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GAIA Basic Angle Monitoring system

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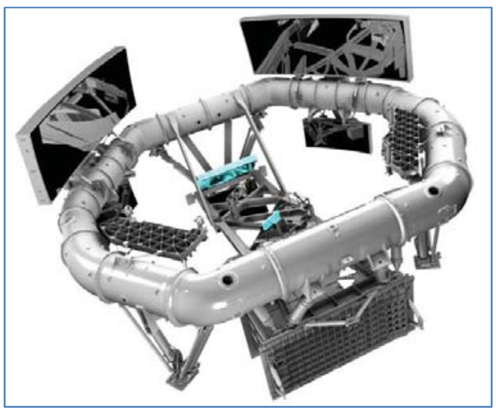
1. INTRODUCTION

1.1 GAIA mission

GAIA[1] is a global space astrometry mission, successor to the Hipparcos mission, launched in 1989. The GAIA spacecraft is being built by EADS Astrium France and is scheduled for launch in 2013. At a distance of 1.5 million km from Earth at Lagrangian point L2, slowly spinning around its axis, GAIA will monitor each target star about 100 times over a 5-year period, precisely measuring its distance, movement, and change in brightness. Through spectrophotometric classification, it will provide the detailed physical properties of each star observed: luminosity, temperature, gravity, and elemental composition. This massive stellar census will provide the basic data to tackle an enormous range of important questions related to the origin, structure, and evolutionary history of our Galaxy. The measurements performed with GAIA will be accurate to 24 microarcsec, about 100 times more accurate than Hipparcos. To achieve this extreme accuracy at an operational temperature of 100 K, the entire GAIA Payload is made out of Silicon Carbide (SiC).

1.2 GAIA Payload Module

Figure 1 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 M1 telescope mirrors (1.45 m x 0.5 m) are fixed on the torus at an angle of 106.5°, the 'Basic Angle'. By design, the overall payload is a-thermal. Remaining small Line Of Sight (LOS) fluctuations of maximum 7 micro-arcsec result only from thermal gradient fluctuations within the payload. For dealing with these small LOS fluctuations GAIA is equipped with a metrology system that monitors the 'Basic Angle' continuously and enables correction by calculation: the Basic Angle Monitoring (BAM) system.



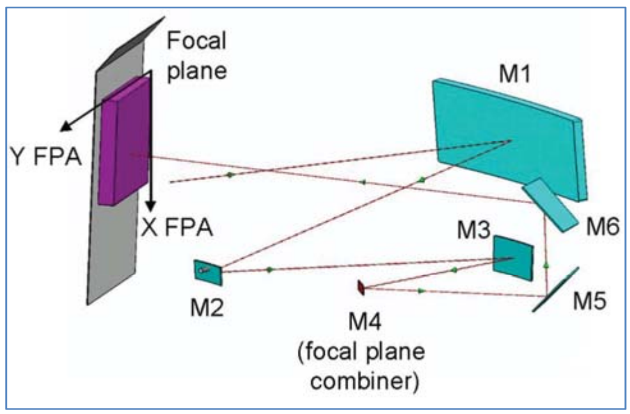


Figure 1: The GAIA Payload Module (PLM) with the two large M1 telescope mirrors on top (left; credits: ESA) and a schematic of the optical configuration

1.3 The Basic Angle Monitoring (BAM) system

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 2, 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 telescopes Astro 1 and Astro 2 via two 'bars' positioned opposite the M1 mirrors. Both beam pairs are projected on the same CCD in the focal plane of the telescope mirrors. This results into two interference patterns on the BAM CCD. Rotation of a telescope mirror induces differential fringe motion, which provides information about the differential variation of the line-of-sight of each telescope. Two CCD detectors in the focal plane, a nominal (N) and a redundant (R) CCD, are dedicated to the BAM function. Each of the two BAM CCD's receives the two fringe patterns generated by the corresponding laser source through the two bars.

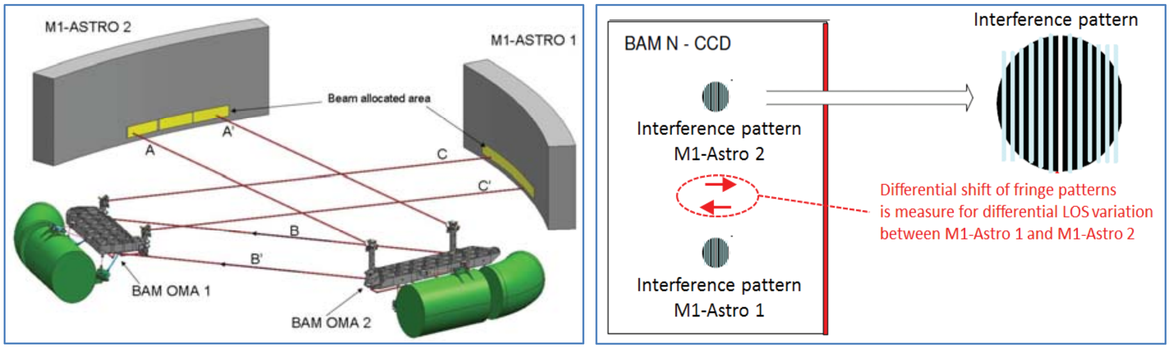


Figure 2: Schematic of Basic Angle Monitoring system with optical beams (left) and principle of fringe patterns on CCD (right).

The BAM bars (BAM OMA 1 and BAM OMA 2) are open-structured base plates supporting optics to create and direct the optical beams (see Figure 3). The light source entrance fibres, collimating optics, filters and beam splitters are only present on BAM OMA 2. The base plates, periscopes, folding mirrors, and collimator optics are all made of SiC. Some components (transmission optics) are necessarily made of glass; these are the beam splitters (fused silica), attenuator filters (BG40) and polarizers (polarcor^{TM}). Each bar is mounted via INVAR iso-static mounts on the GAIA payload main SiC structure (torus).

Figure 3: Details of SiC BAM OMA bar 2 with optics, periscope and Invar iso-static mount (left) and open backside structure of SiC baseplate (right).

1.4 Silicon Carbide (SiC)

The SiC material used for the GAIA mission was supplied by Boostec, France. SiC is a relatively lightweight material ($\rho = 3160$ kg/m^3) with a high stiffness (E = 420 GPa) resulting into 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 SiC can be made 5 times lighter to achieve the same stiffness.

Another advantage is the dimensional stability of SiC due to the combination of low thermal expansion ($\alpha = 2 \cdot 10\text{-}6$ /K; low deformation), a relative high thermal conductivity ($\lambda = 180$ W/m/K; low thermal gradients) and a high degree of isotropy (homogeneous in all directions).

Moreover SiC is a chemically stable material and can be polished to optical qualities which makes it a suitable material for manufacturing mirrors. The main drawback of the material is that in its final state (after sintering) it is highly brittle and extremely hard.

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.
- The beams of each set shall have sufficient overlap in order to create a fringe pattern with sufficient resolution.
- The fringe patterns created by the beams shall have sufficient contrast.

The following table gives an overview of the resulting and realised opto-mechanical requirements applicable at BAM subsystem level. These requirements need to be achieved for a minimum in-orbit lifetime of 5.5 years.

Main performance requirements for the BAM system (beam details in Figure 2)

Baseline angle (= angle beam sets A – C):	106.5° ± 50 µrad
Base length difference (= distance A – A' and C – C'):	600 ± 60 mm; ± 1 mm between beam sets A and C
Beam pointing (deviation from nominal angle):	< 100 µrad
Differential beam tilt (angle between A and A' or C and C'):	< 50 µrad
OPD (path diff. between A and A' or C and C'):	< 8.5 µm
WFE (wave front quality of beams):	25 nm rms
Transmission (optical throughput of beams):	> 0.15%

3. GAIA BAM DESIGN AND CHALLENGES

Ultra-stable mounting of optical components is required to achieve the severe beam pointing, beam tilt, OPD and WFE requirements, both after vibration loads and over the temperature range of more than 190 K. The optical surfaces that are passed by one of the BAM beams amounts up to 18, each surface adding to the total beam tilt and wavefront error.

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

For the transmissive beam splitters, made of Fused Silica and having the same tilt stability requirement of 2 micro-rad, a specific design approach needed to be developed as the glass-SiC interface is susceptible not only to mechanical loads but also to temperature changes. In the final design solution, a thermal compensation mechanism using PEEK and no adhesive interface is used.

For both the SiC mirror and Fused Silica beam splitter mounting configurations, extensive technology development has been performed in the early design phase to arrive at the final design solution tilt stabilities in the required range of 2 micro-rad.

Another significant technology development program was allocated to the fibre collimator, not available at the start of the GAIA BAM program.

The collimator development was dominated by two components:

- *Stable interface between the customer supplied laser source and the SiC BAM.* The development is mainly driven by the cool-down from ambient to 100 K together with the different coefficients of thermal expansion of materials applied (ZrO2 fibre ferrule, Titanium fibre tip, Steel connector body, SiC BAM); in the final design stabilities of less than 750 nm axial and 250 nm radial were achieved (where < 2 µm axial and < 1 µm radial were required).
- *Strongly curved off-axis parabolic SiC mirror to make a perfect collimated beam from the diverging light emitted by the fibre light source.* A main difficulty is its 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 between TNO and the Leibniz Institute of Surface Modification (IOM), a manufacturing process of iterative robot machine polishing and Plasma Jet Machining was developed, which resulted in a surface error in the range of 4.4 – 7.2 nm rms and surface roughness better than 6 nm rms.

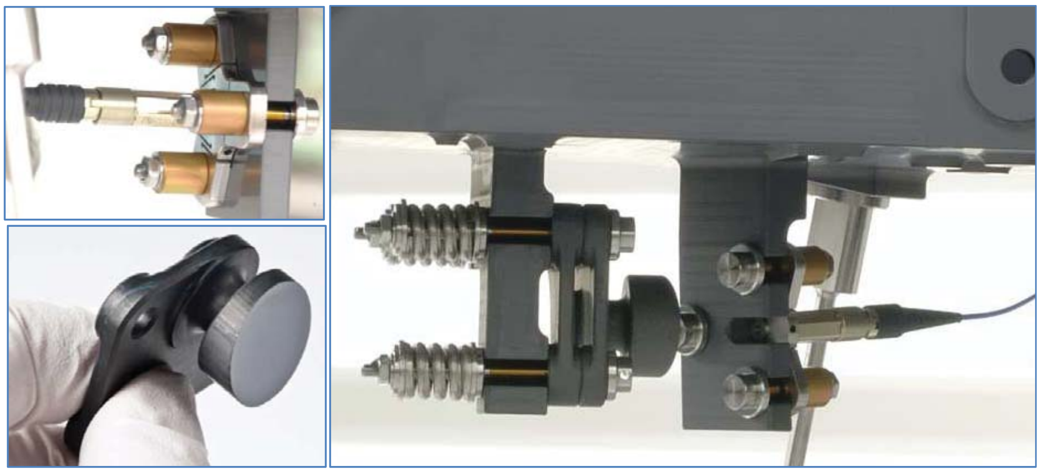


Figure 4: Cryogenic fiber collimator with the two dominating parts: fiber connector interface to SiC BAM structure (upper left) and the strongly curved off-axis parabolic SiC mirror.

4. GAIA BAM REALIZATION AND INTEGRATION

Based on the design definition of TNO, manufacturing of the SiC parts for GAIA BAM, has been performed by Boostec under control of Astrium. The most complex parts to be manufactured were the periscopes and the monolithic 1 meter length baseplates. For the baseplates the main constraint was 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 SiC mirrors were delivered as semi-finished blanks; polishing to high-quality optical components was developed and completed by TNO, using conventional diamond paste polishing for the flat folding mirrors. Tuning of the thickness and tilt angle of the alignment shims was executed as part of the alignment process. The glass-optics in the BAM system were manufactured by TNO; for the beam splitters, optical contacting of Fused Silica plates with a beam splitter coating in between was applied.

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

Integration of all parts was a complex and delicate task involving specially developed tools and operations by specially trained workforces. Apart from all rules and procedures custom for building space hardware, the specifically fragile properties of SiC dictated the pace and sequence of steps. The amount of pre-load applied on bolted interfaces was one of the issues of concern; due to the mechanical surface properties of SiC 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 high stresses on the other hand. For each unique fastener interface the torque-preload ratio needed to be calibrated.

For the large M8 fasteners, used to mount the SiC periscopes to the SiC 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. With these transducers a repeatable accuracy of better than +/- 3% pre-load, independent of the operator skill and including thermal cycling for qualification, has been demonstrated by TNO before application. For use in GAIA BAM, the Titanium M8 fasteners were equipped with a special high temperature coating instead of the standard transducer tin electrode material, in order to avoid the whisker growth in space.

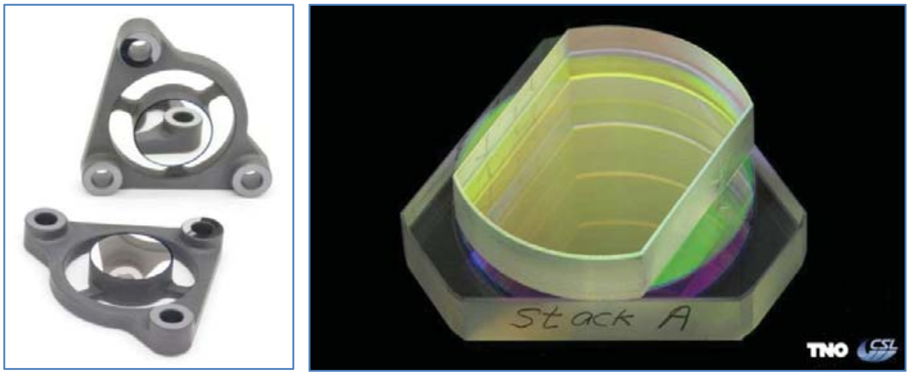


Figure 5: Polished and coated SiC flat folding mirrors and optical contacted fused silica beam splitter

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 SiC 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', 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 NANOMEFOS system were applied. 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 6: Thermal testing of GAIA BAM on Invar set-up.

References

[1] ESA GAIA mission website: http://www.esa.int/esaSC/120377_index_0_m.html