PICO METER METROLOGY FOR THE GAIA MISSION

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ABSTRACT

To measure the relative motions of GAIA's telescopes, the angle between the telescopes is monitored by an all Silicon Carbide Basic Angle Monitoring subsystem (BAM OMA). TNO is developing this metrology system. The stability requirements for this metrology system go into the pico meter and pico radian range. Such accuracies require extreme measures and extreme stability.

Specific topics addressed are mountings of opto-mechanical components, gravity deformation, materials and tests that were necessary to prove that the requirements are feasible. Especially mounting glass components on Silicon Carbide and mastering the Silicon Carbide material proved to be a challenge.

Key words: Opto-mechanics, stability, static determined structure, Silicon Carbide

INTRODUCTION

Gaia Mission

Gaia is a global space astrometry mission, and a successor to the ESA Hipparcos mission, launched in 1989. Part of ESA's Cosmic Vision program, the Gaia spacecraft is being built by EADS Astrium and is scheduled for launch in 2011. 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 photometric 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: Gaia scanning our galaxy – Credit: ESA/Medialab

Astronomical and Space Optical Systems, edited by Penny G. Warren, Cheryl J. Marshall,
Robert K. Tyson, Michael Lloyd-Hart, James B. Heaney, E. Todd Kvamme, Proc. of SPIE
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Gaia Payload Module

The Gaia Payload Module (PLM) consists of two telescopes (1.45 m x 0.5 m) with focal length of 35m that re-images the stars on a common focal plane thanks to a beam combiner. The telescopes are mounted on a torus structure. The payload structure and mirrors are made entirely out of Silicon Carbide (SiC), for reasons of dimensional stability. The overall payload therefore is a-thermal, and the Line Of Sight fluctuations can only result from thermal gradient fluctuations within the payload. The minimum operating temperature of the Gaia payload will be 100 K. The accuracy of the astrometric measurements will be better than 24 micro arc second at 15 magnitude, comparable to measuring the diameter of a human hair at a distance of 1000 kilometers.

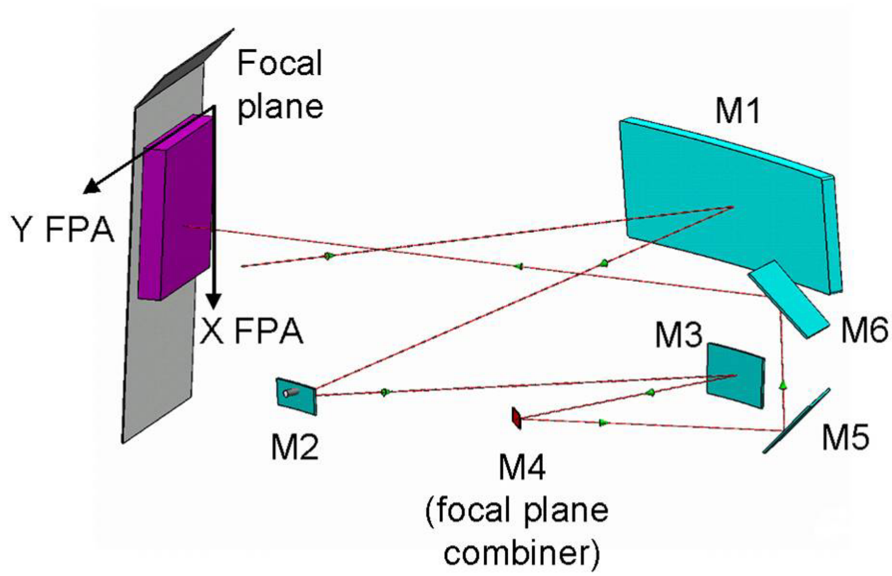

figure 2: Gaia PLM Telescope Optical design

Basic Angle Monitoring (BAM)

The angle between the lines of sight of the telescope is 106.5°. This is called the Basic Angle. The Basic Angle Monitoring (BAM) system continuously measures the angle variations between the two telescopes to be able to correct by calculation for small deviations due to thermal deformations.

Maximum fluctuation of the Basic Angle in flight is budgeted to be lower than < 7 μas rms for the random contribution and < 4 μas for the systematic contribution during the nominal spin period of 6 hours. The Basic Angle shall be monitored in flight with accuracy better than 0.5 micro-arc second rms for every 5 minutes interval 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 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 via optics into two pairs that are sent towards the two M1 telescopes via two "Bars" positioned opposite to the M1 mirrors (see figure 3). Both beam pairs are projected on the same CCD in the focal plane of the telescope mirrors. This results in two interference patterns on the BAM CCD. Rotation of a telescope mirror induces differential fringe motion. This provides information about the differential variation of the line-of-sight of each telescope. Therefore the basic angle variations are linked to the differential variation of both Lines Of Sight.

Two CCD detectors on the focal plane, nominal (N) and redundant (R), are dedicated to the BAM function. Each BAM CCD receives the two fringe patterns generated by the corresponding laser source through the two bars.

1. Design description

BAM consists of two "Bars", being the assembly of a base plate supporting optics to direct the optical beams. Beam splitters and collimating optics are only present on Bar # 2. The base plate, periscopes, folding mirrors, and collimator optics are all made of SSiC. The beam splitters are transmission elements and are made of fused silica. Each Bar is mounted via INVAR isostatic mounts on the Gaia payload main SSiC structure (torus).

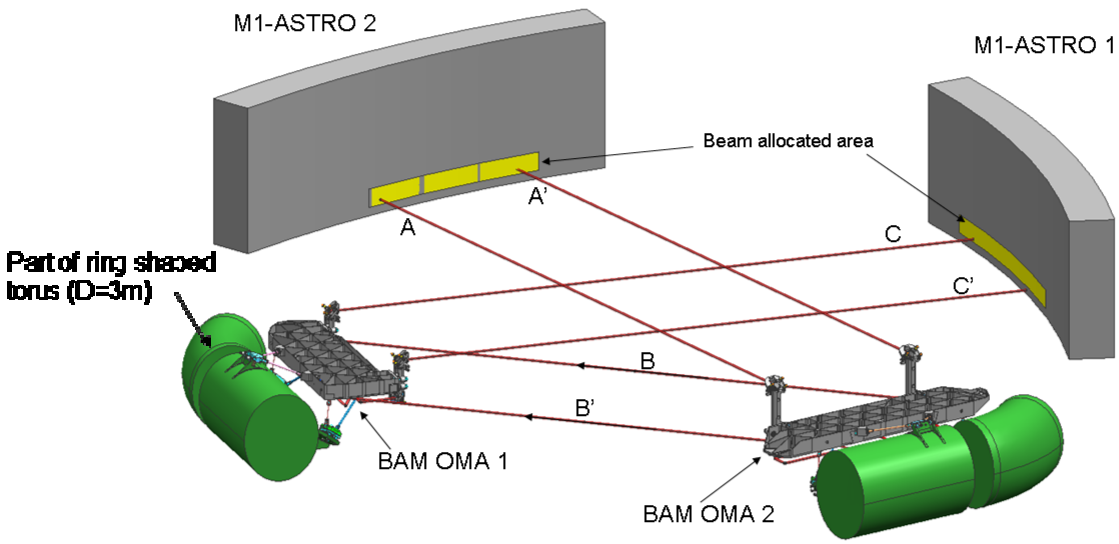

figure 3: Basic Angle Monitoring system with optical beams

The BAM system is depicted schematically in figure 3. Only a few parts of the ring shaped torus are shown. Like BAM-OMA, the two M1 mirrors are fixed to this torus. Also the beam pairs redirected in direction of the focal plane are not present in this picture.

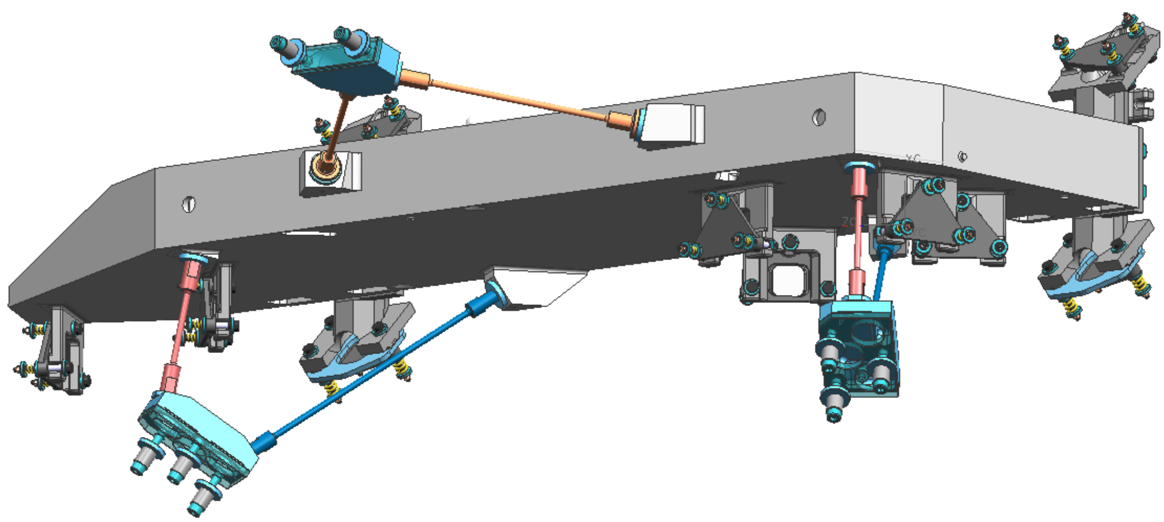

figure 4: CAD model of BAM-OMA Bar#1

1.1 Optical lay-out.

The layout depicted in Figure 5 shows the collimated beam entering the system from COLL1 at the right of beam splitter BS1, splitting the light into two beams. The transmitted beam by BS1 is reflected by mirror FM_1 and FM_2, then split again by beam splitter BS3 into beam A' and beam B'. The other beam is reflected towards BS2 and split again into beam A and beam B. The beams reflected by BS2 and transmitted by BS3 (A and A') are transmitted through periscopes that take the beams out of the plane of the drawing.

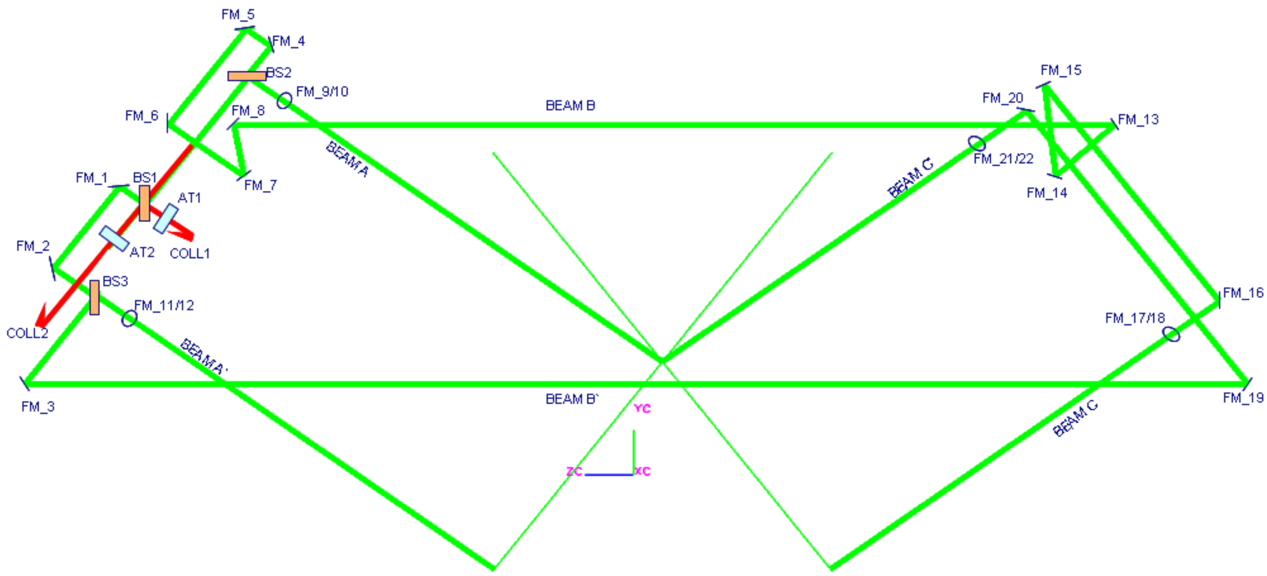

Figure 5: Top view of optical layout of BAM OMA

Due to the angle between both Bars, crossing beam B' is longer than beam B. Path length of beams B and B' however have to be equal to a plane perpendicular to those beams to be temperature invariant. On Bar#1 is compensated for this by lengthening the path of beam C by the mirrors FM13-FM15.

1.2 Optical design requirements

The BAM-OMA system generates two pairs of parallel and coherent beams. Each set is imaged on the BAM CCD detector by the telescopes thereby creating an interference pattern in the focal plane. There are requirements on accuracy of overlap at CCD level which can be translated to a parallelism requirement between beams at BAM-OMA level. This requirement determines the accuracy of tip/tilt alignment and stability of the beams.

The nominal design is as invariant as possible to changes in rigid body movements of the bars. Relative tilt will not lead to optical path length differences. Bar #2 will be invariant by definition, since the source is part of this bar. However for Bar #1 there are design restrictions to guarantee an OPD and angular invariant design. These restrictions are:

1. The input and output beams shall be parallel
    - guaranteed by proper layout of the bar
2. Rigid body movements (both rotation and translation) of Bar #1 should not change the output angle
    - The bar thus needs to act like a retro-reflector. It has an even amount of mirrors.
3. For rigid body movements (both rotation and translation) of Bar #1, the OPD between the two beams shall not change
    - The distances between input and output beams pairs are equal and the beam that enters the bar on top (FM_13) should leave the bar at its bottom (FM_18), the other beam vice versa (FM_19 / FM_22).

The BAM optical system is not invariant for ridged body motions out of the horizontal plane. A tilt of Bar#2 around its long axis will lead to almost twice the tilt angle of the output beams (C-C') of Bar#1. This is a severe effect that inevitable appears when gravity is relieved after launch. The thermo elastic effect of the invar bipods -BAM cools down to 110K- compensates for the majority of this effect.

The input light will be coherent laser light, but still the differential optical path length (OPD) should be kept within a few microns. Reason for this is that a wavelength change of the LASER should not be interpreted as OPD. When the OPD exactly is zero, the "white light fringe" is centered in the interference pattern. The pattern "breathes" on changing wavelength but does not change in location.

Because of the large distance between Bar#1 and Bar#2 a slight difference in temperature could be present. For the extra length of beam B' is compensated by an optical delay line on Bar#1. The temperature difference causes a difference in expansion which in the end affects the OPD of beams C and C'. To create a temperature invariant (a-thermal) system between Bar#1 and Bar#2, the OPD difference between both beams going from bar#2 to bar#1 to has be 'zero' (< 100µm) in the perpendicular plane to those beams. To realize this, path length has been added for beam B on Bar#2 by mirrors FM_6 to FM_8. See also Figure 5:.

The interference pattern needs to have sufficient contrast, resulting in requirements on intensity, wave front and polarization differences between the interfering beams.

Wave front error:	Caused by deviations in component surface shape and alignment errors.
Polarization:	Affected by coatings and by input polarization
Intensity:	Affected by beam splitter efficiency, number of mirrors for each branch and coatings

Requirements on optical performance and stability on components have to be set stricter on increasing number of optical components. Stability of optical components is crucial for the stability of the interference pattern, minimizing the number of components will be beneficial, also with regards to the available volumes which are limited.

The optical system must operate within specification under both ambient and cryogenic conditions (minimum 100 K). The BAM OMA system is made from a single type of SSiC material to secure homogeneous scaling of the optical system. Only thermal gradients in the system will affect the performance.

1.3 Mechanical design

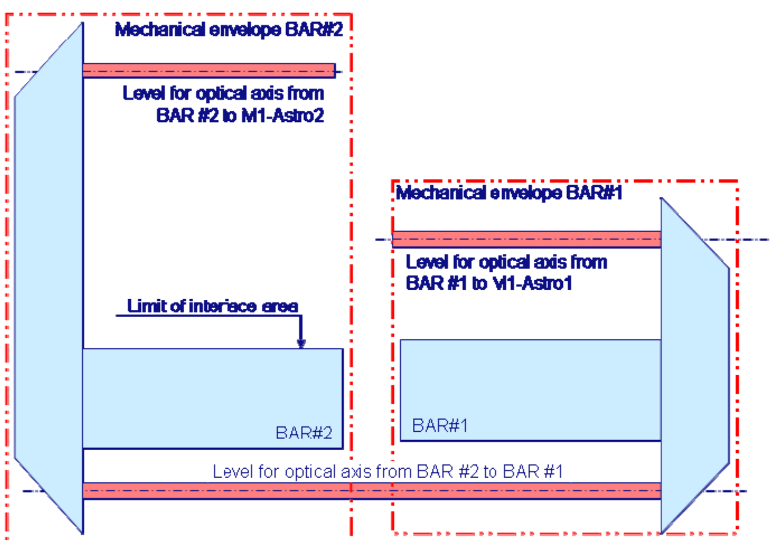

figure 6: BAM optical paths cross section

Both Bars of the BAM system are mounted to the payload torus. To point the interference spots to the BAM CCD's, the output beams of the BAM system have to be in field of view of the two telescope mirrors. To minimize vignetting on the telescope mirrors, all main BAM optics are positioned at the lower side of the base plate and both bars have periscopes..

The height difference of 75mm between the optical levels to M1-Astro#1 and M1-Astro#2 is due to the fact that M1-Astro#2 is positioned 75mm higher on the GAIA torus than M1-Astro#1. Although the beams to the M1 mirrors are depicted horizontal, the beams are slightly tilted to point at the prescribed position on the CCD plane.

1.4 Silicon Carbide

For the first time in history a spacecraft payload module is completely built from sintered Silicon Carbide (SSiC). Due to its specific production process and mechanical properties, the use of Silicon Carbide as a construction material requires a significant different engineering approach than is common for metal designs. All parts are milled oversized out of chalk-like blocks of 'green' SSiC material, after which they are sintered in a special oven at circa 2100°C, to get the required material properties. During this process, the parts shrink about 17%. For part sizes like the BAM base plates of about a meter in length, the design has to cover for this shrinkage.

The allowable safe tensile stress of SSiC is factors lower than that of high strength metals. Due to its high stiffness, any deformation of a part due to external loads like assembly or launch, results in stresses exceeding the maximum easily. To keep stresses sufficiently low, contact areas between two (SiC) parts have to be ground as flat as possible or the contact forces must be very low. Additional lapping as final treatment is often required.

1.5 BAM Base plates

The BAM Base plates for bar #1 and bar #2 are similar designed. They are isostatic mounted to the torus with three bipods. For AIT reasons it is decided that the Base Plates both have six attachment points and the Torus has three for each Bar. Mass is an overall design driver for the GAIA satellite. A maximum weight of 16kg for the complete BAM system is set. The light-weighted base plate is open at the backside for crack detection. The ribs have a minimum thickness of 2mm, pockets are 48mm deep, leaving the face sheet 2mm. The Base Plate has a length of 850mm, is 230mm wide and 90mm high including the integrated brackets for the optics. Mass has been limited to 4.5kg.

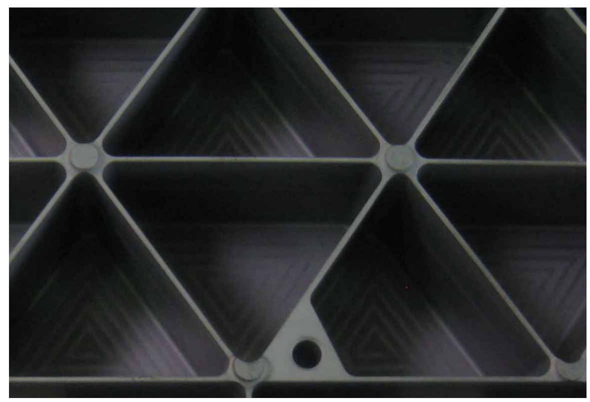

figure 7: Close-up of sintered base plate

To meet the specified optical requirements on superior stability, the fixation brackets of the optical components are integrated with the base plate (monolithic design). The exact location of the optical components is mainly based on equal optical path length for the two sets of beams within the limited allowable volume. The production process however defined in large extent the final layout of the base plates. It is not possible for the milling tools to access the brackets from the side of the base plate and because of the limited accuracy of the sintering process, all interface areas have to be ground after sintering to the desired position and flatness accuracy. Grinding is done with a relative large vertical grinding wheel on a dedicated tool at Boostec.

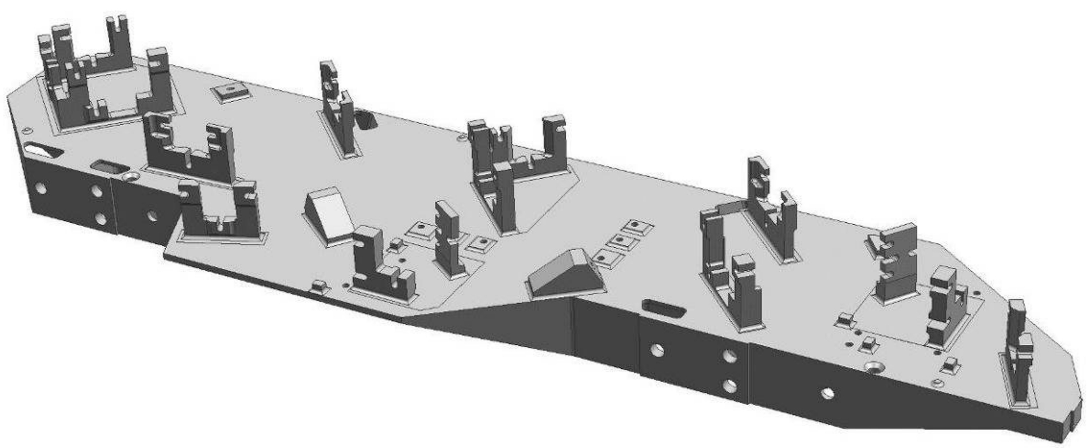

figure 8: Monolithic SSiC Base plate of Bar #2

1.6 BAM Mirrors

A mirror could have a slightly different temperature than its bracket due to limited inter part thermal coupling. To avoid Optical Path Differences (OPD), the reflecting surface is in plane with the interface area of the bracket. Differences in expansion now do not affect optical path length or angles. Volumetric changes will take place at the back side of the mirror.

figure 9: SiC flight folding mirror type A

The flatness of the bracket interface cannot be guarantied below 5µm. TNO has to take into account the worst shape possible. To keep the stresses out of the important reflective area (this would distort the mirror surface quality), the mirror is designed with spokes between the contact areas and the reflective surface.

Tests showed absolute angular stability per mirrors better than 4µrad. This includes launch loads and thermal cycling down to 100K. The mirrors are polished in-house by TNO to a wave front error of less than 3nm rms. A silver coating is applied to the bare porous SSiC to increase the reflection coefficient to ~94%. This is important because the number of reflecting components differ per beam per pair. Large intensity differences would affect the contrast ratio too much.

The requirements on optical beam directions are very stringent; 100µrad over 15 components. It is therefore not possible to mount all optics on production tolerances to the brackets on the Bars. Several mirrors are shimmed to correct for tilt or optical path length.

1.7 BAM Beam splitter mount

Beam splitters are the transmission components in BAM OMA that divide the single source into 4 beams of equal intensity. A special coating was designed to achieve 50/50 ratio at the laser beam wavelength of 852 nm. The encountering faces have a dedicated anti reflection coating to limit ghost reflections.

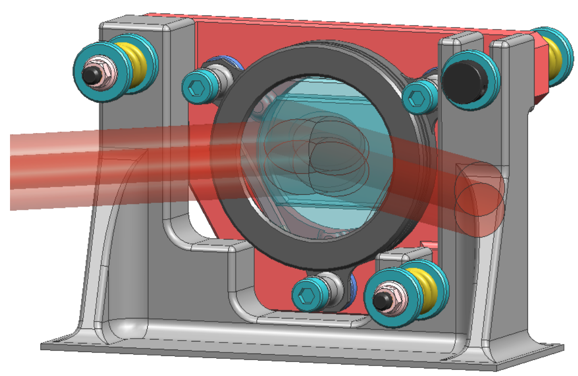

Figure 10: Beam splitter mounted to integrated bracket

Like the mirrors, extreme stability of the beam splitter orientation is required. Mechanical and thermal loads shall not tilt the component more than 1microrad from its nominal aligned orientation. For the beam splitters Fused Silica is used which' CTE does not exactly match the CTE of SSiC. It therefore is very important that the thermal centre lies in the (splitting) optical plane. The beam splitting plane is in plane with the SSiC interface plane. The beam splitter halves are connected via optical contacting. Both measures ensure that small CTE differences between Fused Silica (FS) of the beam splitters do not result in OPD errors. The Wave Front Error (WFE) of an individual beam splitter shall be less than 9nm rms under operational conditions.

To guarantee the optical performance no stress may be induced into the beam splitter. Differences in CTE between FS and SSiC are a potential danger to that. For that reason relative motion must be set free. For mechanical loads however one wants to keep the beam splitter firmly in place. Repetitive relative motions may cause wear to the contact areas of SSiC or FS. A particle of only 50nm in size between one of the three contact areas will lead to a tilt >2 micro radian. The problem of fixating and sliding is solved by dividing the thermo mechanical loads into two steps. Mechanical loads appear during launch, near room temperature. The beam splitter has a radial lock at room temperature. The beam splitter unlocks during cool down and is stress free at the operational temperature of 110K. This way slippage over the contact pads occurs only after launch.

Designing this thermo mechanical mechanism was one of the biggest challenges in the BAM OMA system. An extensive development program has been performed to define the final design for flight.

figure 11. 50/50 Plate Beam Splitters mounted to their flight bracket on the qualification carrier

1.8 BAM fiber Collimator

The BAM accommodates an optical fiber via an AVIM fiber connector. The 852nm light diverges from the free fiber tip to an off-axis parabolic mirror. This mirror collimates the beam to a 9mm parallel one.

The collimating elements need to be as stable as possible mounted and invariant for mechanical loads and temperature changes. Alignment takes place at ambient temperatures while the operational temperature is 110K. Any micrometer lateral or axial relative shift causes additional WFE and tens of micro radian orientation change of the optical beam. To comply to these harsh requirements an innovative fiber mount and collimator mirror have been designed.

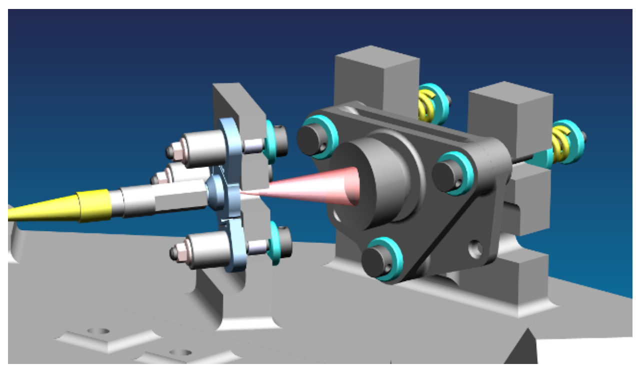

figure 12: Fiber collimator on BAM base plate

1.9 BAM Collimator mirror

The dimensional stability of the collimator optics must be less than 2 micro radian (tilt) and 8nm rms surface error under operational conditions. In order to avoid thermally induced errors, an all-SiC mirror solution was selected to collimate the diverging fiber output to a 9mm parallel beam. The mounting principle to the base plate is identical to the flat folding mirrors. The collimator mirror has a diameter of just 20mm. The flange connected to this mushroom type mirror is ca. 40x40mm. Due to the short focal length of 27mm of the collimator, a strongly curved off-axis parabolic mirror was required (R = 50.17 mm) over an effective aperture of 10 mm. This strong curvature makes it difficult to polish with conventional techniques. TNO developed, in close cooperation with the Leibniz Institute of Surface Modification (IOM), a process for finishing strongly curved off axis parabolic SiC mirrors.

figure 13. Off axis parabolic SiC mirror blank

TNO and IOM use a combination of 3D robot polishing and Plasma Jet Machining (PJM). Plasma enhanced chemical etching is a non-conventional technology for surface machining. The method is based on a microwave or RF excited plasma jet under normal atmospheric pressure or in rough vacuum yielding a high flux of reactive radicals. Material removal is obtained by chemical reactions between the radicals and surface atoms.

figure 14: Zeeko polishing at TNO

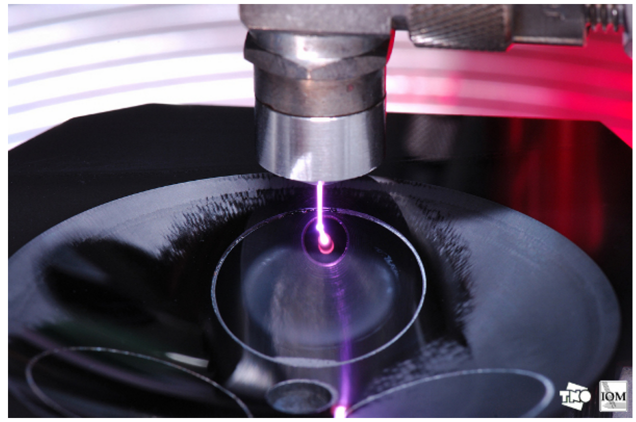

figure 15: PACE process at IOM

Different plasma jet sources have been developed to do deterministic surface shaping and surface figure error correction over a wide spatial range with nanometer accuracy. The half-width of the almost nearly Gaussian like shaped removal functions reaches from about 0.1 mm to about 10 mm. Maximum volume removal rates of about 50mm³/min have been achieved for fused silica and ULE™. Surface machining is accomplished using the dwell time algorithm on CNC controlled multi-axes systems. Far developed mathematical de-convolution routines are used for creating the machining files.

During plasma jet treatment no sub-surface damage occurs in contrast to abrasive methods. This advantage makes the plasma jet technology very attractive for the precise manufacturing of especially spherical and free-form optics. On the other hand the chemical removal mechanism leads to an increase of surface roughness depending on the material and the removal depth. But at the same time potential subsurface damage is removed. A low surface roughness is achieved with a post polishing run on the Zeeko polishing robot at TNO. Successful trial runs by IOM and TNO resulted in a surface error of 8 nm RMS. Production of the flight mirrors has started.

1.10 BAM cryogenic Fiber mount

TNO succeeded in designing an adapter to keep the ferrule tip of the AVIM fiber connector within 1µm position and 10µrad rotation stability under the specified thermal range to 100K and mechanical launch loads. The COTS connector is extended with a special developed spring, after which it can be mounted just like any normal fiber coupling.

The fiber mount is made out of INVAR. The small CTE difference is compensated by three flexures to create a thermal centre.

figure 16: Test model of the fibre mount

2. Information

2.1 Title and author information

Ellart Meijer is Systems Engineer at TNO Science and Industry for the Gaia BAM OMA project.

2.2 Acknowledgements

TNO, in close cooperation with Astrium and ESA, has been involved in the development of the Basic Angle Monitoring system since 1996. Initially an Aluminum setup was designed to prove the feasibility of pico meter resolution measurements. In subsequent years, ultra stable SiC components and polishing processes for SiC were developed. A PhD student of the technical University of Eindhoven graduated on this topic. The C/D phase of Gaia BAM OMA at TNO commenced in November 2006.

TNO Science and Industry

www.tno.nl/gaiabam

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