DESIGN OF A BASIC ANGLE MONITORING SYSTEM IN SILICON CARBIDE

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ABSTRACT

Due to the 10 microarcsecond accuracy, with which Gaia will measure the positions of stars using 2 astrometric telescopes, stability requirements on the payload module are extremely stringent. In order to achieve the required 10 microarcsecond accuracy, a metrology system could be installed on the satellite to monitor variations on the basic angle: the basic angle monitoring system. This system has high stability requirements of picometers in several hours and is therefore, like the rest of the payload module, constructed of Silicon Carbide. This is a ceramic material with good mechanical and thermal properties. However it also needs special attention in design, because final processing is difficult. The mounting of optical components is performed directly on the optical bench, by tensioning the optical components with spiders against the optical bench. Alignment is performed by shifting the component across a plane using an external and removable alignment mechanism. In the near future experiments will be performed to proof the design.

Key words: Metrology; Interferometer; Gaia; Basic angle monitoring; Silicon Carbide.

1. INTRODUCTION

Gaia will use two astrometric telescopes to measure the positions of a billion stars in our Galaxy with 10 microarcsecond (μas) accuracy. The ‘basic’ angle between the two fields of view of the astrometric telescopes of Gaia will be 99.4° (Figure 1). Since the fields of view of both telescopes should be linked to form a highly accurate 3-D map of the Galaxy, variations on the ‘basic’ angle between both lines-of-sight of the telescopes will be measured with 1 μas accuracy, using the basic angle monitoring (BAM) system. A design with high stability is necessary to be able to measure the variations on the ‘basic’ angle with 1 μas accuracy.

The payload module (PLM) will be constructed almost entirely of Silicon Carbide (SiC). This is a ceramic material with very good mechanical and thermal properties (low density, high stiffness, high thermal conductivity and low thermal expansion) and it is a very stable material (high microyield stress, good resistance against radiative and chemical influences).

This paper will discuss a possible optical and mechanical design of the BAM system.

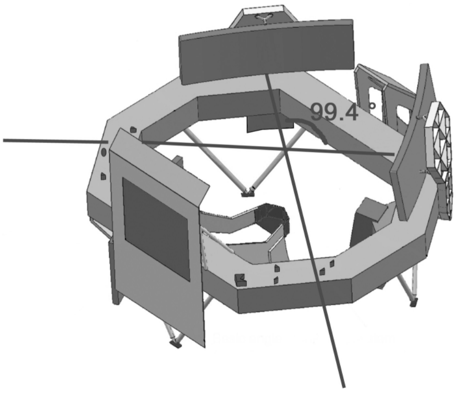

Figure 1. Gaia payload module (Gaia SLTRS project team 2002).

2. OPTICAL DESIGN

The basic angle monitoring system will be an interferometer, consisting of two parts. Each part is positioned in front of a telescope. The parts are named: bar 1 and bar 2. On bar 1 a laser with collimator generates a beam. This beam is split into two coherent beams using a beamsplitter and both beams are redirected using mirrors, to travel in parallel to telescope number 1 (Figure 2). The telescopes will create an overlap and thus an interference pattern on the focal plane of the telescope. Each beam is also split into a third and fourth beam on bar 1. These beams are redirected with mirrors to bar 2. On bar 2, mirrors redirect the beam to travel in parallel through telescope 2. Again the overlap will cause a second interference pattern on the focal plane (Figure 3). If the line-

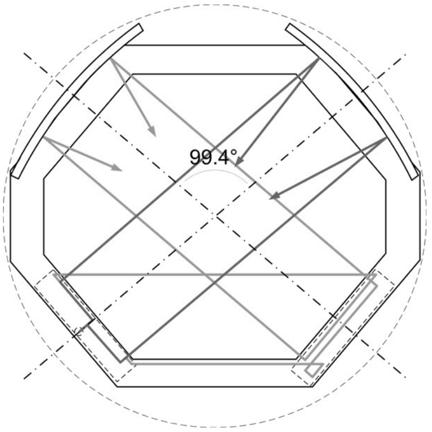

Figure 2. BAM measurement principle.

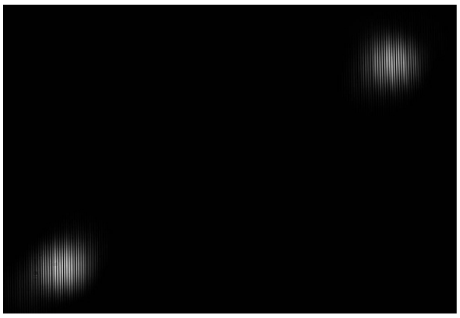

Figure 3. Interference patterns on the focal plane (from Snijders et al. 2000).

of-sight of one telescope rotates with respect to the other, this will cause a shift of one interference pattern with respect to the other. The BAM system will thus measure the variation on the basic angle. The mirrors and beam-splitters on the BAM bars are positioned such that a rotation of one of the bars will not cause a relative shift of one pattern with respect to the other pattern. This shift is a few nanometers for a 'basic' angle variation of 10 μas. Photons caught by the CCD focal plane are counted to be able to measure this kind of shift. The alignment requirements for individual optical components result from demands on the interference patterns and optical path length differences (OPD). The OPD between a pair of beams will need to be smaller than 5 μm. The overlap between two beams should be 90%. From these general requirements, the alignment requirements for an individual optical component result. The stability requirements follow from the maximum variation of the OPD during 6 hours. Since a change in OPD will cause a shift of the interference pattern, the OPD may not change more than 5 pm. The stability requirement on the angle is a direct, linear extrapolation of the angular alignment requirement. If the angular alignment requirement is 6 μrad in 6 years, and it is assumed that a mirror should drift linearly over 6 year, the stability must be 0.14 nrad in a 6-hour cycle.

Table 1. Alignment and stability requirements for individual optical components.

Parameter for one component	**Alignment requirement over 6 years**	**Stability requirement over 6 hours**
Position	1 μm	1.1 pm
Angle	1.2 μrad	0.14 nrad

3. MECHANICAL DESIGN

The mechanical design can be divided into the design of the main structure on which the optical components are mounted (optical bench) and the optical components. These components can be divided into three different types; mirrors, beam-splitters and a retroreflector.

The three main issues for the design of the BAM system are: alignment stability, measurement stability and manufacturability. The main difficulties of the alignment of optical components are: achieving alignment, but also keeping alignment after severe vibrations and thermal changes during launch.

The stability of the BAM system optical components is mainly determined by thermal variations or gradients and by the effect of mechanical stresses. There are also other factors that could influence stability, like radiation. SiC has been chosen for its good resistance against radiative and chemical influences and for its high microyield stress.

In manufacturability the hardness of the material should be considered. Rough shapes can be made in the pre-sintering state (compacted SiC powder). However, after sintering Silicon Carbide is extremely hard, and the material must be polished to get the final shaping and alignment. The locations, which should be polished, are therefore preferably well reachable and the number of these locations should be limited.

3.1. Main Structure

For the design of the BAM system it is decided not to change the principle octagonal ring on which all scientific instrumentation (i.e., astrometric telescopes, spectrographic instrument, etc) is mounted. The choice is made to mount the optical components of the BAM system, directly onto the optical bench of the PLM, like shown in Figure 1. The BAM system will be positioned inside the field of view of the stars. Therefore, the system should be as small as possible minimize light blockage in the field of view. By using direct placement as opposed to a separate optical bench, the system is as small as possible. The number of alignment steps is limited, although the alignment should be performed on the satellite when all scientific instrumentation has already been assembled. For space missions, the mass budget is always an issue. By mounting optical components of the BAM system directly on the optical bench of the PLM, the mass is as small as possible. The fewer parts the better for stability reasons. It is assumed that contacts pose a greater stability risk than the instability of a material due to e.g., internal stresses.

3.2. Optical Components

The design of the optical components is very much linked to the alignment method used for positioning them. The precise alignment of optical components is most important for the x, ψ , and θ-axis. The design of the optical components is based on the following design principles:

1. The number of parts should be limited.
2. Minimal stress (and strain) should be present in the parts, especially in the x-direction for stability reasons.
3. The force loops should be as small as possible and no torsion or shear should be introduced.
4. Only compressive stresses should be introduced in the components.

There are several strategies that can be followed for the alignment of the components:

1. Elastic deformation and force variation. Silicon Carbide is very stiff and very brittle making it unsuitable for elastic deformation of, for example, leafsprings, especially since these element are mainly loaded in a bending mode. With kinematic couplings force variation could be applied. However, stress variation, especially with the risk of relaxation or creep in the pre-tensioning material poses some risk on the stability of the system.
2. Shifting and fixation.
3. Grinding and polishing.

The design of mirrors, beam-splitters and the retroreflector has been performed with the issues stated above, in mind.

3.2.1. Mirrors

The mirror is a triangular block, with on one side a Chemical Vapor Deposition (CVD) SiC coat, which has been polished to an optical flatness of λ/20. On the underside three spherical surfaces are present, which are also coated with a CVD SiC layer. The block has four holes. Three of them are right above the spherical contact areas. The fourth hole is a central through-hole. In the holes just above the contact surfaces three struts (Ti-6Al-4V) are glued in with an adhesive with very low elastic modulus. A spider spring is connected to the struts and a central pullrod is pre-tensioned with an identical spider on the other side. This way stresses are introduced only compressively in the SiC mirror and in a small area, away from the mirror surface. Additionally the stresses introduced in the SiC are not in the x-direction. The surface of the optical bench is also coated with a CVD SiC layer and polished to 25 nm flatness and roughness (Figure 4). Ti-6Al-4V has been selected as a tensioning material, because of its specific stiffness and strength, relatively low thermal expansion and density and more importantly its relatively high resistance against (micro)creep (Marschall & Maringer 1977).

The alignment is performed by first polishing the spherical contact areas on the underside of the mirror so that ψ is aligned. In the next step the x-position and θ-rotation is performed by fixing the mirror to an external alignment mechanism. The spider is already glued into the mirror, but is not yet tensioned. Alignment is achieved by shifting the mirror with the alignment mechanism. Finally, the spider is pre-tensioned with a tensioning mechanism and adhesive is applied around the spherical contact surfaces. This is done, because otherwise the x- and θ-axes would only be fixed by friction.

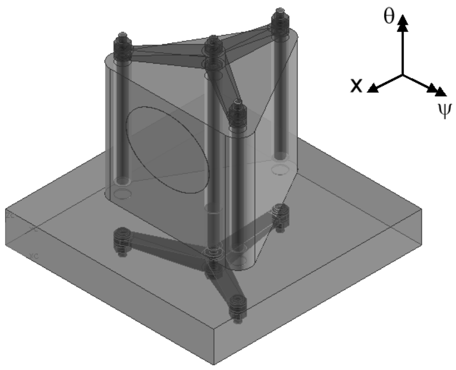

Figure 4. Mirror.

3.2.2. Beam-splitters

The beam-splitter itself will be made of Pyrex. The beam-splitter design therefore necessarily will also have vertical mounting, meaning that stresses are introduced in the horizontal direction. To limit instabilities as much as possible the beam-splitter itself is very thin and the reflecting plane is used as contact surface against again three spherical contact surfaces. These are coated with CVD SiC like the spherical contact surfaces in the horizontal plane. Since a spider would be in the lightpath, another way of pre-tensioning the beam-splitter against its mount is required. It was decided to use a double sinusoidal ring spring, which is made of Ti-6Al-4V. The pre-tensioning is performed by clamping the mount, beam-splitter and spring between two Ti-6Al-4V rings, which are pulled towards each other.

The horizontal mounting is exactly the same as for the mirror, applying a preload with a spider. The main difference here is size. To be able to transmit the beam, the beam-splitter is somewhat larger than the mirror (Figure 5).

Alignment is performed in exactly the same manner as the alignment technique of the mirror. One aspect should be taken into account with regard to the ψ alignment. This alignment is performed when the beam-splitter is removed. The placement of the mirror should, therefore, be very reproducible along the ψ-axis.

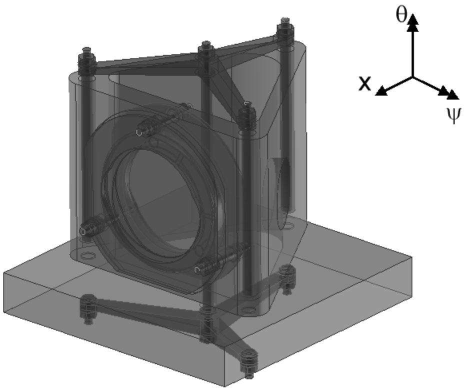

Figure 5. Beamsplitter.

3.2.3. Retroreflector

The retroreflector currently is as shown in Figure 6. The design is similar to the design of the mirror, except for a corner with two exactly perpendicular mirror surfaces cut out of the triangle. To keep the centre of gravity as close as possible to the central pullrod, some mass has been removed from the retroreflector. Because the mass of the retroreflector is larger than the mass of the mirror, a larger pre-tensioning force is applied than for the mirror. This design of a retroreflector has one large drawback; the difficulty of polishing two mirrors to an optical quality of $\lambda/20$, because it is not very well accessible. This drawback is still being discussed with the manufacturers.

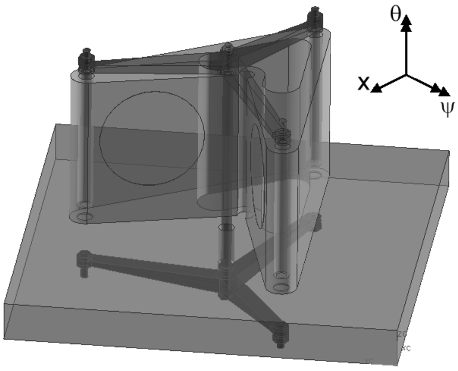

Figure 6. Retroreflector.

4. CONCLUSIONS

The BAM system will be integrated with the optical bench of the PLM. The optical components will be clamped and glued in the horizontal plane to the optical bench using Ti-6Al-4V spiders, such that forces are only applied in the vertical direction, which is the least critical for the stability of the system.

Alignment is performed via polishing of spherical contact surfaces for the ψ-axis and via shifting with an external alignment mechanism for the θ- and x-axis.

Manufacturing discussions with regard to the beam-splitter mounting and retroreflector design are currently conducted.

5. FUTURE RESEARCH

Currently, the design of the BAM system is nearly finished. The final step is to develop an alignment mechanism and tensioning mechanism for the spiders. Parallel to this process, experiments are being prepared to test the BAM system. These tests will commence with vibration and thermal cycling tests and a stability test. Individual optical components will be tested by first aligning the components in an interferometer setup. What kind of interferometer this setup will be, is still under discussion. Experiments will be performed in vacuum for a few hours to measure the stability of the components. In the next step, the setup will be exposed to vibrations. Experiments are performed to check whether the alignment is kept even after vibrations. If this is so, again stability tests will be performed on the set-up. In the final stage the set-up will be exposed to thermal cycling. Again alignment will be checked and stability experiments will be performed. To be able to do these experiments a set-up will be designed with the same designs for mirrors, beam-splitters and retroreflector as for the real BAM system, only less complex.

ACKNOWLEDGMENTS

This research is a TNO TPD and Technische Universiteit Eindhoven project, supported by the NIVR (Dutch Agency for Aerospace Programmes) through the NRT and PEP research programmes.

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