Simulation of deformation measurements with deflectometry

Wansong Li*, Jan Burke**

*VEW GmbH, Edisonstraße 19, D-28357 Bremen
**Bremer Institut für Angewandte Strahltechnik GmbH, Klagenfurter Straße 2, D-28359 Bremen

mailto:Burke@BIAS.de

We present a first assessment for the feasibility of characterising actuator performance and gravity sag for the European Extremely Large Telescope (E-ELT) mirror segments by deflectometry. Artefacts related to noise in the phase measurements translate into bogus Zernike terms, but reliable detection of the relevant Zernike coefficients at the 25 nm level seems possible.

1 Introduction

It is well known that absolute shape measurement with deflectometry is very susceptible to calibration errors – in difference measurements, however, calibration errors will cancel out. Deformation measurements with deflectometry have been suggested in Ref. [1] and recently been demonstrated in practice [2]. In this contribution we build on our previous work in simulating deflectometric measurements [3] and investigate the performance of difference deflectometry in low-uncertainty applications. The task is to characterise the so-called warping harnesses that are used as actuators on each of the 798 mirror facets of the European Extremely Large Telescope (E-ELT) that will be built during the next decade by the European Southern Observatory (ESO) [4]. Fig. 1 gives an impression of the size of the mirror facets.

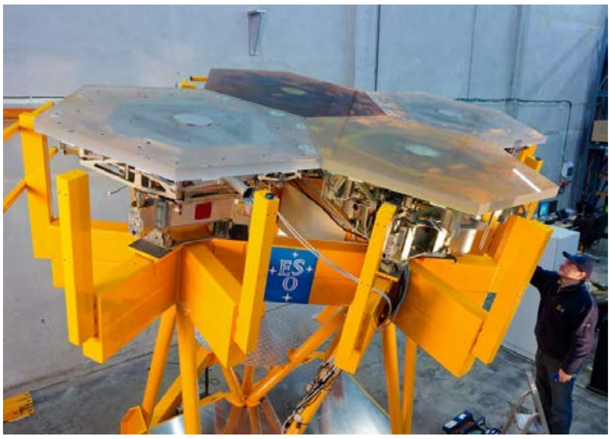

Fig. 1 *Several E-ELT mirror facets on a tiltable test jig at the ESO headquarters in Garching, Germany. Image credit: ESO/H.-H. Heyer*

The simulation assumes a full-area deflectometric test of a mirror facet (size 1.2 m from edge to edge; radius of curvature ≅ 69m) with the reference pattern being a screen about twice the size of the mirror. In practice, this will require considering error sources such as mechanical and thermal instability of experimental parameters, but modelling these would require a specific design. What we do know is that electronic and photon-shot noise will be inevitable in any set-up, and our main interest in this preliminary study is to establish a deformation detection limit due to phase-measurement errors.

2 Simulation environment

We use the BIAS/VEW software package "Fringe Processor" with a simulation plug-in that provides over 100 input parameters for describing the camera, the reference fringe pattern screen, the system geometry, the shape of the object to be measured (including added deformations), and the noise level in the measured phase maps from which the gradient maps are computed. Our setting for the noise level in an absolute phase map is 0.025 pixels rms, where the "pixel" unit refers to pixels on the reference screen and is a measure of the pointing uncertainty of a ray from the camera lens reflected by the surface under test. As a practical example, if the screen is 4 metres away from the mirror, 3 metres wide, and has a resolution of 1600 pixels in the relevant direction, this corresponds to a slope uncertainty of 0.2 mrad on the mirror surface. This performance is experimentally confirmed, and with judicious choice of measurement time, fringe period, phase-shifting method, and camera, pointing uncertainties of less than 0.005 pixels rms are possible.

All of the simulated shapes have an underlying approximately parabolic shape with conic constant –0.9964 as per the E-ELT specification. For simplicity, the outline of the simulated area is circular, not hexagonal, which causes slight errors in the calculation of the polar-coordinate Zernike coefficients, but these can be neglected within the scope of this study. The Zernike terms of interest are Z_3 (spherical), Z_4 and Z_5 (astigmatism), and Z_9 and Z_{10} (trefoil), as only these can be influenced by the warping harnesses. Deformations of 50 nm peak-to-valley were added for each Zernike term, and noisy phase-measurement maps (*x* and *y* phases) were generated for each shape. Our deflectometric reconstruction algorithm was then applied to each pair of phase maps to reconstruct the underlying

DGaO Proceedings 2014 – http://www.dgao-proceedings.de – ISSN: 1614-8436 – urn:nbn:de:0287-2014-B027-3

submitted: 31.07.2014 published: 26.09.2014

shapes and the Zernike error coefficients were extracted from the differences between deformed and undeformed states.

3 Results

First, the noise floor was tested by computing a difference map between a noise-free and a noisy shape map. The results are shown in Fig. 2.

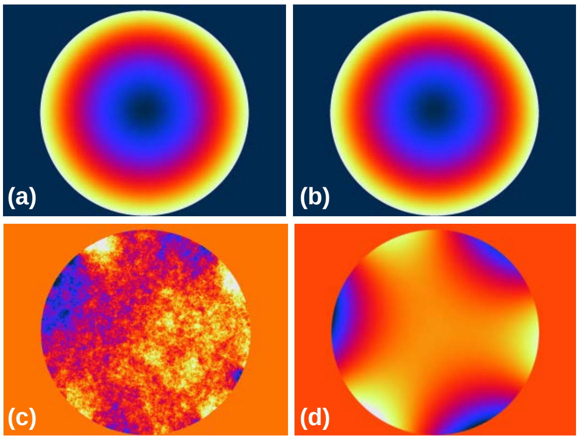

***Fig. 2** (a) Ideal shape of mirror with no noise; (b) simulation of noise-affected shape measurement. Diameter of data region: 1.42 m, colour scale ranges: 3.6 mm. (c) residual error of (b)-(a); colour scale range: 75 nm. (d) contribution from $Z_{3,4\text{-}5,9\text{-}10}$ in (c); colour scale range: 25 nm. $Z_3 = 2.7$ nm, $Z_{4\text{-}5} = 1.7$ nm, $Z_{9\text{-}10} = 12$ nm.*

No difference at all is discernible in the absolute shape maps of (a) and (b): unlike interferometry, deflectometry does not measure the difference with respect to a reference wavefront, but the absolute shape. Its high dynamic range becomes visible upon subtraction of the data, when errors in the nm range become easily visible (c). Many of these errors can be discarded, as they do not match possible deformation modes of the mirror substrate; the remaining contribution (d) reveals Zernike terms that are purely noise-related because the deformation input was zero in this case. The next trial was an input of $Z_3 = \pm 25$ nm (Fig. 3). The bold-set values in the caption show the nominal vs. retrieved value for Z_3; this is reconstructed quite reliably, but also all other Zernike terms are non-zero (red type), and some are similar in magnitude as the input deformation. Fig. 4 and Fig. 5 show the results for Z_5 and Z_{10} deformations as input.

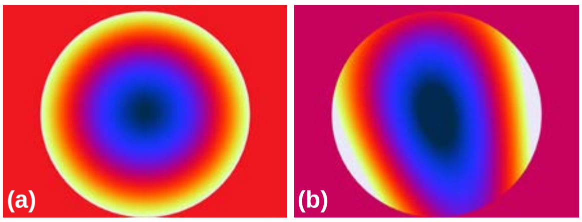

***Fig. 3** (a) Ideal deformation of mirror with **$Z_3 = \pm 25$ nm** and no noise;* rms = 14.4 nm*. (b) retrieved map of $Z_{3,4\text{-}5,9\text{-}10}$ contributions after simulated measurement:* rms = 15.6 nm, ***$Z_3 = 21.7$ nm**, $Z_4 = 19.3$ nm, $Z_5 = 11.1$ nm, $Z_9 = 5.9$ nm, $Z_{10} = 3.4$ nm. Colour scale ranges: 50 nm.*

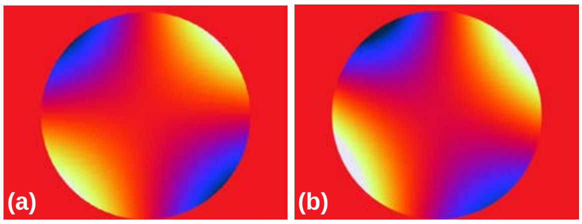

***Fig. 4** (a) Ideal deformation of mirror with **$Z_5 = \pm 25$ nm** and no noise;* rms = 10.2 nm*. (b) retrieved map of $Z_{3,4\text{-}5,9\text{-}10}$ contributions after simulated measurement:* rms = 11.4 nm, *$Z_3 = 2.4$ nm, $Z_4 = 11.2$ nm, **$Z_5 = 25.7$ nm**, $Z_9 = 2.9$ nm, $Z_{10} = 0.9$ nm. Colour scale ranges: 50 nm.*

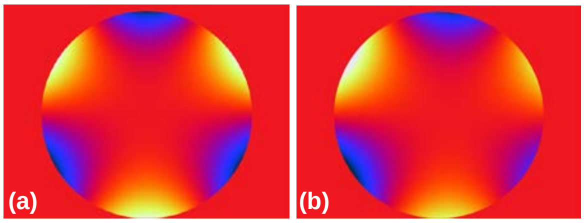

***Fig. 5** (a) Ideal deformation of mirror with **$Z_{10} = \pm 25$ nm** and no noise;* rms = 8.8 nm*. (b) retrieved map of $Z_{3,4\text{-}5,9\text{-}10}$ contributions after simulated measurement:* rms = 8.0 nm, *$Z_3 = 0.1$ nm, $Z_4 = 1.6$ nm, $Z_5 = 6.9$ nm, $Z_9 = 0.9$ nm, **$Z_{10} = 21.5$ nm**. Colour scale ranges: 50 nm.*

4 Summary and Outlook

In all noise realisations considered, the input Zernike coefficients are reconstructed well, but extra Zernike terms always appear, sometimes of similar magnitude. There appears to be no correlation between deformation and error patterns, and false positives look more likely than missed deformations. The sample size for this study was quite small, however, and many more noise realisations (preferably with noisy input fringe patterns instead of noisy phase maps) would need to be studied in order to corroborate the results of this preliminary study.

Acknowledgements

We thank Samuel Lévêque and Andrew Rakich (both of ESO, Garching) for advice and feedback during the investigations described here, and Ralf B. Bergmann (BIAS) and Christoph von Kopylow (VEW) for their support of and interest in this study.

References

[1] T. Bothe, W. Li, C. von Kopylow, W.P.O Jüptner, “High-resolution 3D shape measurement on specular surfaces by fringe reflection,” Proc. SPIE 5457 , 411-422 (2004)

[2] P. Huke, J. Burke, R.B. Bergmann, “A comparative study between deflectometry and shearography for detection of subsurface defects,” Proc. SPIE 9203, in press (2014)

[3] W. Li, M. Sandner, J. Burke, “Simulation study of deflectometry systems,“ DGaO Proceedings 114, A1 (2013)

[4] *http://www.eso.org/public/germany/teles-instr/e-elt*, accessed 20.07.2014