International Conference on Space Optics—ICSO 2018

Chania, Greece

9–12 October 2018

Edited by Zoran Sodnik, Nikos Karafolas, and Bruno Cugny

High performance large lightweight mirrors fabrication adapted to stress-mirror polishing (SMP) technique

S. Lemared

M. Ferrari

T. Dufour

C. Du Jeu

et al.

International Conference on Space Optics — ICSO 2018, edited by Zoran Sodnik, Nikos Karafolas, Bruno Cugny, Proc. of SPIE Vol. 11180, 111806T · © 2018 ESA and CNES · CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2536164

High performance large lightweight mirrors fabrication adapted to stress-mirror polishing (SMP) technique

S. Lemared[a], M. Ferrari[a], T. Dufour[b], C. Du Jeu[b], E. Hugot[a], G. R. Lemaitre[a]
[a]Aix Marseille Univ, CNRS, CNES, LAM, Marseille, France;
[b]Thales-SESO, Aix-les-Milles, France.

ABSTRACT

Earth observation space instruments require very tight optical performances in the most stringent configuration (observation in the optical wavelengths range). The optical quality of mirrors, mainly in term of both shape and roughness polishing quality, has to reach very tight specifications down to a few nanometers. In this paper, we present a new manufacturing process, based on Stress-Mirror Polishing (SMP) technique, dedicated to lightweight mirrors aspherisation. We consider specific features or constraints due to the structure of the honeycomb, while reducing foot-print effects and inhomogeneous surface effects. We also identify the most efficient way to correct and/or anticipate these issues taking into account industrial constraints on real-scale mirrors. In this new process, both SMP technique and lightweight design have to be optimized.

Keywords: Stress Mirror Polishing (SMP), Lightweight Mirrors, Elasticity Theory, Space Telescopes, Primary Mirrors.

1. INTRODUCTION

Future Earth observation missions from geostationary orbits, with a resolution between 4 and 10m on ground, will require primary mirrors of at least 4m diameter. To manufacture such size lightweight mirrors, with these very tight optical specifications, no real state-of-the-art technology is currently available. A new innovative fabrication method is clearly required to combine large lightweight mirrors fabrication with high performance surface quality.
To develop such a fabrication process, several aspects must be considered as high stiffness-to-mass ratio, optical quality of the surface, time consuming of the polishing method and of course existing know-how and industrial facilities.

Since more than 40 years, SMP methods have been developed at LAM in Marseille, in close collaboration with industry. This fast converging manufacturing process for aspherical optics has exquisite results in term of surface quality, but has never been implemented on lightweight large space mirrors.

This new SMP based technique allows to save time on the grinding, pre-polishing and finishing steps while limiting high-frequency Surface Front Error (SFE) during the polishing as it uses large polishing tools. These points are of prime importance for the manufacturing of future large lightweight mirrors.

2. STRESS-MIRROR POLISHING

2.1 Stress Mirror Polishing (SMP) technique

In general, mirrors are polished using a small size tool which drives to tool-prints on the optical surface as high as the tool size. Bernhard Schmidt, a German astronomer, proposed an alternative method in 1930 to aspherize mirrors by combining active optics and full-size spherical tool polishing. He called this method “vacuum pan”, originally used to build the Schmidt corrector plate, which is now the SMP method. Active optics exploits the elastic behavior of materials while the full-size tool polishing provides a continuous optical surface free of high spatial frequency errors.

SMP has been used for several space and based-ground instruments applications until now. The Active-Toric mirror (A-TM3), a part of SPHERE-exoplanet finder on the VLT[1] is a good example of a high-performance mirror using SMP. Some great results have to be mentioned on sky after discovering the first dusty giant exoplanet in 2017[2].

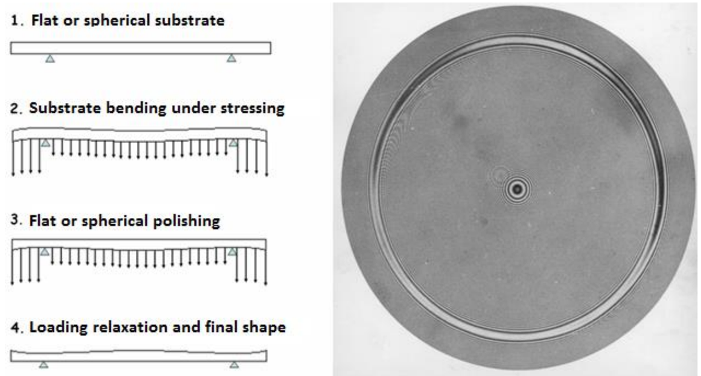

Figure 1: Stress-Mirror Polishing (SMP) principle

2.2 Towards large lightweight mirrors for Space

Nowadays, most of primary mirrors are made in Zerodur ® with a very low Coefficient of Thermal Expansion (CTE) which is very important for its stability in orbit. This glass-ceramic material has been found by SCHOTT using a natural compensation of positive CTE of glasses and negative CTE of cristals. The main challenge of having a low CTE lightweight blank is to maintain a suitable homogeneity[3].

3. POLISHING OF A LARGE LIGHTWEIGHT PRIMARY MIRROR

3.1 Polishing large lightweight mirrors

Polishing a lightweight mirror is not an easy part. Most of the new large primary mirrors have lightweight patterns which contribute to the rigidity and weightless. For these mirrors, the classical polishing method consists of using a very small tool in order to minimize the error on the optical surface. Indeed, lightweight patterns guide the errors in case of higher size than the polishing tool size.

At first sight, the lightweight mirrors polishing using SMP seems to be contradictory. In one hand, SMP technique requires a flexible substrate to make the right deformation while lightweight mirrors have to maintain a certain stiffness to respect mechanical specifications. Moreover, these mirrors tend to print residual aberrations on the optical surface due to the lightweight patterns. In the opposite way, the full-size tool on SMP tries to preserve an excellent surface quality.

So far, SMP has been used for fulfilled mirrors and now the challenge is to make this technique possible for large lightweight mirrors.

3.2 Cassegrain telescope requirements

In this study, the goal is to anticipate the lightweight mirrors behavior under stress-polishing. Specifications have been provided by Thales-SESO in order to produce a certain amount of pure 3[rd]-order spherical aberration (SA3). It will be necessary to deform the sphere into a quasi-parabola with a specific conic constant.

The optical surface is decomposed on an orthonormal basis, the Zernike polynomial basis, as a linear combination of orthonormal polynomials. These are decoupled in two terms: the even and the odd functions:

$$Z_n^m(\boldsymbol{\rho},\boldsymbol{\phi})=R_n^m(\boldsymbol{\rho})\cos(m\boldsymbol{\phi}) \text{ and } Z_n^m(\boldsymbol{\rho},\boldsymbol{\phi})=R_n^m(\boldsymbol{\rho})\sin(m\boldsymbol{\phi}) \quad \text{with} \quad R_n^m(\boldsymbol{\rho})=\sum_{k=0}^{\frac{n-m}{2}} \frac{(-1)^k (n-k)!}{k!\left(\frac{n+m}{2}-k\right)!\left(\frac{n-m}{2}-k\right)!}\rho^{n-2k} \tag{1}$$

4. SMP APPLIED TO A TYPICAL LIGHTWEIGHT MIRROR

Typically, primary mirrors are attached to the space platform thanks to a Mechanical Fixation Devices (MFDs) with an isostatic arrangement. Such arrangement drives to a triangle lightweight stiffener between the MFDs. Thus, it affects the optical surface during the polishing process.
Also, extensions of the optical surface have been added to support the polishing tool without having edge effect located near the useful zone of the mirror.

4.1 With a polishing pressure under gravity

A simple load case is to apply a static polishing pressure of 20 g/cm² (0,002 MPa) on the entire optical surface with an inertial load of 9810 mm/s². As boundary conditions, the idea is to prevent the nodes interfacing with the polishing support to move down and also to have an isostatic mechanical holding at the MFDs.

The optical surface is decomposed in a pupil of 1250mm-diameter. A large amount of Focus (6.6µm RMS) can be noticed in addition to the SA3 as shown in Figure 2. Moreover, high values of Trefoil (5µm RMS) and Hexafoil (2.5µm RMS) have been introduced due to the triangle stiffener. In this article, piston, tip and tilt have been removed in all histograms because of their irrelevant high values and can be removed with alignment process.

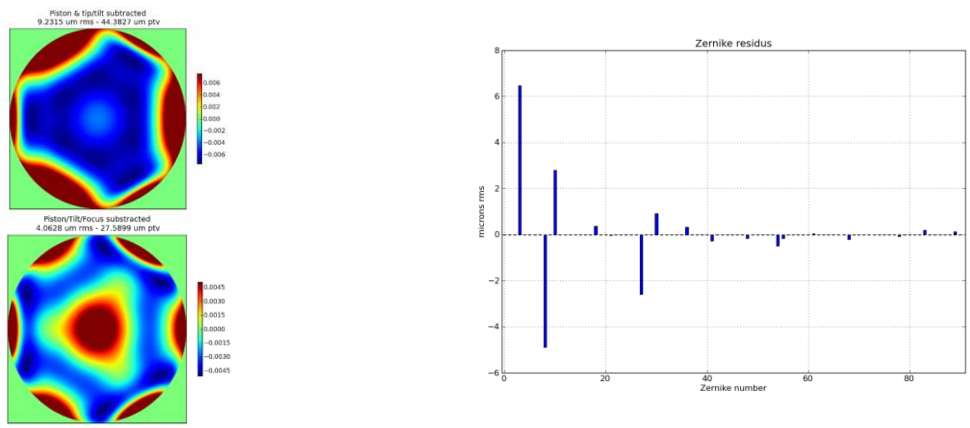

Figure 2: Optical surface decomposition into Zernikes aberrations (histogram) and phase maps without Piston, Tip & Tilt (left-top) and without Piston, Tip, Tilt & Focus (left-bottom)

In order to evaluate the influence of the slopes and extensions we can remove them. Trefoil and Hexafoil are essentially produced by the slopes whereas extensions modify slightly Focus and SA3. A quick simulation removing triangular stiffener and optical surface extensions is sufficient to show in Figure the design effects on the Zernike polynomial decomposition (Figure 3).

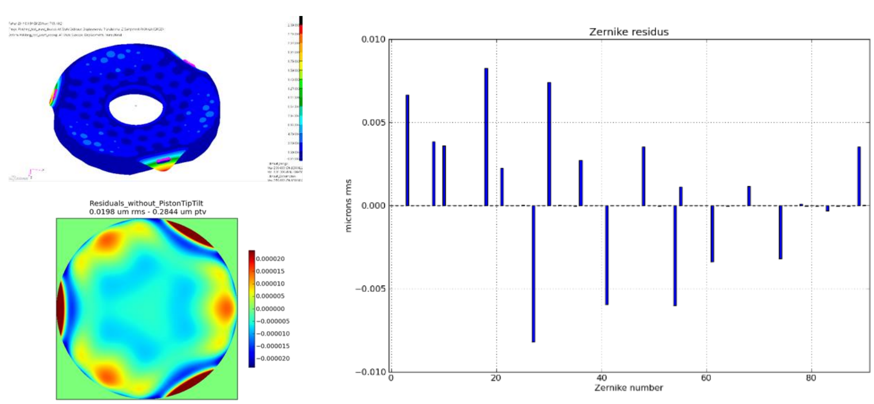

Figure 3: Optical surface decomposition into Zernike polynomials (histogram) and phase maps without Piston, Tip & Tilt (left-top) and without Piston, Tip, Tilt & Focus (left-bottom)

4.2 With a polishing pressure and a central force under gravity

Most of the lightweight mirrors designs are not compatible with SMP technique. In this case, we need to overcome this difficulty by adding a polishing support adapted to the SMP strategy (Figure 4). Its key role is to compensate the lack of rigidity in specific areas.

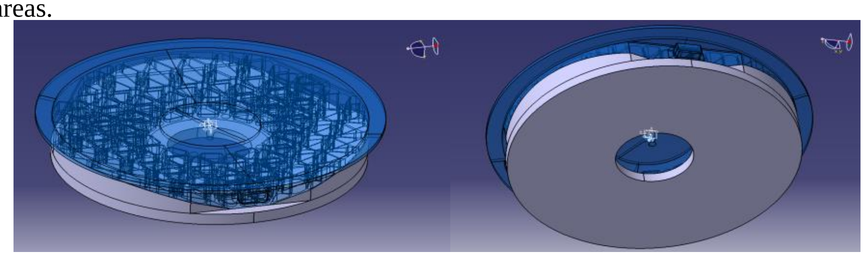

Figure 4: Typical lightweight mirror with a trefoil compensation support

We also want to generate more SA3 through a central axisymmetric variable thickness distribution (VTD) at the center as pointed in Figure 5. Thereafter, this part will be removed keeping a central aperture in the mirror.

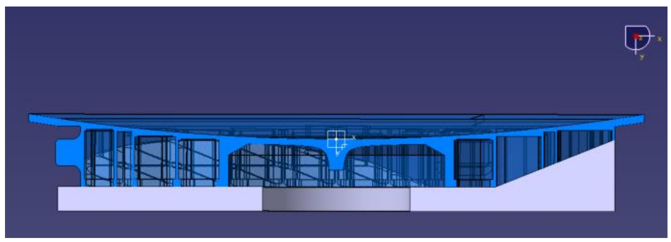

Figure 5: Cut-view of the lightweith mirror

In this configuration, we apply a central pulling force (~1000Newtons) at the base of the variable thickness distribution in addition to the polishing pressure and inertial load (gravity). Trefoil has been reduced from 5µm RMS to 823nm RMS while SA3 has not changed (Figure 6), although spherical harmonics (SA5, SA7, SA9, and SA11) have been generated because of the central VTD.

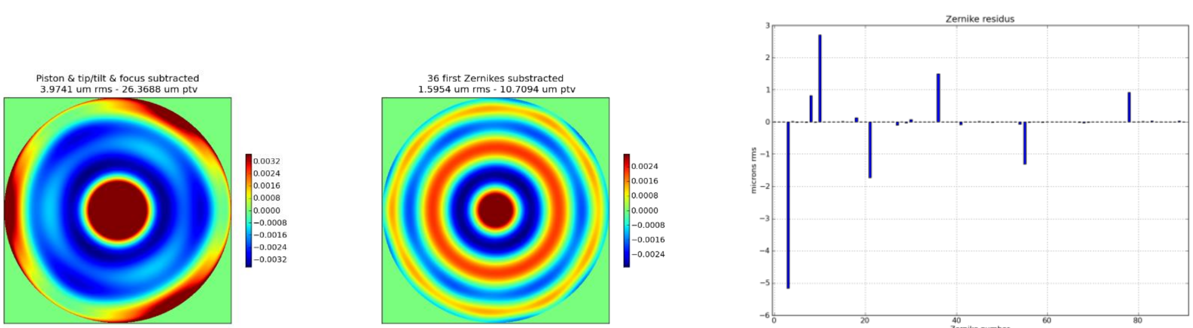

Figure 6: Phase maps without piston, tip & tilt and without the 36 first Zernike polynomials (left) and the Zernike polynomials decomposition histogram (right)

Trefoil can be almost removed (1.4 nm RMS) by making the support active with a pushing system placed under the three slopes. Indeed, a correct amount of slopes pressure (130 g/cm²) decreases the Trefoil value and approaches zero (Figure 7).

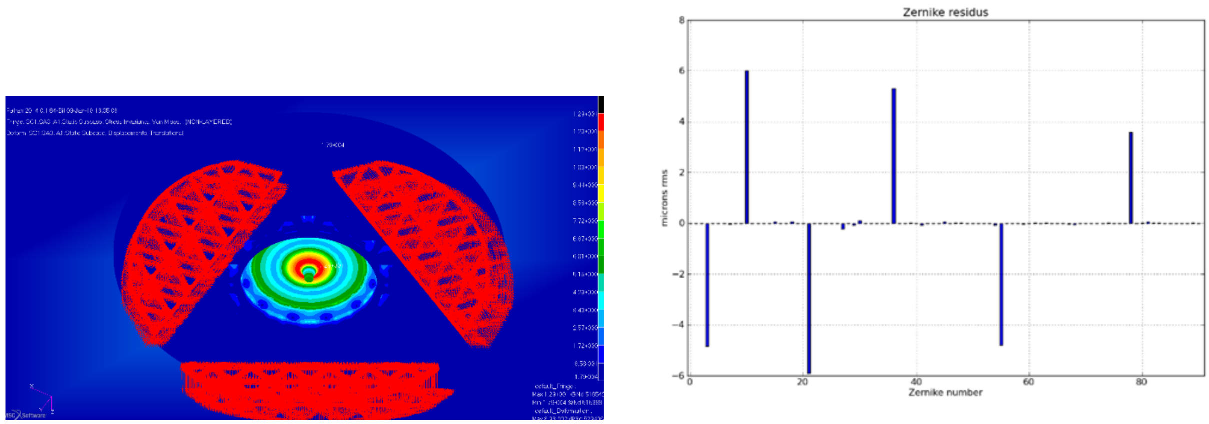

Figure 7: FEA results (left) and Zernike polynomials decomposition histogram (right)

5. SMP OF AN OPTIMIZED LIGHTWEIGHT MIRROR

5.1 Elasticity Theory for Active Optics

Active Optics and Stress-Mirror Polishing are two associated techniques. As a matter of fact, the first one is needed to do the second one. For many years, G. R. Lemaitre has developed active optics with a guideline, making the right deformation using the minimum number of loads[4]. It could be a force, a pressure, or a combination of both.
To generate a single aberration mode with a minimum number of loads, or actuators, he investigated four thickness class distributions: constant thickness distribution (CTD), quasi-constant thickness distribution (q-CTD), variable thickness distribution (VTD) and hybrid thickness distribution (HTD).

In this study the VTD configuration is investigated because we want to produce a pure SA3 and VTD is the easiest way to make it. CTD leads to difficulties because of the bending moments we need to apply over the optical surface limit. HTD is a solution but with more actuators. Then, a tulip-form VTD has been found to produce a quasi-pure SA3 depending on the load case (Figure 8).

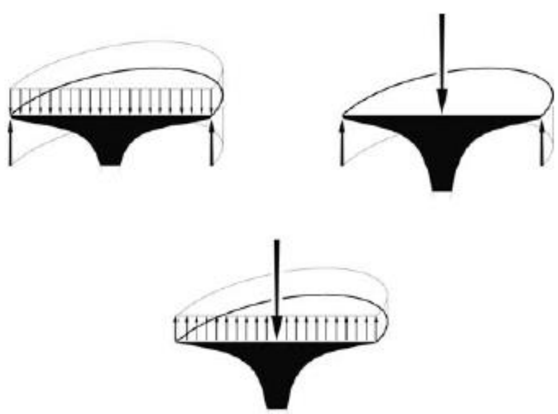

Figure 8: Variable Thickness Distribution (VTD) for three load cases

5.2 Towards a global variable thickness distribution (G-VTD)

We discussed in the previous section that spherical harmonics have been introduced in our model. In fact, these spherical harmonics result from considering a local central VTD instead of a global VTD. SA3 being an axisymmetric aberration, the model has to be similarly axisymmetric.

Therefore, I have made an axisymmetric design based on the elasticity theory of a circular plate. Due to the lightening patterns, mirrors possess two kinds of VTD. The first one is the global variable thickness distribution (G-VTD) that recovers the whole mirror and the second one is the superior skin variable thickness distribution which is the VTD in the bottom of the lightweight patterns (Figure 9).

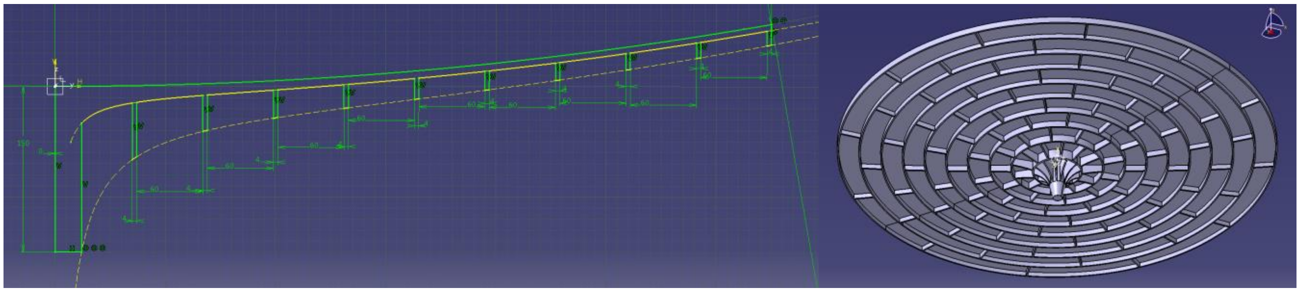

Figure 9: Global Variable Thickness Distribution (G-VTD) (left) and axisymmetric lightweight mirror's model (right)

Two G-VTD types can be plotted depending on the load case. If we just apply a polishing pressure, the G-VTD is more flattened (blue curve in the Figure 10) than a model with a combination of polishing pressure and central force (grey curve in the Figure 10). In the next simulation, we consider the case of a polishing pressure and central force combination.

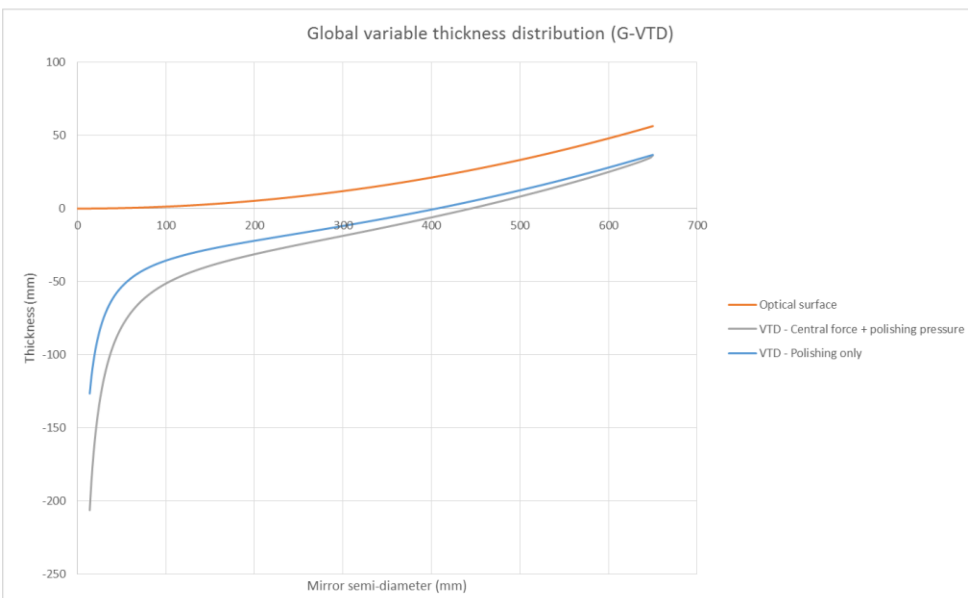

Figure 10: Optical surface's mirror (red curve), G-VTD for a polishing pressure (blue curve) and with adding a central force (grey curve)

A semi-clamped boundary condition at the mirror's edge and a combination of a 20g/cm² polishing pressure with a central pushing force of 1741N bring to a quasi-pure SA3 up to 33 µm RMS (Figure 11).

Some residuals remain such as 560 nm RMS of SA5, 2.5µm RMS of SA7, 1.1 µm RMS of SA9, and 900 nm RMS of SA11. All these spherical harmonics can be removed by properly re-defining the new G-VTD design in order to get SA3 only.

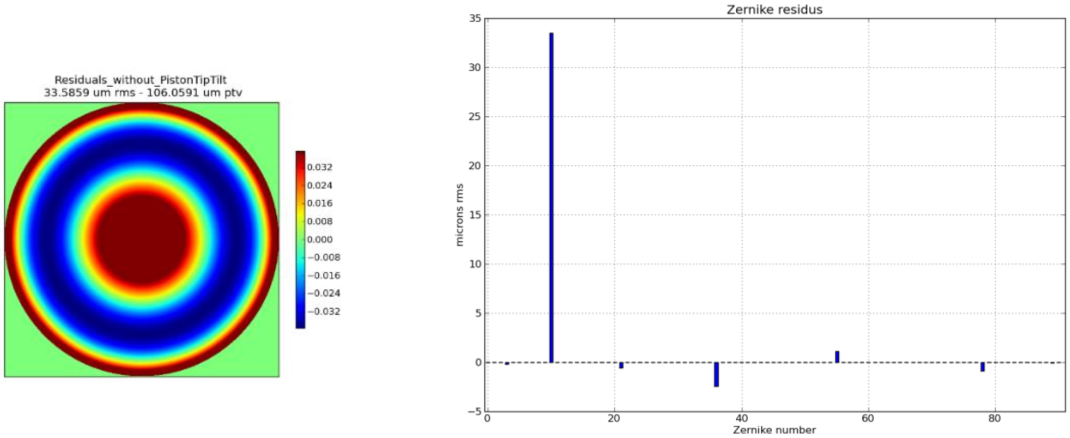

Figure 11: Phase map without piston, tip & tilt (left) and Zernike polynomials decomposition histogram (right)

Moreover, it is important to mention the extreme sensitivity of the Focus. As we can observe in the Figure 12 showing the influence of central force on the SA3, a slight deviation of the amount of the central force rapidly modifies the evolution of Focus while SA3 barely changes. This is quite significant especially in the case of producing only SA3 without any other aberrations.

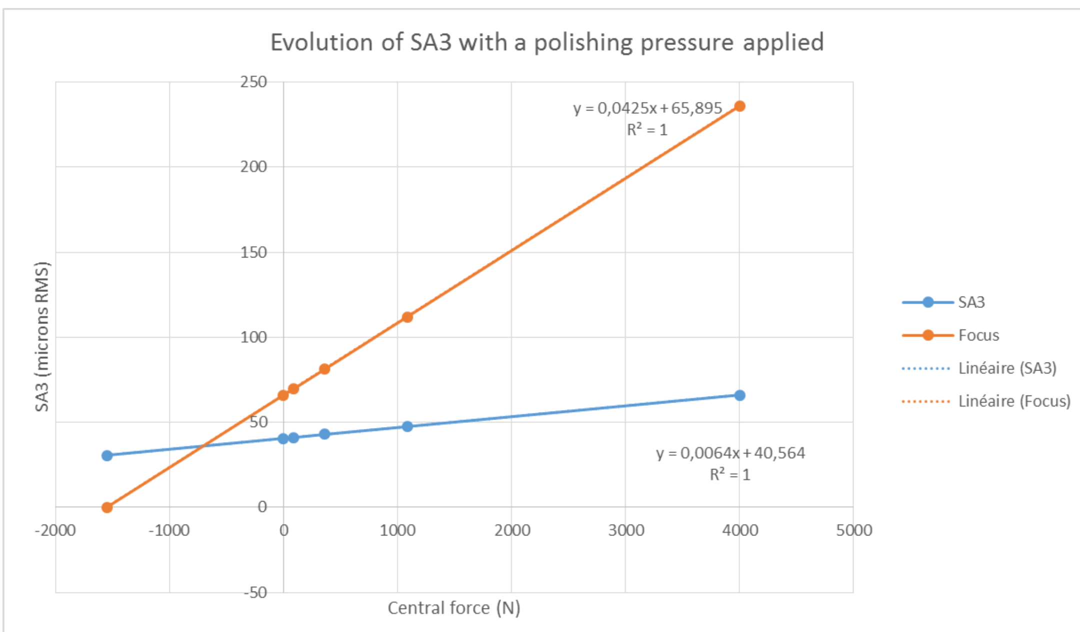

Figure 12: Evolution of SA3 (blue curve) and Focus (red curve) depending on the central force value

6. CONCLUSIONS

At first sight, SMP seems to be incompatible with large lightweight primary mirrors but this study allows to show the opposite thought. Many advantages push us to conciliate these aspects such as a high quality of optical surface but also a considerable gain of time in the polishing process.

The continuation of this project will allow to get a reduced prototype in the next few months in order to validate the FEA results and the polishing process. Also, a parametric set of equations can be generated in order to realize any kind of parabolization. The next step would be a combination of several aberrations in addition of the SA3.

7. ACKNOWLEDMENTS

This study has been achieved as part of my PhD thesis financed by THALES-SESO, in the context of the common laboratory with the Laboratoire d'Astrophysique de Marseille (CNRS-LAM, UMR 7326)

8. REFERENCES

[1] Hugot E., Ferrari, M., et al, "Active Optics methods for exoplanet direct imaging. Stress polishing of supersmooth aspherics for VLT-SPHERE planet finder", Astronomy & Astrophysics 538 (2012)

[2] Chauvin, G., Desidera, S., Lagrange, A.-M, Vigan, A., et al., "Discovery of a warm, dusty giant planet around HIP65426*", Astronomy & Astrophysics, 2017

[3] Hull, T. and Westerhoff, T., "Lightweight ZERODUR mirror blanks: recent advances supporting faster, cheaper, and better spaceborne optical telescope assemblies," Proc. SPIE 9241, Sensors, Systems, and Next-Generation Satellites XVIII, 92411I (2014)

[4] Lemaitre, G.R., [Astronomical Optics and Elasticity Theory], Astronomy and Astrophysics Library, Springer, 2009