Picometre metrology in space

The Gaia mission will create an ultra-precise three-dimensional map of about one billion stars in our Galaxy. Part of ESA's Cosmic Vision program, the Gaia spacecraft is being built by EADS Astrium and is scheduled for launch in 2011. TNO is developing a picometre metrology system – the Basic Angle Monitoring Opto-Mechanical Assembly (BAM OMA) – for this mission.

• *Ellart Meijer and Fred Kamphues* •

Gaia is a global space astrometry mission, and a successor to the ESA Hipparcos mission, launched in 1989. 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; see Figure 1. 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.

Gaia Payload Module

The Gaia Payload Module (PLM) consists of two telescopes (1.45 m x 0.5 m) focalized over 35 m in a common focal plane thanks to folding mirrors and to a beam combiner; see Figure 2. The telescopes are mounted on a torus structure. The payload structure and mirrors are made entirely of silicon carbide (SiC), for reasons of dimensional stability. The overall payload is therefore 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 better than 24 micro arcsec (μas) at 15 magnitude, comparable to measuring the diameter of a human hair at a distance of 1,000 kilometres.

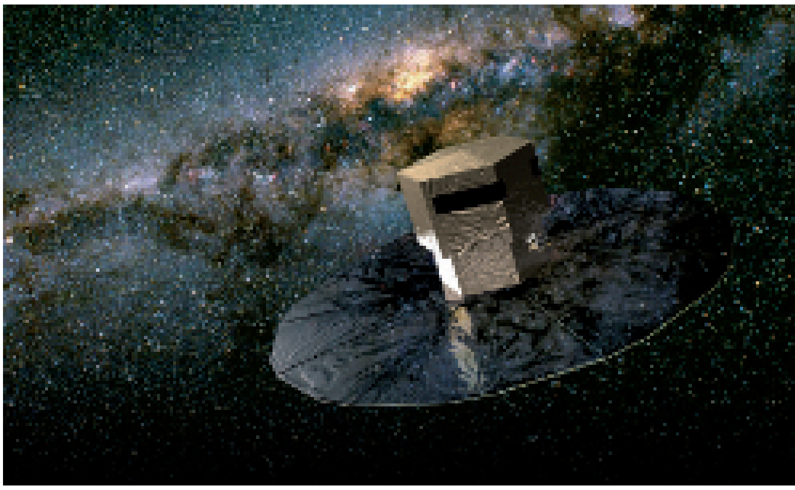

Figure 1. Gaia scanning our galaxy. (Credit: ESA/Medialab)

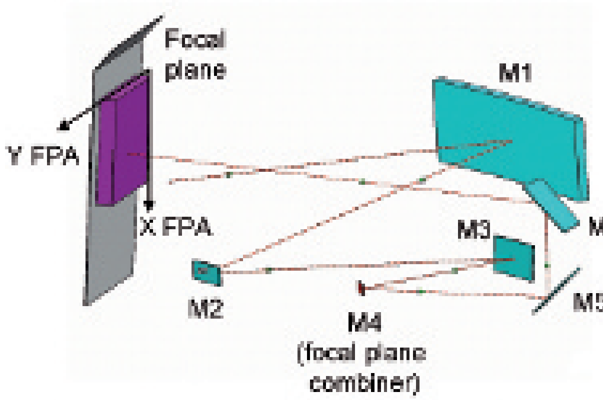

Figure 2. Gaia PLM Telescope Optical design.

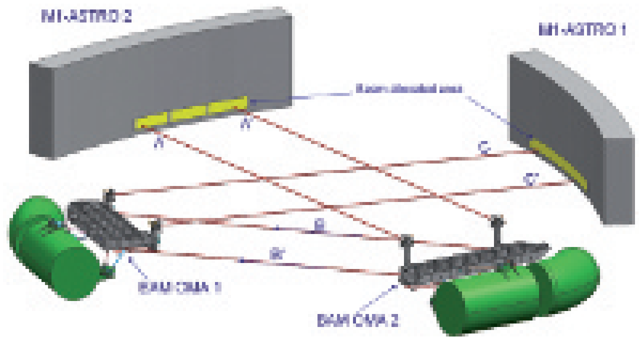

Figure 3: Basic Angle measuring principle.

Basic Angle Monitoring (BAM)

The angle between the lines of sight of the two telescopes is 106.5°. This is called the Basic Angle. A Basic Angle Monitoring (BAM) system continuously measures the angle between the line of sight of the two telescopes, to be able to make corrections for small thermal deformations; see Figure 3. Maximum fluctuation of the Basic Angle in flight is assumed to be lower than < 7 µas rms for the random contribution and < 4 µas for the systematic contribution during the nominal spin period of six hours. The Basic Angle shall be monitored in flight with accuracy better than 0.5 micro arcsec rms for every five 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 picometre 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 split towards the two telescopes. A point source is mounted on a rigid bar (#2) located at the opposite side of telescope #2. The collimated point source generates four beams in total, two beams are sent towards telescope #2 and produce a fringe pattern in the focal plane of this telescope. The two beams left are sent towards bar #1, whose optics deflect the beams which are sent towards telescope #1 and produce another fringe pattern in the focal plane common to both telescopes. The differential fringe motion with respect to the detector frame provides variation of the line of sight of each telescope along scan, and therefore the basic angle variations linked to the differential variation of both lines of sight.

Each bar consists of a structure supporting beam splitters, folding mirrors, and collimating optics (the latter on Bar # 2 only). The folding mirrors and the structure are made of SiC. The beam splitters are transmission elements and are therefore made of fused silica. Each bar is mounted via isostatic mounts on the Gaia payload main SiC structure (torus).

Two CCD detectors on the focal plane, nominal (N) and redundant (R), are dedicated to the BAM function; see Figure 4. Each BAM CCD receives the two fringe patterns generated by the corresponding laser source through the two bars.

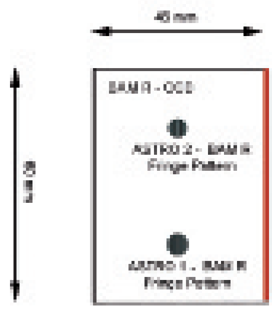

Figure 4. BAM Detection Unit.

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 picometre resolution measurements. In subsequent years, ultra-stable SiC components and polishing processes for SiC were developed. A Ph.D. student from Eindhoven University of Technology obtained his doctor's degree on this topic. In November 2006, the Gaia BAM OMA project kicked off for TNO. Time to design and build flight hardware.

Silicon carbide

For the first time in history, a spacecraft payload module is completely built from sintered silicon carbide (SSiC). The use of silicon carbide as a construction material requires a different engineering approach than is common for metal designs. The production process of SiC parts limits the design freedom and the mechanical properties of the material are a major design driver. Like all ceramics, high tensile stresses are to be avoided. The maximum tensile stress of SSiC is around 100 MPa, factors lower than that of high-strength metals. Due to its high stiffness, any deformation – sometimes 0.005 mm is enough – of a part results in stresses exceeding the maxima easily. To keep stresses in hand, contact areas between two (SiC) parts have to be as flat as possible or the contact forces must be very low. Grinding and lapping as final treatment is very common. Nevertheless, SSiC is the preferred material for the Gaia payload, thanks to the low thermal expansion coupled with a high thermal conductivity, high specific stiffness and excellent dimensional stability. The SSiC parts are manufactured bij Boostec.

Before SSiC parts obtain their final shape, they have to go through a number of production steps. Parts are milled oversized out of chalk-like blocks of 'green' SSiC material. After milling they are sintered in a special oven at circa 2100 °C, to obtain the required material properties. During this process, the parts shrink 17% with an accuracy of 0.4%. This may look accurate, but with part sizes of about a meter in length, this means 4 mm length variation to the nominal dimensions. The design has to cover for this uncertainty for optical and mechanical interfaces, since excessive grinding is slow and expensive. A minimal amount of grinding is required to achieve the required surface accuracy.

BAM bars

The BAM OMA consists of two bars carrying optical components. The optical layout of the Gaia BAM-OMA is designed to meet the specified requirements to be able to measure the Basic Angle variation of the telescope mirrors. The exact location of the optical components however, is to a large extent defined by the production process of the base plates (due to the large diameter of the grinding wheel). To achieve superior stability, the fixation brackets of the optical components are integrated with the base plate (monolithic design); see Figure 5.

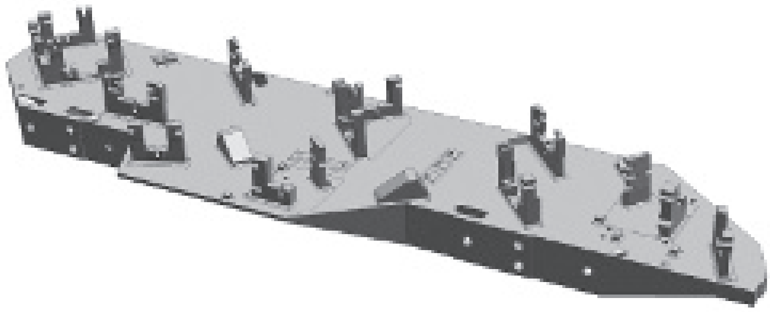

Figure 5. Base plate of Bar #2.

The milling needs to be done with the vertical axis and because of the limited accuracy of the sintering process, all interface areas have to be ground after sintering to the desired position accuracy and flatness. Grinding is done on a dedicated tool at Boostec. Due to close spacing, bracket angles and mutual distances have to be thought over very early in the design.

To keep overall mass low, the base plates have been lightweighted at the backside; see Figure 6. The ribs have the a minimum thickness of 2 mm, pockets are 48 mm deep. To allow crack detection of the sintered parts, it is not possible to close the back. This affects overall stiffness of the base plate. To compensate for this, the height of the plate was increased.

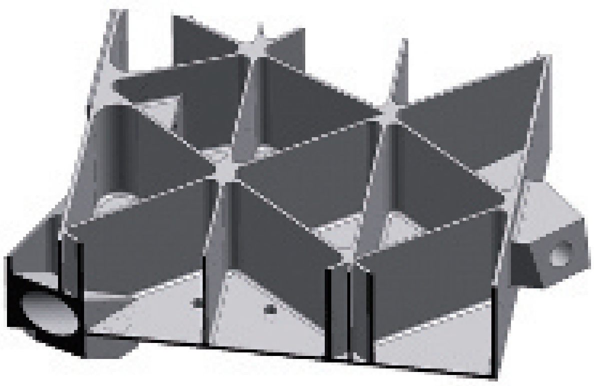

Figure 6. Lightweight section of Bar #2.

The requirements on optical beam direction are very stringent and the number of reflecting components is large. It therefore is not possible to mount all optics on production tolerances to the brackets on the bars. Several components are shimmed to correct for tilt or optical path length. The optical system must operate within specification under both ambient and cryogenic conditions (minimum 100 K). SSiC shrinks when cooled down. The optical design is such that homogeneous scaling of the system has no effect on performance (a-thermal design). Therefore the BAM OMA is made from a single type of SiC. Only thermal gradients in the system will affect the performance. Because of the high thermal conductivity of SiC, gradients may only be expected at interconnections of parts due to limited thermal coupling.

BAM mirrors

A mirror could have a slightly different temperature than its bracket. To avoid optical path differences (OPD), the reflecting area is in plane with the interface area of the bracket; see Figure 7. Differences in expansion now do not affect optical path length or angles. Volumetric changes will take place at the back side of the mirror. The flatness of the bracket interface cannot be guaranteed below 0.05 mm; here we have to take the worst shape possible into account. To keep the stresses out of the important reflective area, the mirror is designed with spokes between the contact areas and the reflective area. The absolute angular stability of the mirrors is better than 2 microrad. This includes launch, cool down to 100 K and 5 years of operation. The mirrors are polished in-house by TNO to a surface error of less than 2 nm rms.

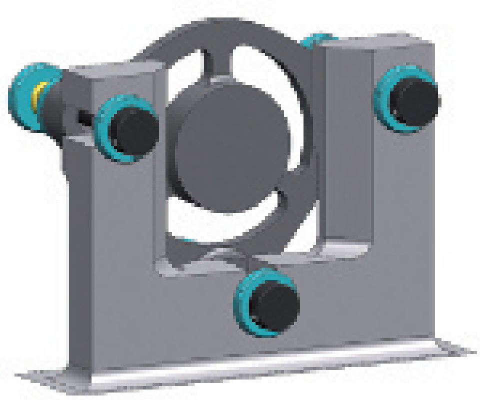

Figure 7. Flat folding mirror mounted to its bracket.

Beam splitter

Beam splitters are the only transmission components in the BAM OMA. A special coating was designed to achieve 50/50 ratio at the laser beam wavelength of 852 nm; see Figure 8. Like the mirrors, extreme stability of the orientation of the beam splitter is required. Mechanical and thermal loads shall not tilt the component more than 1 microrad from its nominal aligned orientation.
Like the mirror, the (splitting) optical plane is in line with the SSiC interfaces. The beam splitter halves are connected via optical contacting. Both measures ensure that small CTE (thermal expansion coefficient) 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 6 nm rms under operational conditions.

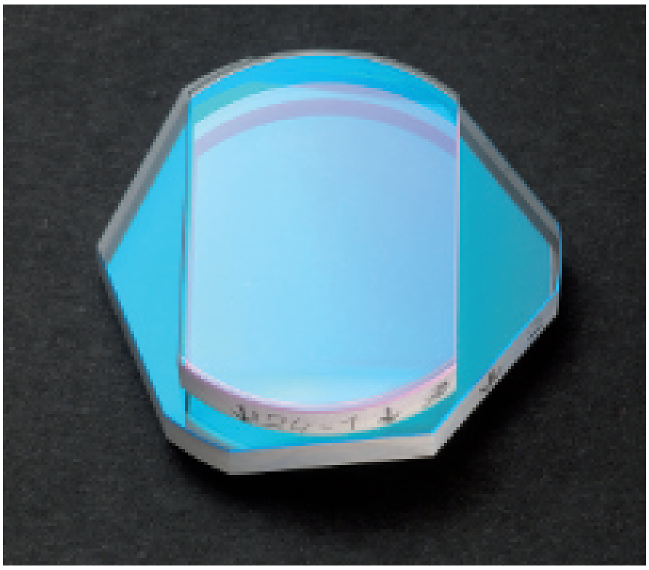

Figure 8. 50/50 Beam splitter.

In order to avoid radial stresses and optical deformation during cool down, the beam splitter is designed to slide over its SSiC contact areas; see Figure 9. A particle of only 50 nm in between of one of the three contact areas will lead to a tilt of over 2 micro radian. To avoid damage to these contact areas, a passive design locks the beam splitter during launch. Designing this mechanism was one of the biggest challenges in the BAM OMA system. An extensive development program was done to verify the performance under ambient and cryogenic conditions; see Figure 10.

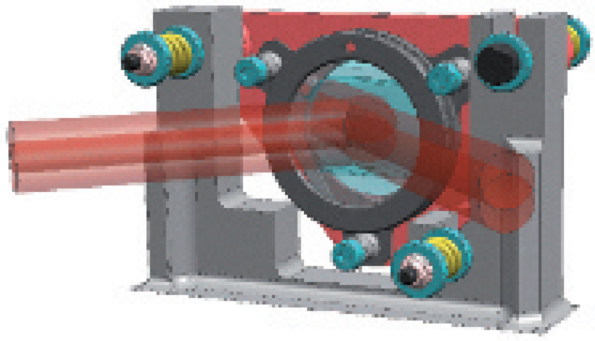

Figure 9. Beam splitter mount with optical path shown.

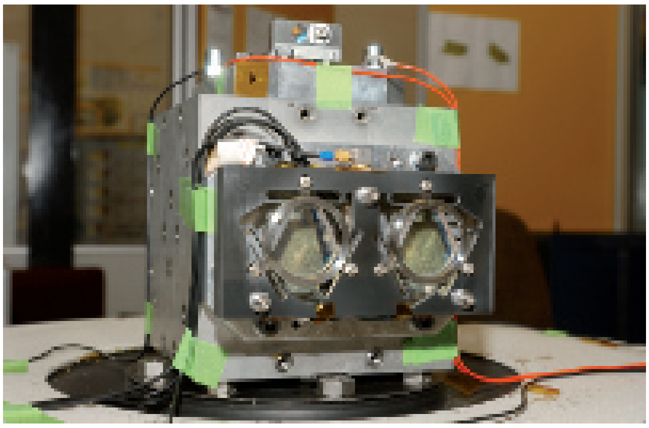

Figure 10. SiC beam splitter vibration test at NLR.

Fibre collimator

The dimensional stability of the collimator mirror must be less than 2 microrad (tilt) and 16 nm rms WFE under operational conditions. In order to avoid thermally induced errors, an all-SiC mirror solution was selected for the fibre collimator; see Figure 11. The mounting principle is identical to the flat folding mirrors. Due to the short focal length of the collimator, a strongly curved off-axis parabolic mirror was required. This strong curvature makes it difficult to polish and TNO is currently developing alternative methods for conventional polishing.

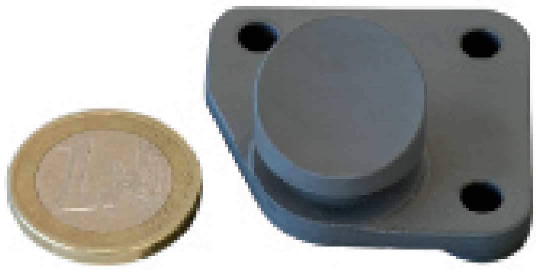

Figure 11. Off-axis parabolic SiC mirror blank.

Application in other areas

The knowledge and experience that TNO has gained with Gaia will be invaluable for other industry segments as well. In the semicon industry, requirements for ultra-high precision and stability will naturally further increase, as new technology is becoming available. TNO is open to co-operation with other partners for the development of ultra-stable silicon carbide instruments and components.

Authors' note

Ellart Meijer is a systems engineer at TNO Science and Industry for the Gaia BAM OMA project. Fred Kamphues is a consultant at Mill House and works on component development for Gaia. Fred is also a writer and photographer.

Information

TNO Science and Industry
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