Ultraprecision Manufacturing and Alignment of the GRAVITY K-Mirror for the Very Large Telescope Interferometer

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1 Introduction

GRAVITY will be a new interferometric near-infrared instrument for the Very Large Telescope Interferomter (VLTI) of the European Southern Observatory (ESO) [1]. The wavefront sensors of the instrument employ a K-mirror system for image derotation. It is a three mirror configuration that rotates about an axis in line with the incomming beam. This de-rotator is located inside the VLT Coudé labs at ambient temperatures (0° - 15° C). The entire de-rotator includes a rotation stage as drive system and the attached optomechanical K-mirror assembly. In case of the GRAVITY instrument the K-mirror consists of a prismatic shaped mirror and a flat mirror which have to be polished to a surface shape deviation less than 30 nm root mean square (rms) and a surface roughness less than 2 nm rms. In order to prevent diffraction effects, periodic structures like diamond turning marks have to be removed in the polishing process. The tip-tilt errors of the individual mirrors are critical in the sense that they cannot be compensated by re-adjusting the whole de-rotator. Hence the maximum tip-tilt angle error of the mirror surfaces have to be within 8 arc seconds. Besides the optical performance of the mirror surfaces the

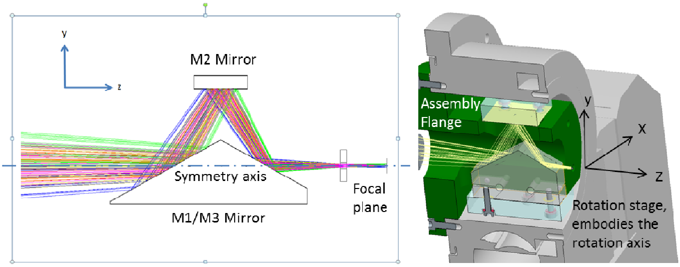

Figure 1: Beam path and de-rotator with K-mirror assembly

thermal behavior and deterministic alignment and assembly process are the main difficulties for the de-rotator system.

2 Athermal Design

To avoid thermal induced figure and position deviations and to converge towards the thermal expansion of the rotation stage interface (stainless steel) an athermal design was developed. It is based on the usage of a CTE-tailored aluminum-silicon alloy as a substrate material and electroless nickel (NiP) as a polishing layer for the mirror surfaces [2]. As a result of the survey made by dilatometric measurements, the influence of different silicon contents of the substrate material are determined for temperatures down to -180°C. Using an alloy with a silicon contents between 39 wt% and 41 wt% the CTE mismatch is less than 0.5 $*10^{-6}$ K^{-1} (Figure 2). This way it is possible to reduce the bimetallic bending, as the main impact to dimensional stability over temperature, significantly.

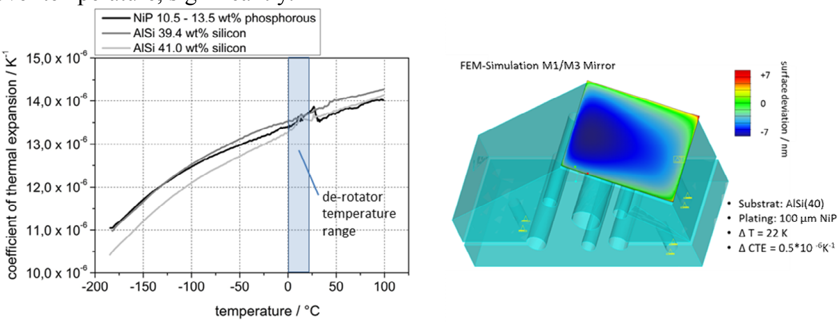

Figure 2: *left:* Realized CTE-matching *right:* Temperature motivated shape deviation of the M3-Mirror

In consequence of the athermal behaviour of the material combination, thermal induced expansion does not affect the de-rotator function. To ensure the optical specification of the mirrors itself finite elements method simulations (FEM) were carried out. By applying a polishing layer of NiP with a thickness of 100 µm and considering the difference between the manufacturing temperature (22 °C) and the lowest working temperature (0 °C) the calculated figure deformations are less than 15 nm peak to valley (p-v). Figure 2 illustrates the FEM results of the M3 mirror. To confirm the adequacy and accuracy of the calculations, a test mirror made from the selected material composition was investigated. Interferometric measurements at the temperature range from 0° C to 24 °C were performed for a clear aperture of 40 mm. The results documented in figure 3 emphasize the suitability of the athermal approach.

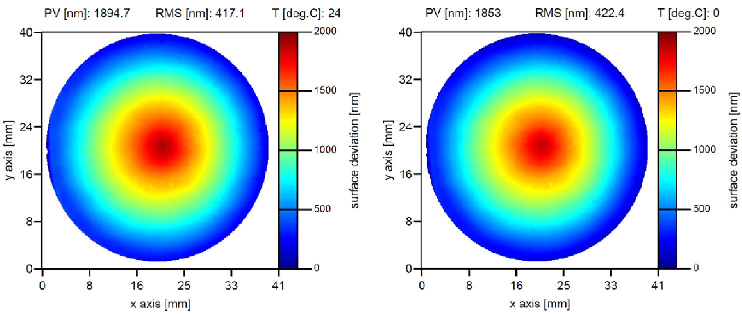

Figure 3: Surface deviation at different temperatures, (left: 24 °C, right: 0°C)
Mirror substrate: AlSi40, Polishing layer thickness (NiP): 60 µm

3 Manufacturing and Alignment Methods

The main challenge of a de-rotator system is the positioning of the mirrors relative to each other as well as the alignment of the rotation axis relative to the axis of symmetry in Tx, Ty, Tz and Rx, Ry. Individual mirror offsets in Tx and Ty can be compensated by adjusting the de-rotator relative to the axis of rotation. The Tz offset is adjustable using the following off-axis parabola. The mirror offsets in Rx and Ry are very sensitive regarding the pupil center which should not vary by 1/10 of a sub-pupil (18 µm) over a full rotation. In a detailed tolerance analysis the following values are deduced:

- Mirror positioning in Tx, Ty, Tz: better than 50 µm
- Mirror tip-tilt error (Rx, Ry): better than 8 arcsec
- Rotation axis and symmetry axis should be aligned in Tx, Ty better than 10 µm lateral shift and better than 8 arcsec in tip-tilt (Rx, Ry).

The approach to achieve these specifications is the ultraprecise manufacturing of the optical surfaces as well as the mounting structures in one and the same machining setup. Thus, the position and orientation of the optical surfaces is well known with respect to the mechanical coordinate system. For the prismatic M1/M3-Mirror, the M2-Mirror and the mounting plate a typical flycutting process can be used to realize a surface flatness well below 0.5 µm. In case of the prismatic M1/M3 mirror a setup with an index table provides angular tolerances below 4 arcsec. Shape accuracy and micro roughness will be improved by local polishing techniques while preserving the angular tolerances. For the assembly flange, both flycutting and diamond turning are required in one setup. The machining technique is based on a four axis ultraprecision machine with a flycutting head and a turning tool. The workpiece is mounted onto a spindle that can be operated as C-axis.

All manufacturing tolerances and the assembly steps can be easily checked by interferometric measurements respectively by goniometric measurements with less than one arc second accuracy. The same measurement techniques can be applied to align the de-rotator relative to the axis of rotation of the stage.

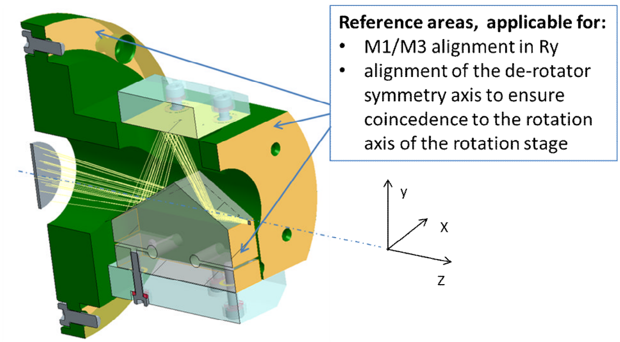

Figure 4: De-rotator assembly with optical detectable areas for system alignment

4 Conclusion

Common K-mirror assemblies need to be aligned in a time consuming, iterative adjustment procedure. By the strict application of ultraprecise manufacturing methods for both, optical elements and mounting structures, the required assembly effort for the GRAVITY K-mirror could be significantly reduced. Finite element simulations and experiments demonstrate the advantages regarding the expansion controlled substrate material in combination with electroless nickel as a polishing layer.

References:

[1] Eisenhauer, F. et al., "GRAVITY: Microarcsecond Astrometry and Deep Interferometric Imaging with the VLT," Astrophysics and Space Science Proceedings, p. 361 (2009).

[2] Rohloff, R.-R.; Gebhardt, A.; Schönherr, V.; Risse, S.; Kinast, J.; Scheiding, S.; Peschel, T.; A novel athermal approach for high performance cryogenic metal optics, SPIE Astronomical Telescopes and Instrumentation 2010, SPIE Proc. Vol. 7739 (2010) 77394E