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# MEASUREMENTS BY ESPI OF SURFACE DEFORMATIONS OF A HEATED MIRROR AND COMPARISON WITH MULTIPHYSICS SIMULATIONS

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## I. INTRODUCTION

Observations from space are almost exclusively performed by means of mirrors. To achieve higher performance, larger and larger mirrors are manufacture usually in aluminum alloy in order to be cost-effective. However from the optical performance point of view, the coefficient of thermal expansion (CTE) of aluminum is an important drawback. Therefore the use of active heating is required in order to prevent optical performance degradation. Anyway thermal gradient cannot be fully avoided and most likely this gradient will change over time: the instrument being sometime closer/further from a heat source and due to material aging.

Of course, mirror performance at different temperatures can be experimentally tested on Earth. But the mirror would have to be redesigned and remanufactured if the performance requirements are not met. Therefore, modeling the optical performance under thermal load is of high interest to combine both cost effectiveness and optical performances. On the one hand using fewer materials reduces cost, on the other hand using fewer materials makes the instrument more prone to thermal gradient and the thinner the mirror, the larger the deformation due to this thermal gradient.

This paper presents experimental results of deformation measurements of a mirror surface heated with thermal resistor and compares these results with numerical model (finite element analysis). Mirror displacements have been measured by electronic speckle pattern interferometry (ESPI) and the deformation have been deduced by subtracting rigid body motion (RBM) from the measured displacements.

## II. GENERAL DESCRIPTION OF THE EXPERIMENT

From the experimental point to view, we need to measure the surface deformations of a given mirror. The object investigated is a 80 mm diameter off-axis parabolic mirror, monolithic and made off aluminum manufactured by AMOS. This mirror is heated by a flexible thermal resistance from Minco, placed on the side of the monolithic structure, in the back position (as shown in Figure 1). This position has been selected in order to maximize the temperature gradient, which is recommended to create larger deformation and make the comparison between numerical simulation and experimental results.

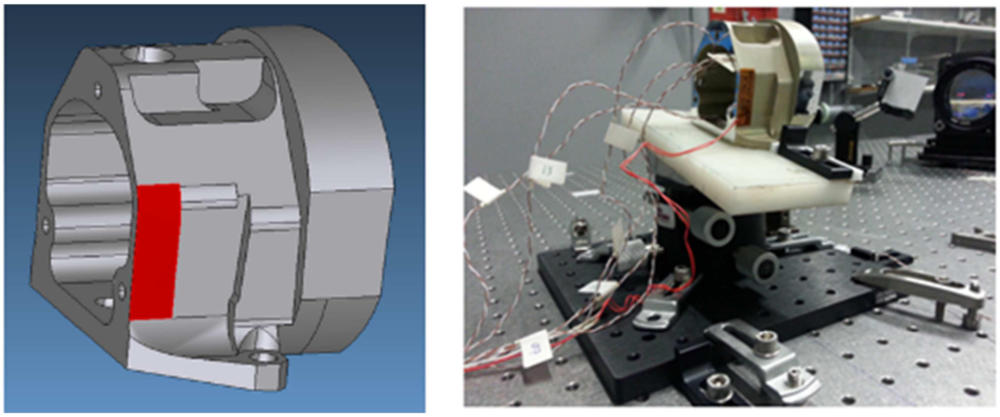


**Fig. 1.** Position of the heater on the mirror (left: simulated, right: experimental)

To avoid heat loss by conduction, the mirror is placed on a nylon insulator plate. The mirror is simply posed on this nylon plate in order to avoid mechanical stresses that we have been more complicated to model. Two stoppers (one on one side and the other in the front) are used to easily put the mirror back in place. Electronic speckle pattern interferometry (ESPI) has been used to measure the surface displacements of the heated mirror with a DPSS laser performing at a wavelength of 532 nm. This technique requires a diffusing surface to create speckle grains, the object beam is sent towards a diffuser before it reaches the mirror to be characterized. The experimental setup is shown hereunder (see Figure 2).

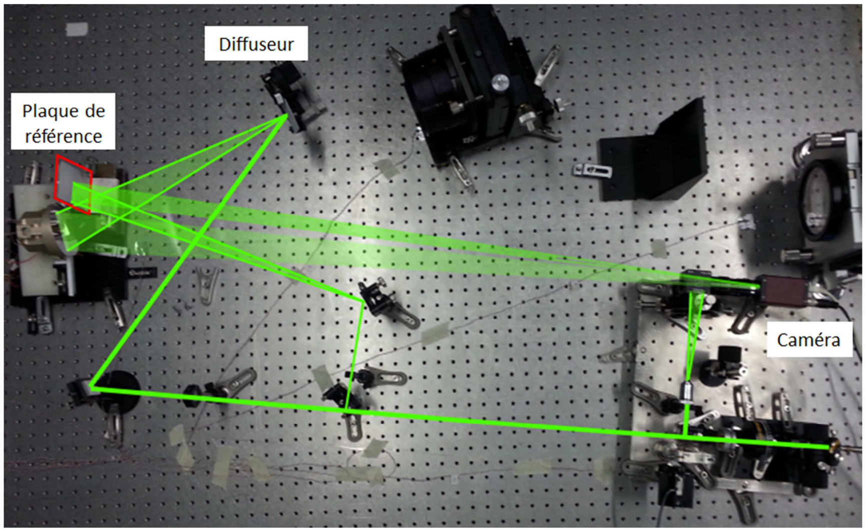


**Fig. 2.** Experimental setup and path of the beams useful for the ESPI.

Although only the difference between the final state (hot mirror) and initial state (room temperature mirror) has to be calculated, phase measurements are performed continuously (one measurement every height seconds) in order to execute temporal phase unwrapping.

Surface displacement measurements have been performed at two different thermal powers: 0.5 and 2.0 W. Typically, the time required to perform a one measurement at 2 watts is about 8 hours. This measurement time can be explained by two main factors. First, mirror displacements (deformation + RBM) must be less than one half of wavelength [1] so that temporal unwrapping can be performed in accordance with the Nyquist–Shannon sampling theorem. Second, the thermal power is increased step by step up to 0.5 or 2 watts otherwise, turbulences of the air would vitiate experimental results.

Experimental measurements performed by ESPI allow determining displacements of the mirror relative to the camera (the reference beam is not affected by the heater and is considered as stable). These displacements can be separated in three components: the RBM of the table on which the setup lies (arising from thermal variations in the laboratory during the experiment), the RBM of the heated mirror and the deformation of the mirror. While not necessary to determine the mirror deformation, a reference plate in Invar has been placed next to the mirror, in the field of view of the camera, in order to discriminate the first component from the others. So, we are measuring in the same time the phase variation of a rough object (the invar plate) and a specular object (the mirror) by means of a diffuser.

## III. DETERMINATION OF THE DEFORMATIONS BY POST-PROCESSING CALCULATIONS

Treatment of camera acquisition is performed by software processing. The step is to records five temporal phase-shifted interferograms by means of a piezoelectric transductor. From these five acquisitions, the phase is calculated from a common five-bucket algorithm using quarter-wavelength shifts of the reference beam between each successive measurement [1]. The calculated phase evolution will always be between 0 and $2\pi$. Therefore we used a temporal phase unwrapping algorithm to determinate the absolute displacement. To be applicable, the displacement measured between time $t$ and time $t$-1, should not exceed one half wavelength (which is 266 nm in our set-up).

The measured displacements do not correspond only to the deformations value. Indeed the mirror will undergo dilatation, translations and rotation movements. The optical table could also undergo deformations due to temperature variations. With a CTE around $10^{-5}\,K^{-1}$ and an optical path around 3 meters, a variation of 0.1 K leads to a variation of the optical path of $3\,\mu$m. To get rid of all these RBM in order to have only the deformation of the surface of the mirror, we perform a fit based on the least square method. The difficulty we face is the determination of RBM – which are 3D displacements – on the basis of 2D information: we measure the displacement the mirror surface and not a volume.

Several fit have been investigated. The accuracy of each fit has been estimated by computer simulation. For this, we simulated the measurement of pure RBM displacements and perform the RBM removal. The residual value, which corresponds to the deformation measurement, give use the deformation accuracy because the value should be null. The fit that minimize the value of the accuracy is given by:

$$z_{fit} = a\,R_x(x,y) + b\,R_y(x,y) + c\,t_z(x,y) \tag{1}$$

where $z_{fit}$ is the estimated contribution of the RBM, $R_x(x,y)$ and $R_y(x,y)$ are the displacements of the surface of the mirror after a rotation around the *x*- and *y*-axis respectively and $t_z(x,y)$ represents the displacement after a translation along the *z*-axis, and *a*, *b* and *c* the fit coefficients. The result of the simulation of this fit is shown at Fig. 3. The RBM contribution that has the biggest impact on the error is the translation of the mirror along the *y* axis, where the error is 0.12 µm for 100 µm of translation (.i.e. 1.2 nm per micrometer of lateral displacement).

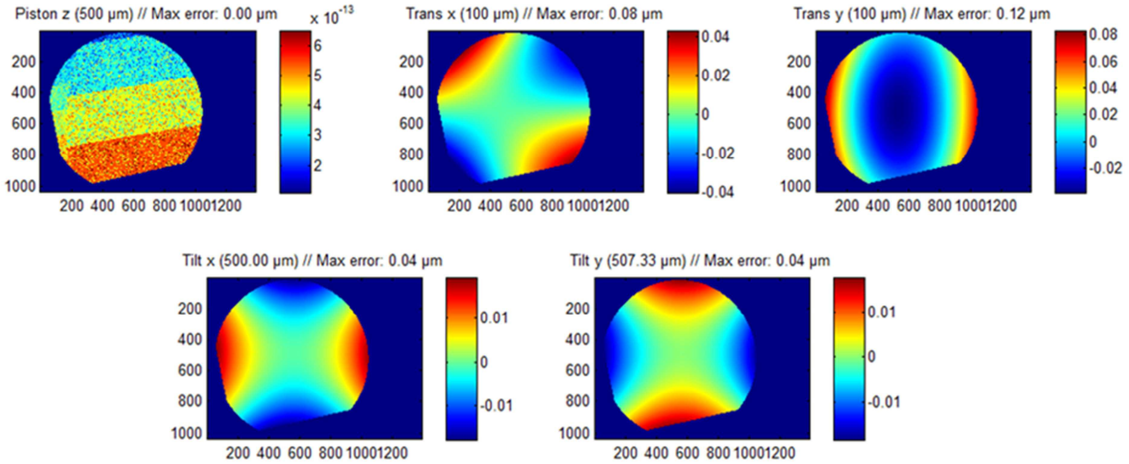


**Fig. 3.** Computer simulation of the removal of pure RBM displacements. From top-left to bottom-right: piston, translation along x, translation along y, tilt around z, tilt around x and tilt around y. The peak-to-valley error is indicated on top of each subfigure for a RBM amplitude given between parenthesis. Color scales are in micrometers.

As it can be observed on Fig. 1, the mirror has also two additional reflective surfaces: one on the lateral side allowing and another on the back side. Using a theodolite, rotation can easily be measured. The lateral resolution of the image recorded by the camera is 80 µm (1000 pixels used to record 80 mm, the diameter of the mirror), which is large compared to the prediction obtained by the numerical model. Therefore experimental values have been used for the rotations and the values obtained from simulations have been used to estimate the residual fit error. These values are presented in Table 1.

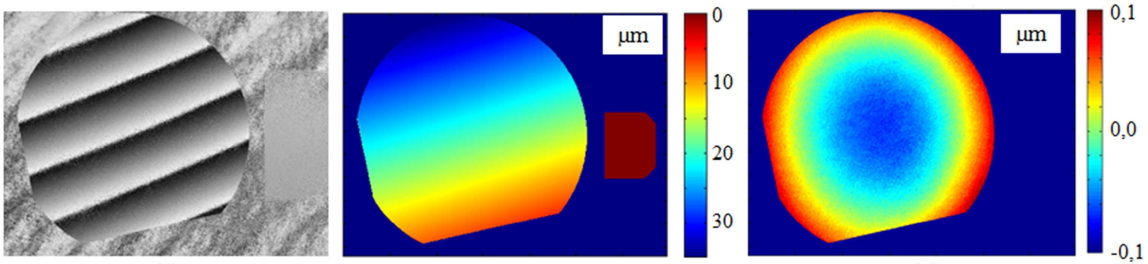
**Table 1.** Rigid body motion values obtained by simulation for *x*, *y* and *z* translations (*Δx*, *Δy* and *Δz*), and measured experimentally for rotation round x, y and z axis (*Rx*, *Ry* and *Rz*)

| | ***Δx*** | ***Δy*** | ***Δz*** | ***Rx*** | ***Ry*** | ***Rz*** |
|---|---|---|---|---|---|---|
| **0.5 watts** | 4.4 µm | 4.3 µm | 2.6 µm | 0.93’ | < 0.2” | 15.1” |
| **2.0 watts** | 13.2 µm | 12.9 µm | 7.8 µm | 1.15’ | < 0.2” | 52.6” |

Based on these RBM, we can calculate the accuracy of the measurement performed in the lab to be of the order of 7 nm peak-to-valley due to the RBM removal error.

## IV. EXPERIMENTAL RESULTS AND COMPARISON WITH NUMERICAL MODELS

In Fig. 4, the three main steps are presented. Fig. 4(a) shows the modulo-2π fringes. After the temporal unwrapping the total displacement is easily obtained. Fig. 4(b) shows the total displacement of the mirror after the removal of the optical table RMB thanks to the reference plate. Finally, Fig. 4(c) shows the displacement map, in other words the displacements from which the RBM were subtracted.



(a) (b) (c)

**Fig. 4.** Results for a heat power of 0.5 watts. (a) Phase measurement. (b) Mirror displacements. (c) Mirror deformation after RBM subtraction.

*A. Results at 0.5 watts*

While the maximum displacement is around 30 µm, the deformation peak-to-valley is around 0.2µm while in the very worst case the fit error is 14.7 nm.

If we now compare the numerical simulation results to the experimental results and look at the difference between the two, we found a maximal error of 27 nm and a RMS error of 6.5 nm i.e. 4% of the peak-to valley deformation.

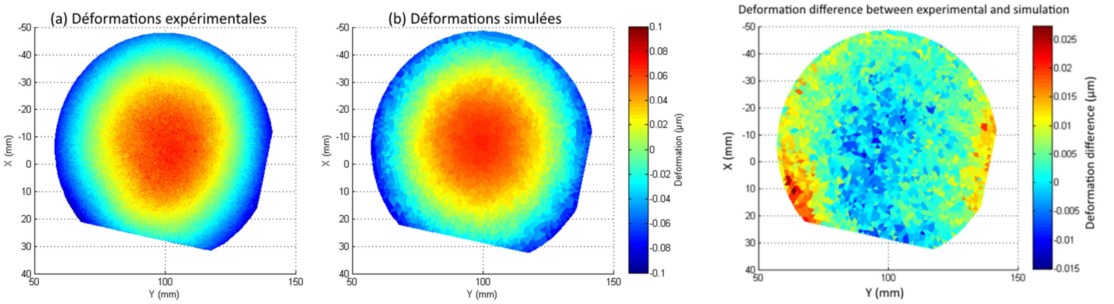


**Fig. 5.** (a) Experimental deformations, (b) deformations obtained from numerical models, (c) difference between the experimental and numerical values at 0.5 watts.

*B. Results at 2 watts*

The same comparison between the experimental deformation and the numerical deformation is resented here. The amplitude of deformation is about 0.5 µm and the maximum difference between the experiment and simulation is about 100 nm and the RMS error is 29.4 nm (4.9% of the peak-to-valley deformation)

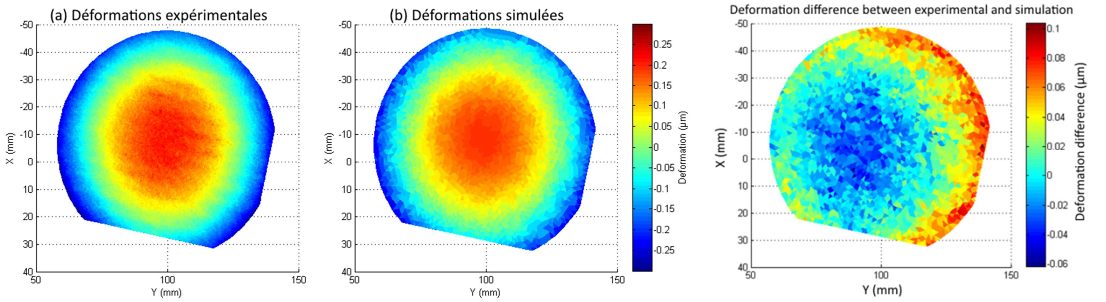


**Fig. 6.** (a) Experimental deformations, (b) deformations obtained from numerical models, and (c) difference between the experimental and numerical values at 2 watts.

## V. CONCLUSIONS

The experimental measurements are consistent with the numerical simulations despites the small deformation amplitudes. This means firstly that the temperature variations match between the experiments and the simulations and secondly the deformations associated with these temperature changes also correspond so that finally when the RBM are subtracted, the RMS error is smaller than 5% of the peak-to-valley deformation.

This study opens the doors to the investigation of full optical system like three-mirror anastigmat telescope which requires not only simulating the behavior of the mirror surface but requires simulating the whole system.

## VI. ACKNOWLEDGEMENT

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