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Evaluation of deflectometry for E-ELT optics

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Abstract. A deflectometrical facility was developed at Italian National Institute for Astrophysics–OAB in the context of the ASTRI project to characterize free-form segments for Cherenkov optics. The test works as an inverse Ronchi test in combination with a ray-tracing code: the under-test surface is illuminated by a known light pattern and the pattern warped by local surface errors is observed. Knowing the geometry of the system it is possible to retrieve the surface normal vectors. This contribution presents the analysis of the upgrades and of the configuration modifications required to allow the use of deflectometry in the realization of optical components suitable for European Extremely Large Telescope and as a specific case to support the manufacturing of the Multi-conjugate Adaptive Optics Relay (MAORY) module.

Key words. Optics – Metrology – Deflectometry

1. Introduction

Deflectometry is a well-known method for direct surface slope errors measurement. It consists of a variation of the Ronchi test (Cornejo-Rodriguez et al. 1981) performed using a lightened screen instead of a masked light source. The method is highly recommended when large optics have to be characterized because it allows to measure the whole surface shape with a spatial resolution in the millimeters scale taking few pictures with significative time saving with respect to a point-by-point profilometric approach. The technique capabilities were recently demonstrated by Su et al. (2014) who used it to measure the 5 m diameter Large Synoptic Survey Telescope tertiary mirror and the 8.45 m diameter Giant Magellan Telescope primary mirror. In the context of the ASTRI - *Astrofisica con Specchi a Tecnologia Replicante Italiana* (Pareschi et al. 2013) project we developed an in-house deflectometry facility (Sironi et al. 2014) to supply the metrology for the free-form mirrors manufactured at INAF-OAB. In this contribution we propose a deflectometry facility design that fulfills the MAORY mirrors requirement.

2. Slope requirement

Since deflectometry directly measures slope errors, we retrieved the slope errors requirement for MAORY optics to set a possible deflectometrical facility configuration and test its feasibility. In this calculation we considered the two proposed designs for MAORY and their requirement.

The shape error requirement for MAORY is expressed in terms of *rms* of the Zernike polynomials, they are $Z4 < 500$ nm, $Z5 - Z10 < 15$ nm and $Z10 - Zn < 10$ nm on patches of 350 mm diameter. The *rms* slope of each

Table 1. Description of MAORY design and related requirement in terms of slopes. Right part of the table reports the parameters of each mirror of the two considered configurations: curvature, conic constant (k), off-axis distance (r_0). Right part of the table reports the data used to extract the slope requirement: scale factor (f), radius of curvature error related to the 500 nm *rms* requirement for $Z4$ maximum error, the slope *rms* related to $Z4$ error, the minimum slope obtained for each mirror for the two sets of Zernike polynomials $Z5-Z10$ and $Z>10$.

M#	Curvature [1/mm]	K	Diameter [mm]	r_0 [mm]	f	δRoc [mm]	Z4 Min α [sec]	$Z5-Z10$ Min α [$msec$]	$Z>10$ Min α [$msec$]
M1	1/68685	−0.9964	1400	0	1.4	14	0.24	44.2	44.2
M6	0	0	1220x800	0	0.68	–	0.39	4.24	5.30
M7	1/20820	-1.05	1220	0	0.82	4.03	0.58	5.07	5.30
M8	0	0	800	0	1.25	–	0.89	7.73	5.30
M9	0	0	700	0	1.43	–	1.02	8.84	5.30
M10	1/9900	−1.1	810	340	1.23	3.78	0.88	7.64	5.30
M11	1/6500	0	1200	0	0.83	0.40	0.59	5.16	5.30
M12	−1/2140	−0.1	350	0	2.86	–	2.04	17.68	5.30
M13	1/5340	−0.06	880	0	1.14	0.51	0.81	7.03	5.30
M14	0	0	910x640	0	2.19	0.51	0.55	5.56	5.30
M6	1/12780	−0.12	1000	0	1.0	2.26	0.71	6.19	5.30
M7	−1/6583	-0	600	0	1.67	1.66	1.19	10.31	5.30
M8/9	1/1330	−0.6	750	0	1.33	4.36	0.95	8.25	5.30
M10	−1/10250	−0	600	340	1.67	4.04	1.19	10.31	5.30
M11	1/11380	−0.2	1200	0	0.83	1.24	0.59	5.16	5.30
M12	1/5340	−10	900	600	1.11	36.62	0.79	6.37	5.30
M13	0	0	910x640	0	0.90	–	0.55	5.56	5.30

Zernike polynomial is a function of the polynomial index, the surface diameter and the amplitude of the introduced wave. As a reference we started calculating the total shape error and local slope of a reference flat mirror with 1 m diameter and 10 nm amplitude for each Zernike term (Fig. 1). It is possible to move from the obtained trend to the slope of the Zernike polynomials of each MAORY mirror multiplying the obtained values for a scale factor and for an amplitude normalization. The scale factor is expressed as $\Phi_{ref}/\Phi_{m\#}$ where Φ_{ref} is the reference mirror diameter and $\Phi_{m\#}$ is the diameter of each mirror. The scale factor associated to MAORY mirrors are in the range $0.66-2.86$. The amplitude normalization is expressed as the $\sigma_{ref}/\sigma_{req}$ where σ_{ref} is the *rms* shape error cumulated on the reference surface while σ_{req} is the requirement associated to that polynomial interval. The amplitude normalization obtained for the Zernike polynomial interval $Z5-Z10$ is 0.61 while the one calculated for the interval $Z11-Z200$ is 0.08. We underline the slopes requirement for $Z10-Zn$ have been obtained considering the 350 mm patch scale factor instead of the whole mirror one. These normalization factors can be assumed as the worst possible case since they give the same weight to each Zernike index. The typical spectral density of shape irregularities shows instead that lower frequencies have higher amplitudes, thus the region where slopes are lower is

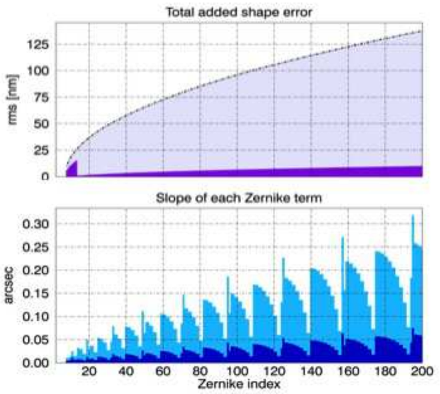

Fig. 1. Total slopes (upper panel) and shape errors (lower panel) of each Zernike term obtained generating the Zernike polynomials on a round surface with diameter of 1 m and amplitude of 10 nm.

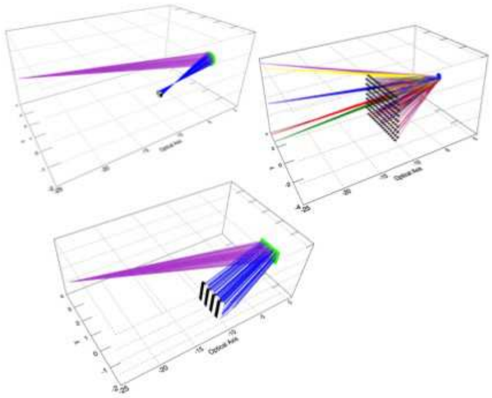

Fig. 2. Simulations of the reflections obtained in the assumed configuration on three kind mirrors. Upper panel: M8-config 2, the most concave mirror. Central Panel: M6-config 1, a flat mirror. Lower panel: M12-config 1, the most convex mirror.

over normalized. The obtained slopes requirement is expressed in table 1 for each considered mirror.

3. Facility configuration

To set a possible deflectometrical facility configuration we considered the minimum allowed slope error and chose the facility components to obtain an adequate angular resolution. Since we should measure angles up to 4 milliarcseconds we set the camera-mirror distance in order to allow the shift of a photon deflected by this angle to be appreciable in terms of pixels.

Considering the measuring facility angular resolution as 0.5 the value to be measured, a pixel dimension of 5 μm and an interpolation capability allowing the detection of 0.1 pixel, we obtain a camera-mirror distance of $\sim$ 25 m. Once this distance is set, the objective focal length is chosen to cover the CCD area with the mirror image. Hence, more objectives would be necessary in dependence of the diameter of the under-study mirror. The shorter objective would be used to measure M11 of the design 2 while the longest to measure M6 of the design 1, they will have focal length of $\sim$ 350 mm and of $\sim$ 1400 mm respectively. Assuming this setup, we simulated the effect of the reflection on the involved surfaces (using a ray-tracing code) to find which dimension a screen should have to cover the image area. We studied three different cases: M8 of configuration 2 that is the most concave mirror, M6 of configuration 1 a flat mirror with the biggest dimension, M12 of configuration 1 the most convex mirror. We found that it is not possible to cover the area of the image produced by the convex mirror using single camera. The problem can be solved with stereoscopic image acquisition (Knauer et al. 2004), in the specific case of M12 a screen of 100 inches should be observed by 5 different cameras, with the central one at 3 m off-axis to avoid vignetting effect. Hence, an ad hoc solution to respect the required angular resolution can be found. Unfortunately, there are specific errors that affect the measurement accuracy, in particular the errors in the distances mirror-screen and mirror-camera directly produce an error in $Z4$ evaluation. Considering M11 of configuration 1 we found that the requirements on the radius of curvature measurement accuracy is of 0.4 mm. Proceeding as in the previous calculation we ask the measuring error to be one half of this value. So we should guarantee the distances between the involved objects (disposed at 25 m one to the other) to have an accuracy of 0.2 mm. This will require a continuos temperature control, a strict require-

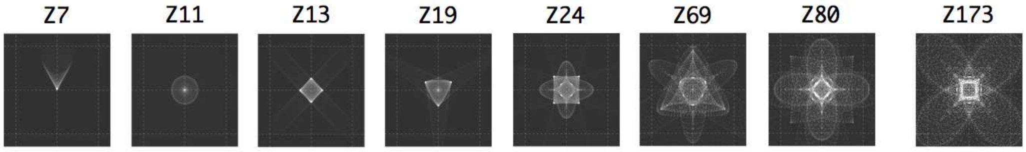

Fig. 3. PSFs simulated for M1 with shape error expressed in Z terms with amplitude of 10 nm (on an aera of 80x80 μm). The simulation was performed for each index up to 200, we report here some examples.

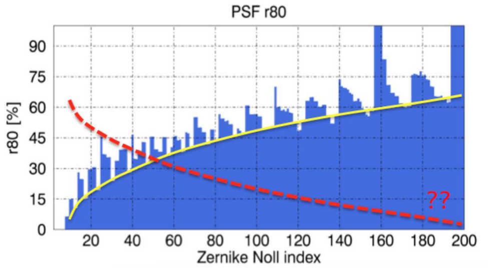

Fig. 4. The blue area express the r80 dependence on Zernike index. The yellow line represents the fitting line and the red dashed line the proposed requirement curve for the Zernike terms amplitude composing the surface shape error.

ment on structure hardness and frequent calibrations.

4. Conclusions

Considering the shape error requirement of E-ELT optics we retrieve the correlated slopes requirement and set the angular resolution a deflectometry facility should have to properly measure these optics as ∼ 2 *marcsec*. A facility with this resolution can be configured but to guarantee the measurement accuracy for low spatial frequencies it is necessary to introduce a precise cavity calibration system. Anyway, we propose to set the requirement on the Zernike terms amplitude as function of their index instead as a cut-off. Studying the effects on the PSF produced by shape error due to single Zernike terms all with the same amplitude of 10 nm on a mirror with M1 optical design (Fig. 3) we obtained their weights on the image degradation and these data can be used to set a new requirement. Considering this approach the required angular resolution will be lower and the experiment less challenging (Fig. 4). As last note, we point out that it is not convenient demanding a meterological machine capable to measure with high accuracy all the spacial frequencies. Deflectometry is time and cost saving in inspecting medium and high spatial frequencies but is tricky for lower ones. In conclusion it will be more profitable to adopt an hybrid solution taking advantage of the synergy between deflectometry and profilometry (Civitani et al. 2015). The first will be devoted to measure medium-high frequencies error skipping the cavity calibration difficulties required to measure the lower ones. The second will be used to acquire a limited number of points–containing the otherwise excessive measuring time–to measure low-frequency errors.

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