure 14: Gaia Payload Module testing by EADS Astrium SAS: Left: PLM on the shaker for vibration testing at Intespace in Toulouse, France. Right: PLM installation in the TV chamber at CSL Liege, Belgium. Credits: EADS Astrium SAS[5].

REFERENCES

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