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Authors	SIRONI, GIORGIA, CANESTRARI, Rodolfo, Tayabaly, Kashmira, PARESCHI, Giovanni
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Evaluation of novel approach to deflectometry for high accuracy optics

Giorgia Sironi[a], Rodolfo Canestrari[a], Kashmira Tayabaly[a,b], Giovanni Pareschi[a]
[a] INAF-Osservatorio Astronomico di Brera - Via Bianchi 46, 23807 Merate, Italy
[b] Politecnico di Milano - Via La Masa 1, 20156 Milano, Italy

ABSTRACT

A deflectometrical facility was developed at Italian National Institute for Astrophysics-OAB to characterize free-form optics with shape errors within few microns rms.

Deflectometry is an interesting technique because it allows the fast characterization of free-form optics. The capabilities of deflectometry in measuring medium-high frequencies are well known, but the low frequencies error characterization is more challenging. Our facility design foresees an innovative approach based on the acquisition of multiple direct images to enhance the performance on the challenging low frequencies range.

This contribution presents the error-budget analysis of the measuring method and a study of the configuration tolerances required to allow the use of deflectometry in the realization of optical components suitable for astronomical projects with a requirement of high accuracy for the optics. As test examples we took into account mirrors for the E-ELT telescope.

KEYWORDS: deflectometry, metrology, mirrors qualification, free-form optics, ray-tracing

1. INTRODUCTION

Deflectometry is a well-known method for optics testing. It allows the direct extraction of the surface normal vectors of a reflecting surface from the observation of deflected photons direction. The deflectometry principle is based on a classical optic test, the Ronchi test [1], [2]. This test consists in the by-eye observation of a known black and white pattern reflected by the optical surface to be tested. In that case the person looking at the mirror would observe the mirror covered in a pattern of stripes revealing the mirror's surface. Nowadays the human eye has been substituted by a camera recording the image created on the surface of the mirror. Hence, modern deflectometrical tests consist in taking series of pictures of an illuminate surface. The extraction of the direction of the surface normal vectors is thus reduced to a triangulation problem.

The main advantage of deflectometry is that it allows obtaining optical surface slope error with a spatial resolution in the millimetres scale taking few pictures, with a significant time and cost savings with respect to a point-by-point profiling approach. This feature makes deflectometry very suitable for all the industrial purpose involving surface inspection (automotive, medical, architectural glass etc.) and pushed the commercialization of deflectometrical benches. The accuracy required by these kinds of industrial applications is usually too low for astronomical optics but it is known that the technique has the capability of being extremely accurate. An historical example is represented by the Long Trace Profilers (LTP) [3] whose working principle is properly the measurement of the deflection angle, caused by the local surface slope, of a laser beam. LTP were developed to measure x-ray optics with accuracy better than 0.1 microradians and recently upgraded to an accuracy of 10 nanoradiants[4] [5] allowing the reconstruction of single profiles with an accuracy of few tens of nanometres. In the last years, the University of Arizona made a great leap forward in deflectometry. Who developed SCOTS [6], a deflectometrical software that allows the shape characterization of astronomical optics with accuracy within tens of nanometres.

At the Astronomical Brera Observatory (OAB) that is part of the Italian National Institute for Astrophysics (INAF) we developed an in–house deflectometry facility [7] [8] required to be accurate for testing the mirrors of the ASTRI Cherenkov telescope [9]. ASTRI is prototype for the small size class telescopes for the Cherenkov Telescope Array

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(CTA) [1]. Cherenkov telescopes are designed not to focus point-like source but to observe electron showers. Hence their optics have loose requirement on shape error (~ 10 μm rms) but should cover large fields-of-view. Considering these requirements, the Cherenkov Telescopes optical components are usually realized as segmented mirrors. Their manufacturing and characterization should be fast and cost-effective due to the high multiplicity of the segments (as an example the number of the small class telescope that will be installed at the CTA south site is 70, each mounting 18 panels). A deflectometrical approach, realized in its low-cost, low-accuracy version, is perfectly matching the Cherenkov telescope case.

Our intention is to upgrade our facility to reach better accuracy making our deflectometrical laboratory suitable for characterizing astronomical optical components in their manufacturing phase. INAF is leading the opto-mechanical development of the Multi-conjugate Adaptive Optics Relay (MAORY) [12] for the European Extremely Large Telescope (E-ELT) project [11]. MAORY requires high accuracy optics with shape error less then 15 nm on all the Zernike polynomials beyond the spherical component. Although still under study, we used MAORY optical design as test case to understand the upgrade our deflectometrical facility should implement to be applicable as quality test in high accuracy optics manufacturing process. MAORY optical design is yet under study but all the proposed solutions include large aspheric mirrors with required of few nanometres rms. The realization of the MAORY components is strictly dependent on the metrology accuracy, hence their characterization is particularly challenging.

In this paper we introduce our deflectometrical facilities configuration, then we analyse the MAORY case to set the measuring requirements. Finally we propose a possible configuration to achieve the required measuring accuracy.

2. DEFLECTOMETRY FACILITY AT OAB

The first deflectometry facility at OAB was designed to test Cherenkov mirrors manufactured in-house. The guidelines for the instrument design were to be able to measure one mirror with spatial frequency in the millimetre range in less then 1 hour with accuracy better then 10 μm. The accomplishment of these requests represented a big step forward in the mirror supplying chain with respect to the procurement of a 3D coordinate measuring machine. Hence we could save both time and money. We developed a working facility with commercial components, with a total cost within 10 keuros, capable to acquire data in few minutes with spatial frequency within 1 mm. As a comparison, we point out that comparable spatial frequency coverage could be obtained with a single point acquiring measuring machine in about 6 hours.

A picture of the realized deflectometry laboratory is presented in Figure 1. The facility for ASTRI Cherenkov mirrors could not be compact because their optical design is not focusing. Each ASTRI's mirror has off-axis polynomial profile and since they are designed to operate in double reflection with a polynomial secondary mirror they are, as single mirrors, not focusing surfaces. The reflected images produced by some of these mirrors have lateral dimension never smaller then 1 m. This is why to measure ASTRI mirrors we needed a screen size bigger then 1 m.

In our laboratory added a second step we to the standard deflectometry measurement procedure consisting of the direct observation of the image reflected by the mirror in direct illumination. For this test the camera is replaced with a LED light source and the reflected image is observed on a flat panel [7]. The comparison between the image simulated by the ray-tracing of the measured slopes (Figure 2 right panel) and the pictures acquired in direct illumination (Figure 2 left panel) shows the capability to reconstruct the mirror's local structures. Moreover, the repetition in a close loop of the direct illumination test at different distances allows the removal of misalignment errors. Hence this validates deflectometry method for characterizing mid-low frequencies errors regime. With the presented facility we fully characterized the mirrors and extracted the PSF at the focal plane of ASTRI telescope [13]. The typical range of the slope errors for ASTRI mirrors is of few arcminutes.

Considering the promising results of the facility realized for the Cherenkov mirrors characterization a second compact facility was assembled. The new portable facility simply consists in a small computer screen holding the camera on top. This setup allows characterizing focusing optics almost close to 2f configuration, guaranteeing better sensitivity in resolving the local defect. To test the portable facility capabilities an experimental measurement was made on a squared shaped spherical mirror with radius of curvature of ~ 34 m and side dimension of 500 mm. To understand the quality of the results we decided to acquire, similarly to the Cherenkov mirrors facility, the PSF in direct illumination. The experimental setup is presented in Figure 3: the 2f facility available at INAF-OAB [14] was modified simply adding the screen-camera device next to the CCD camera.

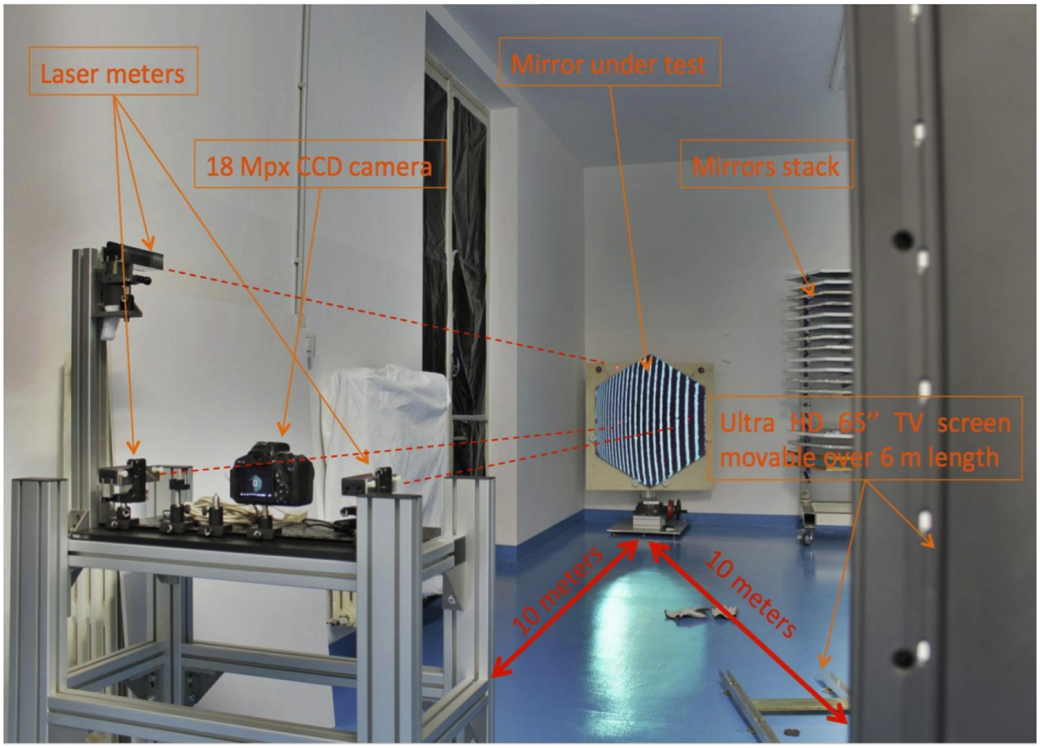

Figure 1 - Picture of INAF-OAB deflectometry laboratory. Each point of the mirror can be associated with the position of a specific pixel on the screen. Knowing the distances between the screen, the camera ad the mirror the normal vector to the surface at the considered point can be calculated (original image presented in arXiv:1402.3515 [astro-ph.IM]).

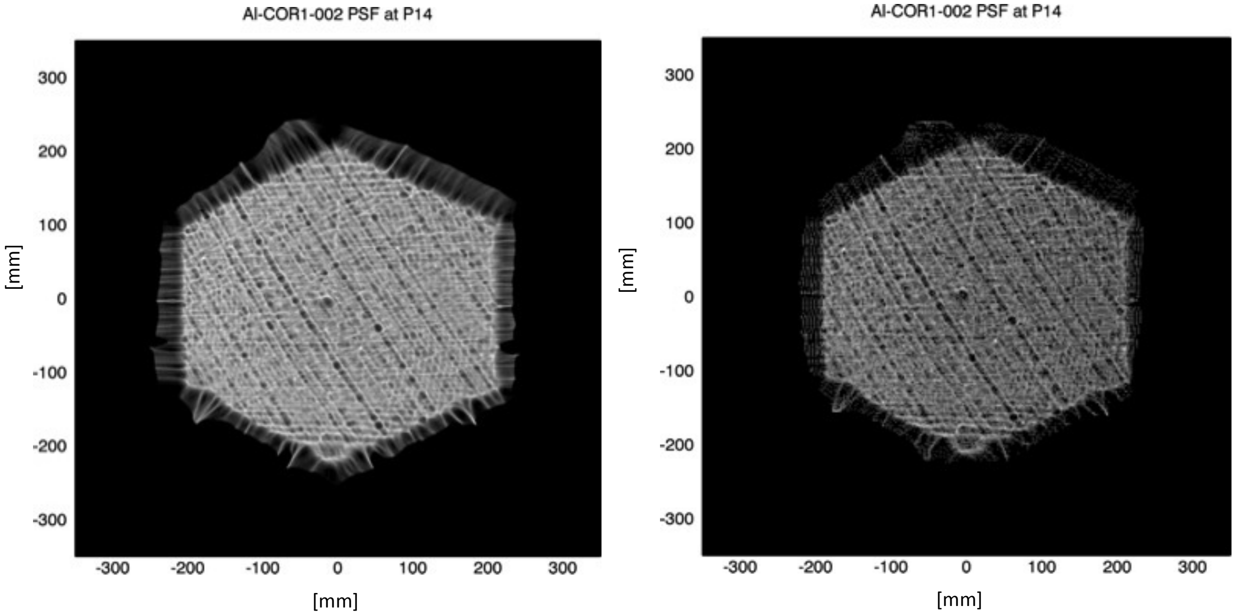

Figure 2 - Left: Picture of the image generated by the reflection on the directly illuminated mirror; Right: image obtained by means of the ray-tracing simulation considering the measured slope errors.

The deflectometrical test was performed and the image of the PSF was acquired by means of the CCD, maintaining fixed the distance between the device and the mirror (~ 34 m). Finally we simulated the mirror's PSF, considering the obtained normal vectors, and compared it with the photometrical PSF acquired illuminating the panel.

The photometrical mirror's PSF, the simulated one and the measured shape are reported in Figure 6. The measured shape has an rms of 3.5 μm and the corresponding slopes map have an rms of 0.15 arcseconds and 0.19 arcseconds on the x and y direction respectively.

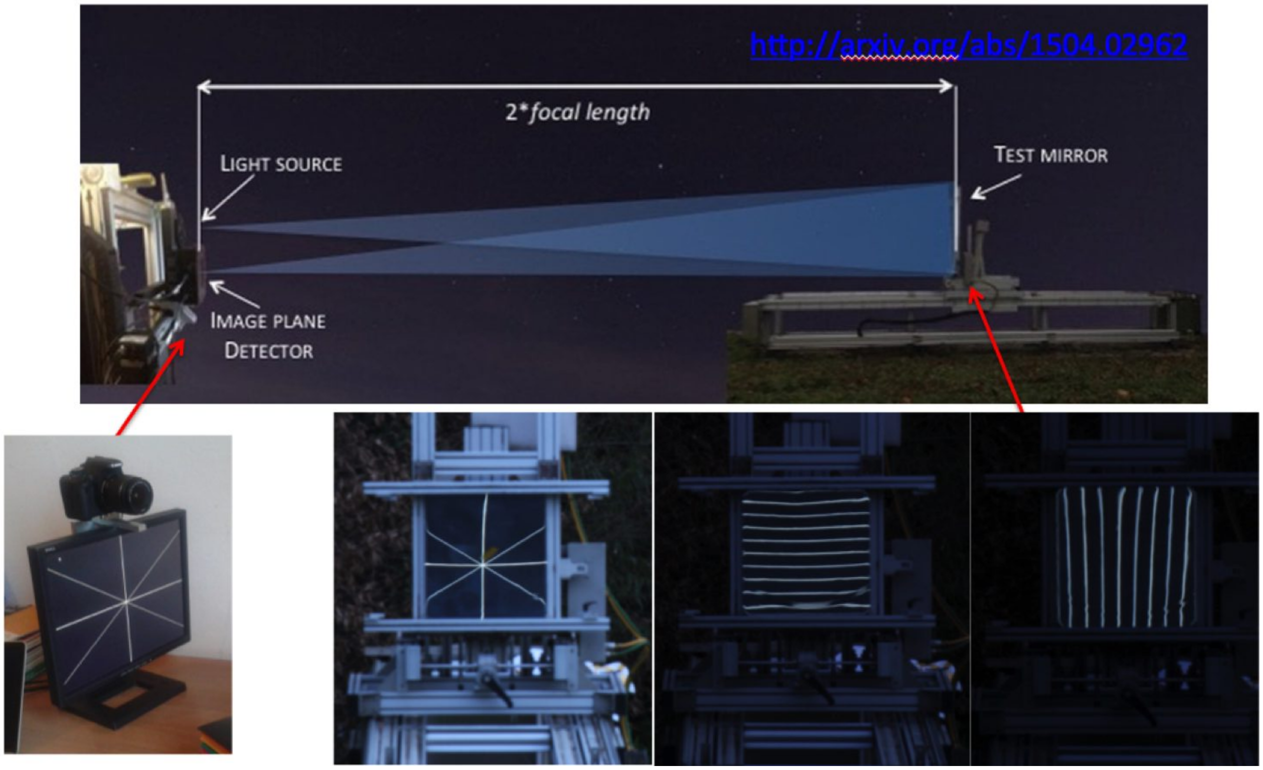

Figure 3 - Sketch of the 2f facility available at INAF-OAB [14], for the deflectometrical test the screen-camera device was positioned aside the CCD camera (on the left in the image).

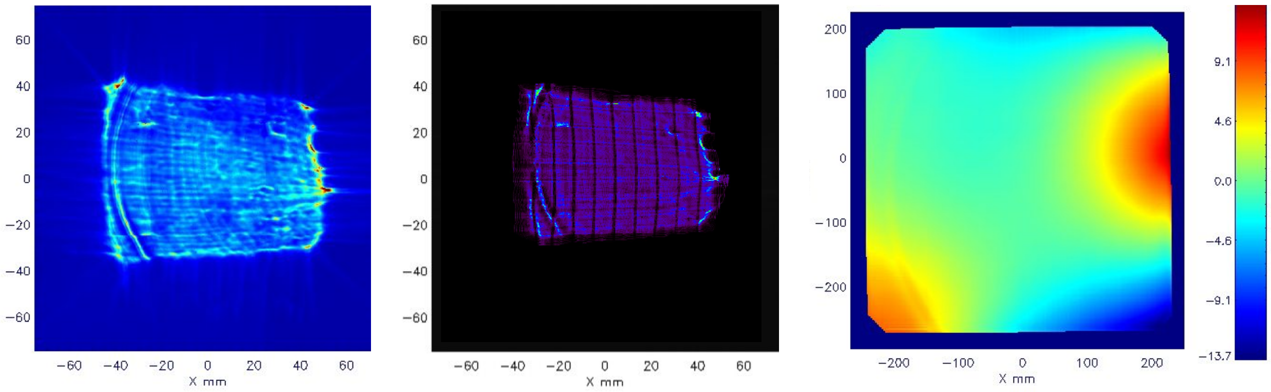

Figure 4 - Left: image of the PSF acquired by means of the CCD. Centre: simulation of the PSF obtained processing the measured surface's slopes. Right: measured shape, rms = 3.5 μm, x slopes rms = 0.15 arcseconds, y slopes rms = 0.19 arcseconds.

3. THE MAORY CASE

Considering the strong dependence on deflectometrical measurements accuracy on the acquisition configuration we made a brief analysis of the upgrades necessary to improve our deflectometry laboratory and reach the accuracy required for measuring optics with shape errors in the nanometric range. As an example of high accuracy optics, we considered the MAORY case. MAORY is a post-focal adaptive optics module for E-ELT, it will re-image the telescope focal plane with diffraction limited quality and low geometric distortion. The MAORY project is led by INAF and the instrument will be part of the first light instrumentation of E-ELT. The instrument shall have unvignetted FOV of 53''x 53'' with a wave front error less then 54 nm. The optical design of MAORY is still under development; in this paper we will refer to the last two proposed optical designs (hereafter configuration 1 and configuration 2) [15] (see Figure 5). The set of optical components involved in the shown optical path include flat, convex and concave mirrors with size up to 1.2 m of diameter and radius of curvature up to 6.5 m. Manufacturing and align these optical components is extremely challenging, and alternative optical design are under study to facilitate the optics procurement. The surface quality requirement for MAORY is expressed in terms of shape error rms of the Zernike polynomials: Z4 +shall be less then 500 nm, Z5-Z10 shall be less then 15 nm and Z10-Zn shell be less then 10 nm on patches of 350 mm diameter.

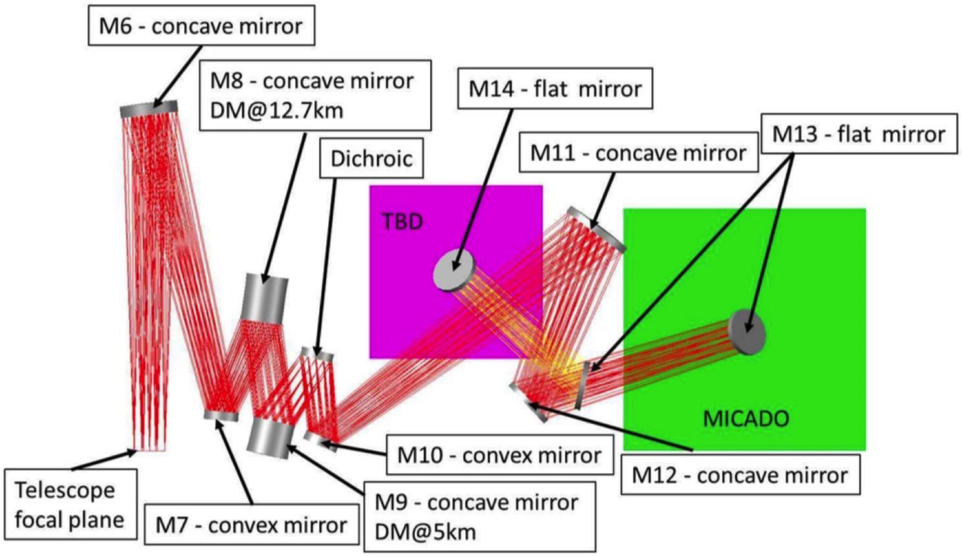

Figure 5 - Post focal relay optical path as presented By Lombini M, Diolaiti E. in [15].

3.1 Slope requirement

Deflectometry directly measures slope errors, heights can be recovered by integrating the surface normals in different ways. Examples of commonly adopted integration algorithms can be found in literature (some examples are [16], [17], [18]). Integration of the normal vectors is an important part of the work when heights are needed, but introduces shape errors on its own. To isolate the impact of measuring errors due to deflectometry we decided to work directly on slopes. We retrieved the slope errors requirement for MAORY optics to set a possible configuration for a deflectometrical facility and tested its feasibility. For this work we considered the two proposed design for MAORY and their requirements.

The rms slope of each Zernike polynomial is a function of the polynomial index, of the surface diameter and of the amplitude of the introduced wave. As starting point we calculated the total shape error and slope error (both on x and y direction) a reference flat mirror with 1 m diameter presents when single Zernike polynomials with amplitude of 10 nm are added to the starting surface. The values were recorded for Zernike terms up to index 200. The plots of the total cumulated shape and slope errors are displayed in Figure 6. Then we moved from the curve obtained for the reference mirror case to the single MAORY mirrors. The requirement translated in terms of slope errors was obtained for each MAORY mirror multiplying the obtained values for a scale factor and for amplitude normalization. The scale factor is expressed as Φ_{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 σ_{ref} / σ_{req} where σ_{ref} is the weight of the single Zernike polynomial on the total cumulated error 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* has been obtained considering the 350 mm patch scale factor (as expressed by the shape error requirement) instead of the whole mirror one. The obtained slopes requirements are shown in table 1 for each MAORY considered mirror, the upper block of the table refers to the configuration 1, the lower one to the configuration 2.

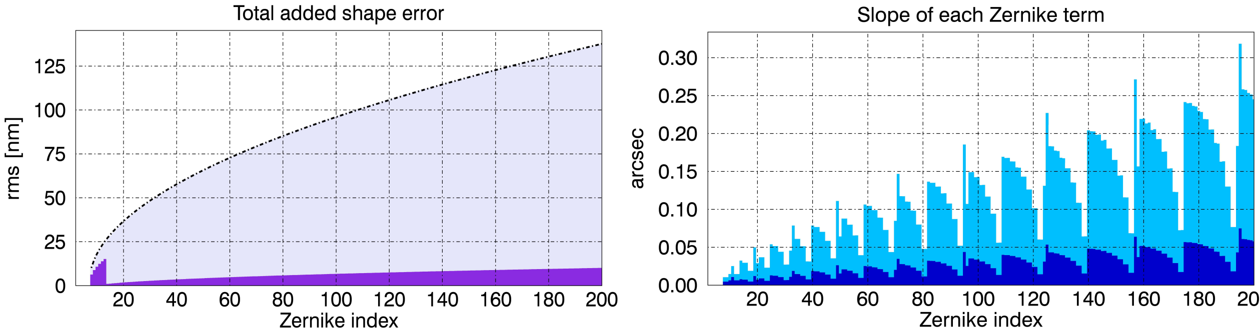

Figure 6 - Total slopes (upper panel) and shape errors (lower panel) of each Zernike term obtained generating the Zernike polynomials on a round surface with diameter of 1 m and amplitude of 10 nm.

	M#	Curvature [1/mm]	Diameter [mm]	f	Z4 Min α [$msec$]	$Z5-Z10$ Min α [$msec$]	$Z>10$ Min α [$msec$]
Configuration1	M6	0	1220x800	0.68	0.39	4.24	5.30
	M7	1/20820	1220	0.82	0.58	5.07	5.30
	M8	0	800	1.25	0.89	7.73	5.30
	M9	0	700	1.43	1.02	8.84	5.30
	M10	1/9900	810	1.23	0.88	7.64	5.30
	M11	1/6500	1200	0.83	0.59	5.16	5.30
	M12	−1/2140	350	2.86	2.04	17.68	5.30
	M13	1/5340	880	1.14	0.81	7.03	5.30
	M14	0	910x640	2.19	0.55	5.56	5.30
Configuration2	M6	1/12780	1000	1.0	0.71	6.19	5.30
	M7	−1/6583	600	1.67	1.19	10.31	5.30
	M8/9	1/1330	750	1.33	0.95	8.25	5.30
	M10	−1/10250	600	1.67	1.19	10.31	5.30
	M11	1/11380	1200	0.83	0.59	5.16	5.30
	M12	1/5340	900	1.11	0.79	6.37	5.30
	M13	0	910x640	0.90	0.55	5.56	5.30

Table 1 - Description of MAORY design and related slope error requirement. The upper block of the table refers to the configuration 1, the lower one to the configuration 2. Left part of the table reports the parameters of each mirror. Right part of the table reports the data used to extract the slope requirement: scale factor *f,* slope *rms* related to *Z4* error, the minimum slope obtained for each mirror for the two sets of Zernike polynomials *Z5-Z10* and for *Z>10*.

3.2 Possible 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 (requirement on Z5-Z10 for M6 of configuration 1) 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 should be at leas the 50% of 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 ~ 25 m. Once this distance is set, the camera's objective focal length is chosen to have a spatial resolution on the mirror within 1 mm. Hence, different objectives would be necessary to measure different mirrors. The shorter objective would be used to measure M11 of the configuration 2 while the longer to measure M6 of the configuration 1. The adoption of objectives with focal length of ~ 350 mm and of ~ 1400 mm will ensure a resolution better then 100 μm along the single profile and better then 1 mm on the map (if the minimum frequency on the light pattern on the screen is set to 10 pixel). 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 a single camera. The problem can be solved with stereoscopic image acquisition, like proposed by the University of Erlangen team in [19], 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 effects. The results of the ray-tracing simulations for the three considered mirrors are shown in Figure 7. The result of this analysis is that the achievable accuracy is strongly dependent on the mirror characteristics and on the setup configuration but it is possible to find a configuration, common to all the considered mirrors, respecting the required angular resolution.

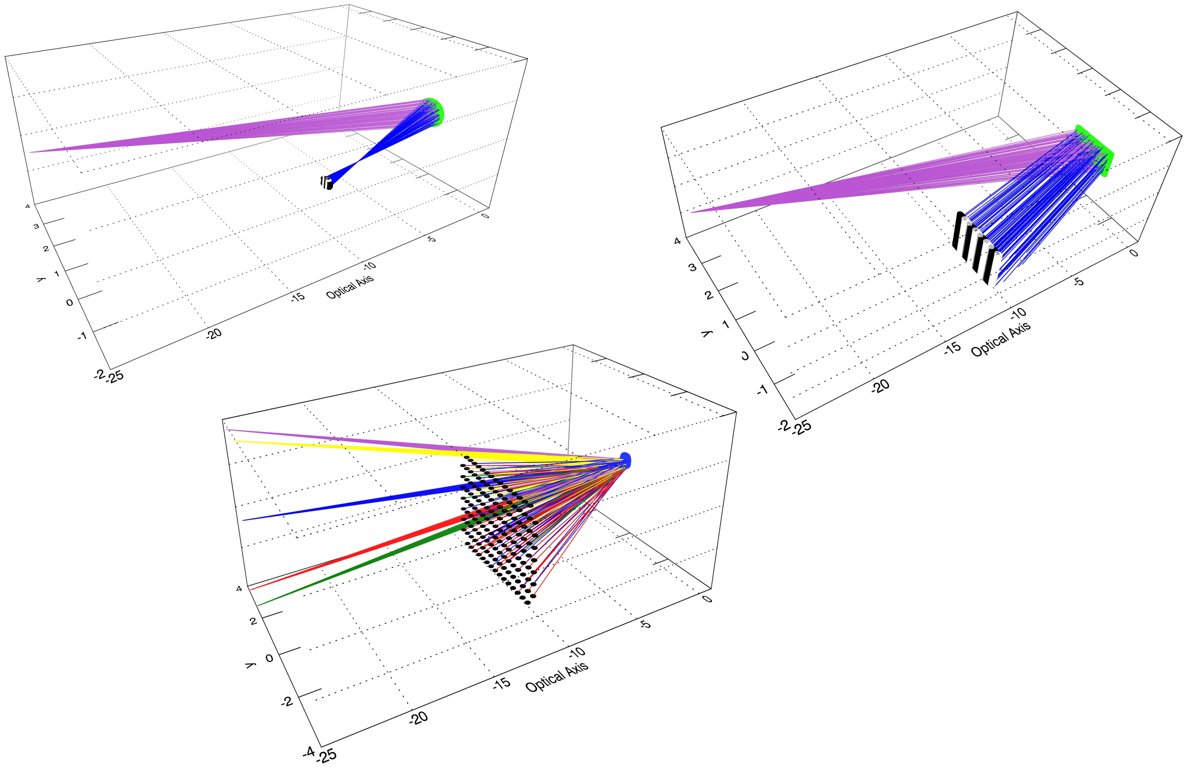

Figure 7 - Simulations of the reflections obtained in the assumed configuration for the three considered mirrors. Left: M8-config 2, the most concave mirror would be measured in extra-focal position. Centre: M6-config 1, flat rectangular. Right: M12-config 1(the most convex mirror), this case requires the use of 5 cameras for stereoscopic vision to observe the entire mirror surface.

3.3 The spherical component

The measurement of the spherical component is the most complicated for a deflectometrical test; in fact the defocusing error behaves like a distance measurement error. Thus, setting up a requirement on the spherical component of the shape error means to setting up a requirement on the accuracy of absolute distances measurements (camera-mirror-screen), corresponding to a setup calibration. Unfortunately, considering a fixed value requirement for the peak-to-valley error of the spherical component means to set a variable tolerance error on measured distances. Considering the following expressions for the peak-to-valley and for the corresponding error on the radius of curvature:

$$PV = RoC - \sqrt{RoC^2 - l^2} \qquad\qquad \delta RoC = Roc - \frac{(PV+\varepsilon)}{2} - \frac{l^2}{2\cdot(PV+\varepsilon)}$$

where RoC is the radius of curvature, l is the lateral dimension of the considered mirror and ε corresponds to the error on the peak-to-valley of the spherical component of 500 nm; we obtain the maximum allowed error on the measured radius of curvature spreading from ~12 μm for M8-9 of configuration 2 to ~1 mm for M7 of configuration 1. Proceeding as for the other requirements we should ask that the maximum measuring error is one half of these values. So, for the most challenging case we should guarantee that the distances between the involved objects (disposed at 25 m one to the other) are measured with an accuracy of ~ 5 μm. This requirement is really strict and will be hardly reached even adding environmental control and metrological systems to continuously calibrate the cavity (laser trackers accuracy is of about 15 μm on a maximum distance of 20 m). In this case the most opportune solution is to measure the spherical component with a profiler.

On the other hand, instead of fixing the peak-to-valley maximum error of the spherical component, we would recommend to specify the tolerance on the radius of curvature. Physically, this would mean setting a maximum value on the shift along the optical axis permitted by the opto-mechanical mounts. In this case we can require a tolerance on the absolute distance of about 500 μm, accuracy easily reachable with a laser tracker. Moreover we propose to apply the direct illumination method also to improve the spherical component measurements. As already mentioned, the chance to have a close loop between simulation and direct illumination data offers the opportunity to decrease the impact of misalignment errors. To improve results on the spherical component estimation we propose to install a high accuracy translation stage with a limited length (we considered 1.5 m) and acquire images in direct illumination at different distances. The caustic curve produced by the sequence of PSFs will have an angle that is directly connected to the mirror focal length. So we propose to follow the caustic with a number of pictures instead of having a single absolute distance measurement as focal length detector.

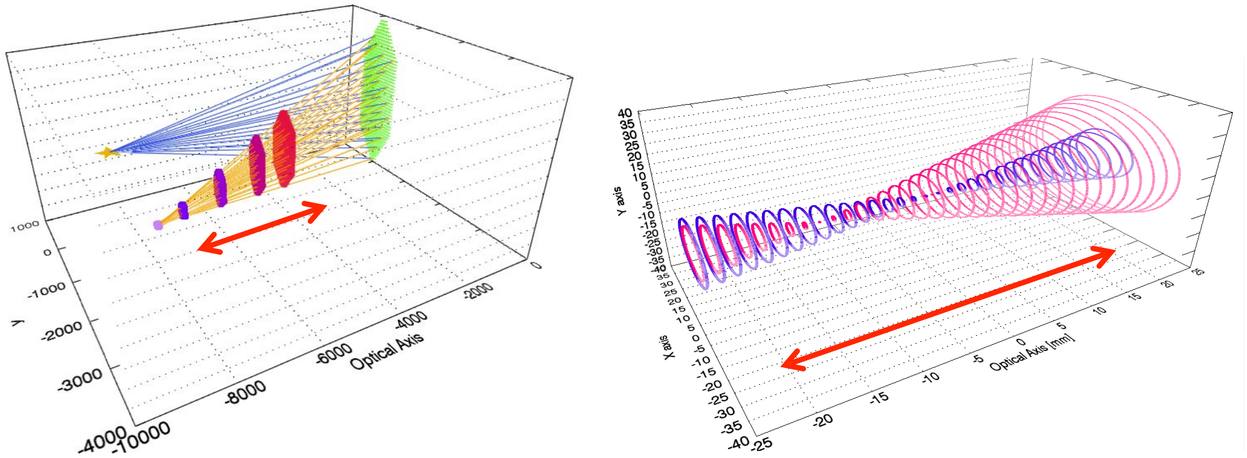

Figure 8 - Left: Representation of the direct illumination test, the image of the PSF has to be acquired at different distances and compared with the corresponding positions ray-tracing simulations. Right: Representation of caustic curves generated by mirrors with different radius of curvature, both the focus position and the cone angle changes with the RoC.

This method has two main advantages: the first is to have a better statistic, since each picture would have its distance measurement. The second is that the caustic curve could be followed independently to the absolute position of the focus. For instance, on a 4 m range, there will be a ~150 μm difference between the change in dimension of a PSF generated by the most critical mirror for what concerns the spherical component measurement (M8-9 of configuration 2), and the PSF generated by the same mirror adding a spherical error with peak-to-valley of 500 nm, would change of ~ 150 μm.

4. CONCLUSIONS

At the INAF-OAB, we developed an in–house deflectometry facility to test the mirrors of the ASTRI Cherenkov telescope which mirrors' shape errors have a typical range of tens of microns with corresponding slope errors on the order of few arcminutes. A second compact facility was assembled to work close to 2f configuration guaranteeing better sensitivity. Starting from the experiences of this two facilities configurations we made a brief analysis of the upgrades necessary to improve our deflectometry laboratory to reach the accuracy required for measuring optics with shape errors in the nanometric range. As an example of high accuracy optics, we considered the case of the E-ELT instrument MAORY. We converted the shape error requirements in slopes errors requirement. We calculated that a deflectometrical facility should reach an angular resolution of ~ 2 milliarcseconds to properly measure the optics of MAORY. 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 absolute distances measuring system. So, possible solutions are to add a number of metrological devices to continuously calibrate the cavity or to adopt a hybrid solution taking advantage of the synergy between deflectometry and profilometry. In this case deflectometry will be devoted to measure medium frequencies error skipping the cavity calibration difficulties required to measure the lower ones. Profiling will be used to acquire a modest number of points (limiting the otherwise excessive measuring time) to measure low-frequency errors. An example of this solution is presented in [20]. Finally, we point out that the requirement on the spherical component should be relaxed, and in this case good results on the spherical component measure could be achieved with a series of direct PSF imaging among subsequent focal distances. With this solution the analysis of the caustic will offer a measure of the spherical component avoiding extra-accurate absolute distances measurements.

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