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WAVEFRONT SENSOR FOR THE GAIA MISSION

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I. ABSTRACT

TNO has developed, built and tested the Wave Front Sensor (WFS) for ESA's Gaia mission. The WFS will help Gaia create an extraordinarily precise three-dimensional map of more than one billion stars in our Galaxy. Part of ESA's Cosmic Vision programme, Gaia's build is led by EADS Astrium and is scheduled for launch in 2012. The Wave Front Sensor will be used to monitor the wave front errors of the two main telescopes mounted on the GAIA satellite. These mirrors include a 5-degree of freedom (DOF) mechanism that can be used to minimize the wave front errors during operation. The GAIA-WFS will operate over a broad wavelength (450 to 900 nm) and under cryogenic conditions (130 to 200 K operation temperature). The WFS uses an all reflective, a-thermal design and is of the type of Shack-Hartmann. The boundary condition for the design is that the focal plane of the WFS is the same plane as the focal plane of the GAIA telescopes. The spot pattern generated after a micro lens array (MLA) by a star is compared to the pattern of one of the three calibration sources that is included in the WFS, allowing in flight calibration. We show the robust and lightweight opto mechanical design that is optimised for launch and cryogenic operation. Details are given on its alignment and commissioning. The WFS is able to measure relative wave front distortions in the order of $\lambda/1000$, and can determine the optimum position of the focal plane with an accuracy of 50 μm

II. INTRODUCTION

The ESA Gaia mission is a successor to the ESA Hipparcos mission. It's ambitious objective is to create the largest and most precise three dimensional chart of our galaxy by providing unprecedented positional and radial velocity measurements for about one billion stars in our Galaxy and throughout the local group. Each of its target stars will be monitored about 100 times over 5 year, precisely charting their distances, movements and changes in brightness. It is expected to discover hundreds of thousands of new celestial objects, such as exoplanets and failed stars, GAIA should also identify tens of thousands of asteroids.

Gaia is being built by EADS Astrium and is scheduled for launch in 2012. This article is about the wave front sensor that TNO build for this mission. This Wave Front Sensor will be used to monitor the wave front errors of the two GAIA telescopes mounted on the GAIA satellite. The wave front errors may be corrected by a 5-DOF mechanism incorporated in the GAIA telescopes, which also function in orbit. The GAIA-WFS will operate over a broad wavelength (450 to 900 nm) and under cryogenic conditions (130 to 200 K operation temperature). The WFS uses an all reflective, a-thermal design and uses a Shack-Hartmann micro lens array (MLA). The focal plane of the WFS is the same as the focal plane of the telescopes. The pattern generated by a star is compared to the pattern of one of the three calibration sources that is included in the WFS

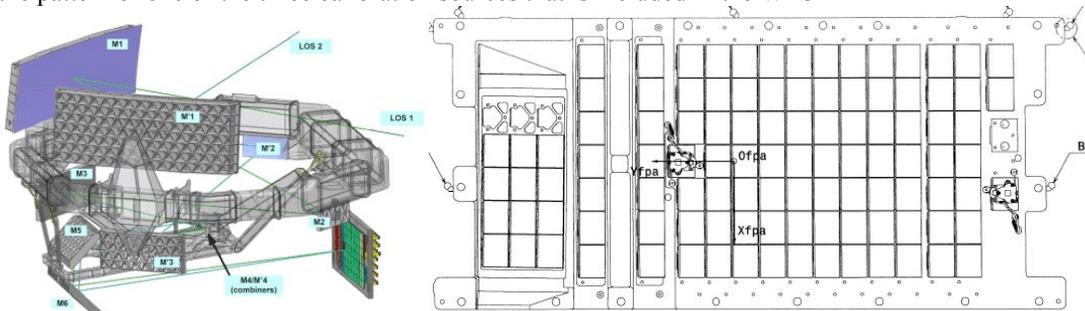


Fig. 1 A schematic view of the inside of GAIA. Two telescopes (M1) image the stars on a huge focal plane which consists of 108 CCD's. Two CCD's are reserved for wavefront measurements.

This paper presents the robust and lightweight opto-mechanical design that is optimised for launch and cryogenic operation. Furthermore, details on its alignment and commissioning are also presented. The WFS can measure wave front distortions in the order of $\lambda/1000$, and determines the focal plane with an accuracy of 50 μm

Table 1. The main requirements for the WFS are listed.

- Shack Hartmann measurement method
- Measurement of wave front errors in-orbit and on-ground
- In-orbit calibration by fibre sources
- Entrance FOV: 0.2×0.5 arcmin² (2×5 mm²)
- Sampling of wave front: 3×9 points per pupil
- Uses 1 CCD in the GAIA FPA (59×45 mm²)
- Mechanical envelope: approximately $60 \times 60 \times 150$ mm³
- Mass: < 500 gram
- Mechanical interface with SiC FPA
- Operation at 160 K (130-200 K)
- Relative grid distortion < 300 nm ($\approx \lambda/1000$ rms at MLA)
- Magnification: $1/6 \pm 1\%$
- FP accuracy 20 μ m

The interface with SiC, the weight, the low distortion and the operational temperature were the driving force for the opto mechanical design.

III. WFS PRINCIPLE

The task of the WFS is to measure the wave front error of the GAIA telescopes on the ground as well as in orbit. To this purpose two small fields at the edge of the astrometric field of view are used. These small fields are relayed to two WFS instruments. In each WFS two fold mirrors are used in front of the GAIA focal plane (CCD plane) allowing to producing a sky image at the WFS entrance slit.(field limiter) The WFS entrance slit measures 2×5 mm², corresponding to the GAIA telescope entrance field of view of $0,2 \times 0,5$ arcmin². The optical path of the WFS, extending between the slit and the GAIA focal plane, includes a beam splitter, imaging optics and a micro-lens array. The imaging optics images the exit apertures of the GAIA telescopes next to each other on the micro-lens array. The micro-lenses each produce an image of the entrance slit on a dedicated CCD at the GAIA focal plane. Thus each micro-lens corresponds to a sample of the telescope pupil and the position of the star image it produces depends on the wave front tilt at that point of the pupil (Shack Hartmann sensor principle). Each WFS instrument ‘sees’ both telescopes of GAIA, allowing to measure wave front distortion at two different GAIA pointing directions. The principle is shown in Fig. 2

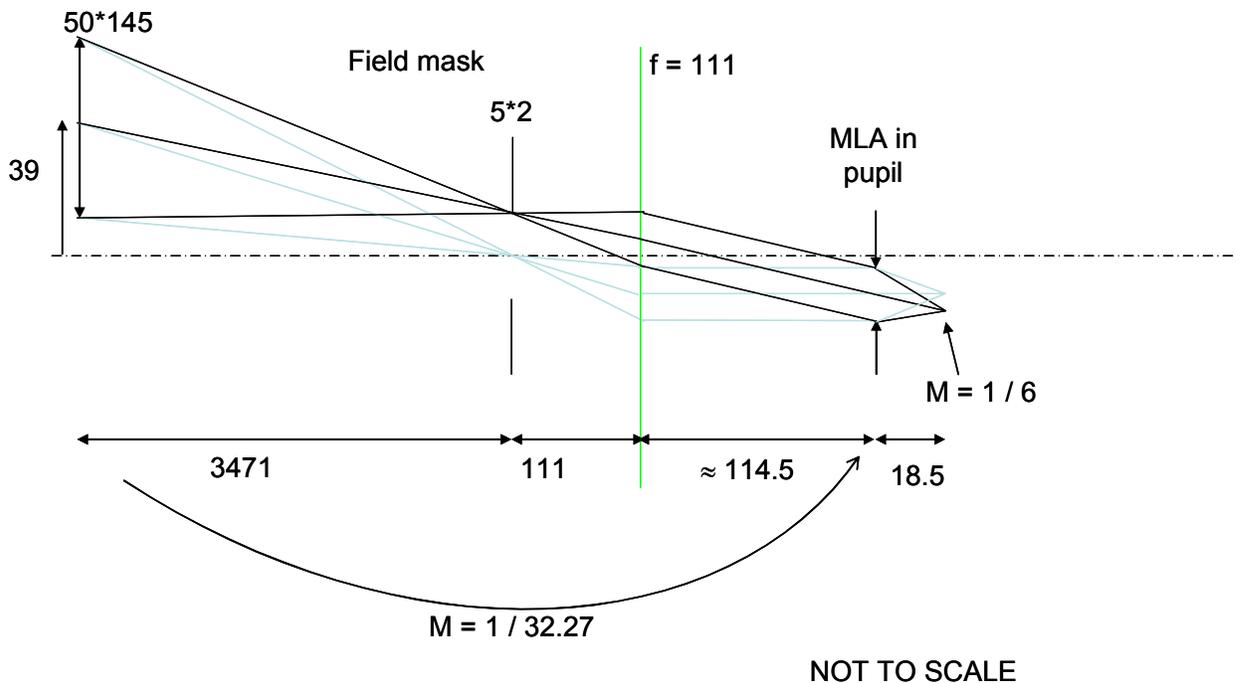


Fig. 2 Optical chain from telescope exit pupils to GAIA FPA. The two telescopes apertures with dimensions of 50×145 mm are imaged on a MLA. In the focal plane a fieldmask is placed with the dimensions of 5 by 2 mm.

In order to have a well predictable temperature dependence, the focusing element is a mirror instead of lens, also ensuring low chromaticity (wavelength range to be considered is 450 to 900 nm). Optical simulations showed that in order to reach all requirements with a refractive element, that element would consist of 4 different types of glass (due to the wavelength range 450-900 nm), which is unnecessary complex (and risky).

For the microlens array, the wavelength requirement has less influence: the spots are well diffraction limited. The MLA has to be robust to minimize risk during mounting/alignment and cooling down the instrument to 130K. An MLA made from one single piece of fused silica has been chosen, which was then qualified for these environment conditions.

Actual Optical design

A spherical mirror M1, at low angle is used to image the GAIA exit pupil on the MLA (Fig. 3). The two folding mirrors allow that the focus plane of the MLA is in the same plane as the GAIA telescopes. The Beam splitter just after focus allows the insertion of calibration sources, for the in flight calibration.

The low angle of incidence ensures low aberration, and the use of mirror optics results in a design that is insensitive to temperature differences, even allowing alignment at ambient, while operation is at 160K.

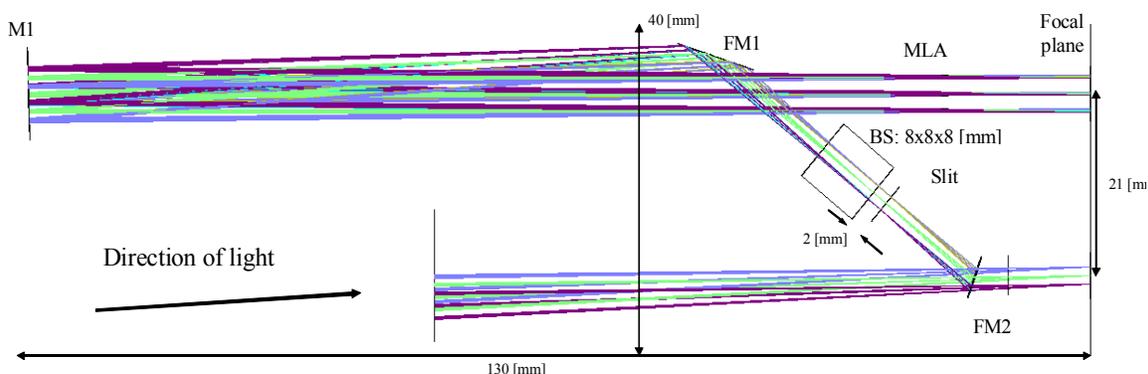


Fig. 3 The optical design for the GAIA-WFS. M1 images the light from the exit pupils on the MLA. A Beam splitter is used to incorporate calibration sources virtual in the focal plane. Fm1 and Fm2 are plane folding mirrors.

The optical chain after the telescopes exit pupils (3.5 meter to the left) up to the focal plane is shown in Fig. 2. Two flat folding mirrors (FM2 and FM1) are used to guide the light to a spherical mirror (M1), which images the telescope on the MLA. The beam splitter (BS) behind the slit permits the introduction of 3 calibration sources (in the form of 3 single mode fibres tips) not shown in the figure. Also the general dimensions are displayed: The area span by the mirrors is in the order of 130 by 40 mm.

The two WFS instruments differ in the angle of FM2, since the two WFS instruments will be mounted on a different place on the GAIA focal plane, and will thus have a different nominal incident angle. This angle difference also leads to a slight focus difference of the not central calibration fibres.

IV. MECHANICAL DESIGN

Mechanically the WFS design consists of an Invar interface structure and an optical housing, an Invar tube to mount the optical components on, see Fig. 4. The Invar interface has flexures to compensate for thermal expansion differences between the SiC support structure and the WFS. The three footings of the Invar interface are bolted to the SiC support. The WFS will be aligned to the CCD plane using Invar shims under the 3 footings. For alignment 2 reflective references are provided (X-Y, X-Z)

The optical column is mounted on the Invar interface structure. The optical parts (3 mirrors, Beam splitter, MLA and a Ferrule) are mounted on the outside of the optical housing. Optical components including the ferrule are readily accessible during mounting and alignment, because of their exterior attachment to the housing .

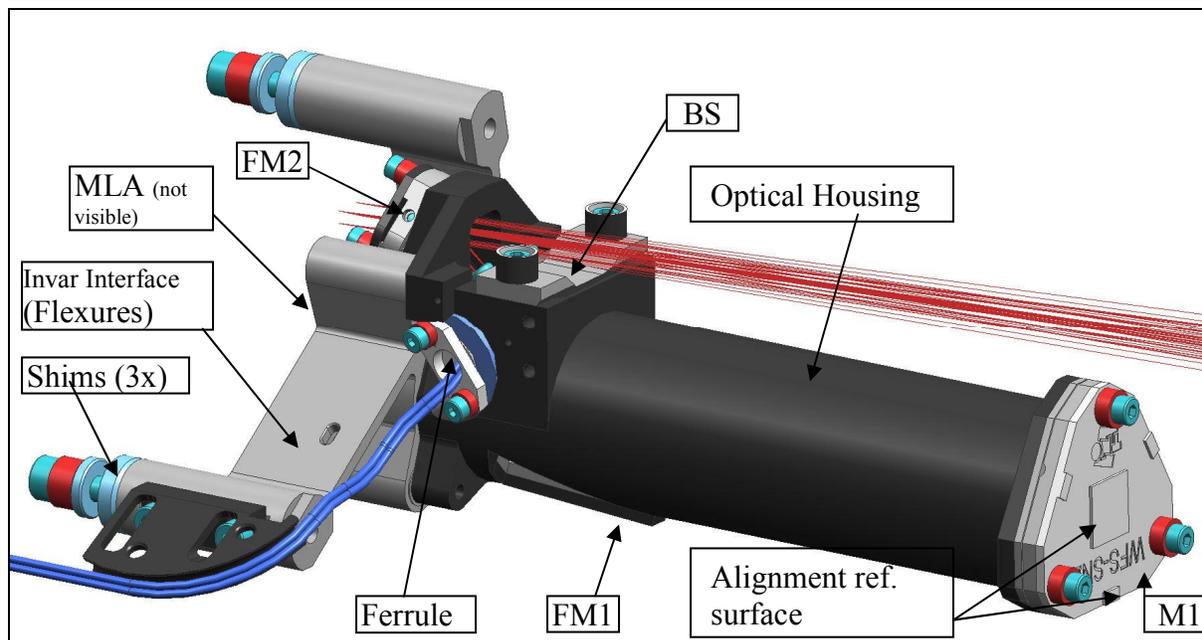


Fig. 4 Overview OMA design, indicating the two folding mirrors (FM1 and FM2), the spherical mirror (M1), the beam splitter (BS), the micro lens array (MLA), the ferrule which consists of 3 monomode fibre tips as calibration sources and the structure.



Fig. 5 The WFS qualification model. The WFS's exterior is black for stray light reasons. The interface to the SiC GAIA-focal plane is by 3 tangential invar flexures. Three calibration fibres can be seen (blue). The WFS is 150 mm high, and weighs less than 500 grams.

V. ON GROUND SUPPORT EQUIPMENT

The purpose of the on ground support equipment (OGSE) is to demonstrate the performance of the qualification and flight hardware. The main functions are listed:

- Simulate the GAIA telescopes.
- Simulate a star inside the FoV of the telescopes

- Simulate the environment (130k to 200K, operational at 160K)
- Measure the performance of the WFS with sufficient resolution

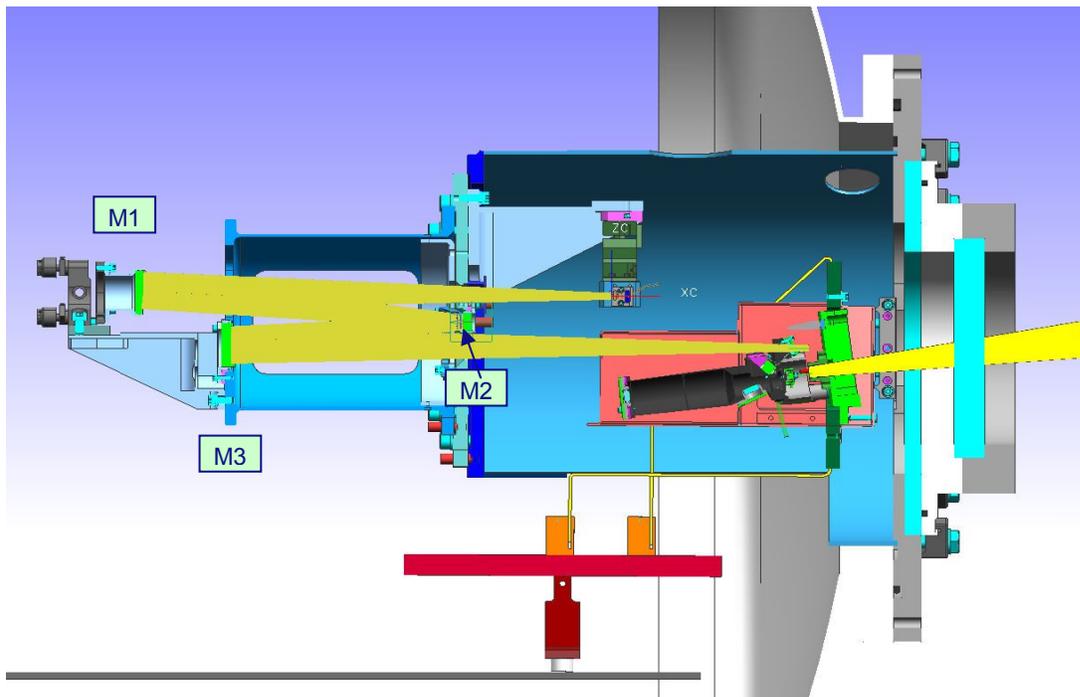


Fig. 6 Cross section of the OGSE (inside the vacuum chamber). The system consists of a fibre which is mounted on an xyz-translation stage. An a-symmetrical Offner system (M1, M2 and M3) image the fibre on the focal plane. The WFS is mounted inside a cold box. Only the box with the WFS is cooled.

VI. PERFORMANCE

The performance of the WFS for different environmental conditions has been determined. Since the alignment is performed at ambient, it should be ensured that the WFS does not change when cooling down to operational temperatures. In Fig. 7 a time-trace is given of the focus change during cooling down from 300K to 130K. The operational temperature is 160K. The measurement confirms the temperature stability of the invar/fused silica design.

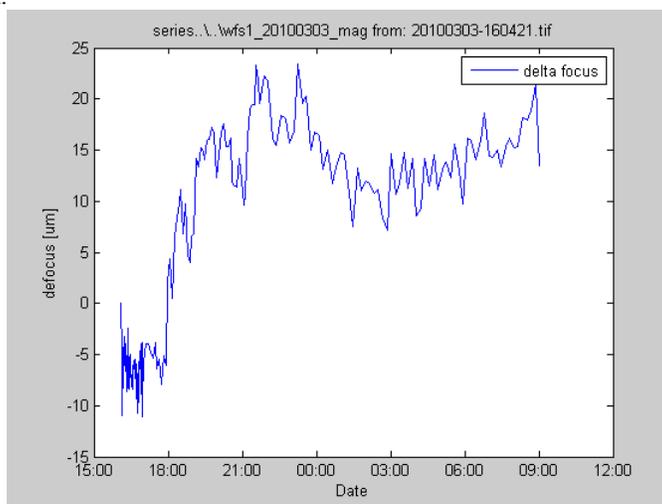


Fig. 7 The focus stability of the WFS in micrometer versus the time. With the internal calibration fibre used as source, the spot pattern can be used to evaluate a focus change. The WFS temperature started at 300K. At 16:00 the temperature controller was set to 130K, which was achieved at 21:00. The WFS remained cold for the night.

The other main performance requirement is differential grid distortion: within the FoV of the WFS, the differential grid distortion should remain below 300 nm at spot-position, which equals to about 0.7 nm rms at

MLA level. To determine this requirement the differential grid distortion over one line-scan in the field of view is determined.

The performance is noted for the grid consisting of all spots, and for 89% of the spots (omitting the extreme spots). The requirement is on all spots, but from the difference between the 89% and 100% values the measurement noise can be estimated.

Atmospheric distortion, vibration, random distortion due to the OGSE, in addition to the inherent WFS performance, will influence the measured results, which is specified at a maximum deviation value.

During the test campaign of the WFS, at different moments a series of optical measurements have been performed to determine the optical performance. In the test campaign these series are numbered from 1 to 4.: 1: Ambient, 2: vacuum 300K, 3: 160K, 4: 300K (repeat of 2) These points are chronological in time. For these points one scan in the FoV is presented: a star travelling from location C1 to C2 to C3, and the distortion is compared to a star at location E2. (position of calibration star) This covers the full field in the y direction.

In Fig. 8 results are given of this scan. The measurement noise is 100nm, and since the performance value is specified on extremes this noise is added to the determined performance.

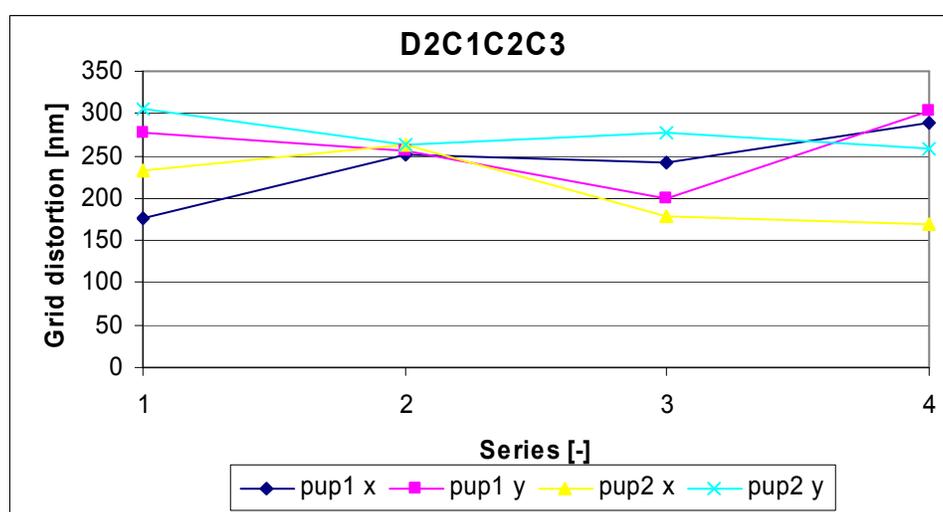


Fig. 8 The differential grid distortion over one line at different conditions (horizontal axis). The performance is measured at ambient RT (1), vacuum RT (2), at 160K (3) and at RT (repeat) (4).

VII. CONCLUSION

The GAIA wavefront sensor has been designed, build and tested. The optical performance is 300 nm differential grid distortion, which equals 0.7 nm rms wavefront error at MLA. Demonstrating the high performance is not an easy task, requiring high quality test equipment (for instance: vacuum window, external lenses camera and mechanical manipulators)

An absolute focal plane accuracy of 50 μm is achieved, which is very good considering the low NA of the optical system (<0.04). The main limitation to this performance is a 20 μm measurement uncertainty in determining to 'real' focal plane, which is encountered twice during the alignment. Apart from this (random) effect there is a predictable offset (of 15 μm) due to temperature change, resulting in the overall 50 μm uncertainty.

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- [2] L.L.A. Vosteen et al, "Wavefront sensor for the ESA-GAIA mission", Proc. SPIE, VOL 7439, 2009.