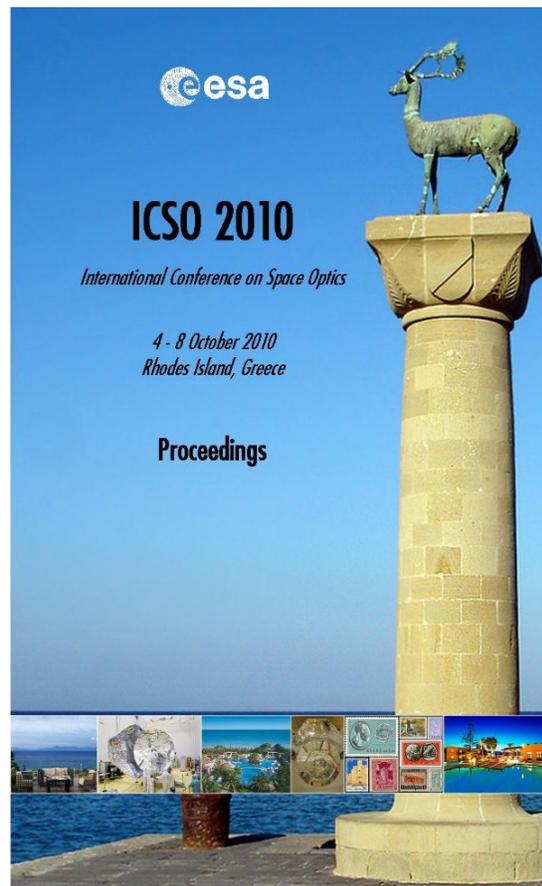


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ACTIVE OPTICS: OFF AXIS ASPHERICS GENERATION FOR HIGH CONTRAST IMAGING

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I. ACTIVE OPTICS AND STRESS POLISHING

Active Optics methods, based on elasticity theory, allow the aspherisation of optical surfaces by stress polishing but also active aspherisation in situ. Researches in this field will impact the final performance and the final cost of any telescope or instrument. The stress polishing method is well suited for the superpolishing of aspheric components for astronomy. Its principle relies on spherical polishing with a full-sized tool of a warped substrate, which becomes aspherical once unwarped. The main advantage of this technique is the very high optical quality obtained either on form or on high spatial frequency errors. Furthermore, the roughness can be decreased down to a few angstroms, thanks the classical polishing with a large pitch tool, providing a substantial gain on the final scientific performance, for instance on the contrast on coronagraphic images, but also on the polishing time and cost. Stress polishing is based on elasticity theory, and requires an optimised deformation system able to provide the right aspherical form on the optical surface during polishing. The optical quality of the deformation is validated using extensive Finite Element Analysis, allowing an estimation of residuals and an optimisation of the warping harness. We describe here the work realised on stress polishing of toric mirrors for VLT-SPHERE and then our actual work on off axis aspherics (OAA) for the ASPIICS-Proba3 mission for solar coronagraphy. The ASPIICS optical design made by Vives et al is a three mirrors anastigmat including a concave off axis hyperboloid and a convex off axis parabola (OAP). We are developing a prototype in order to demonstrate the feasibility of this type of surface, using a multi-mode warping harness (Lemaitre et al). Furthermore, we present our work on variable OAP, meaning the possibility to adjust the shape of a simple OAP in situ with a minimal number of actuators, typically one actuator per optical mode (Focus, Coma and Astigmatism). Applications for future space telescopes and instrumentation are discussed.

II. STRESS POLISHING OF SUPERSMOOTH SURFACES

The polishing of optical surfaces is a delicate operation, the basics of which are given in several books [1][2]. The sphere - the plane - is the natural surface generated by the friction of two solids of similar dimensions in a relative motion with 3 degrees of freedom. However, the use of aspherical surfaces is useful in many optical instruments and telescopes, and their fabrication is time-consuming and costly. The surfacing of aspherical surfaces has motivated several developments since the 1930's. The German astronomer Bernhard Schmidt, pioneer in Active Optics, realised the entrance corrective plate of his wide-field telescope by figuring the plate under pressure with a full-size spherical tool [3]. Although Schmidt just made experiments, André Couder detailed this technique with elasticity equations [4].

During the last few years, research has been pursued to solve the problem of figuring an aspherical surface of optical quality. Various modern techniques are based on deposition of thin films of variable thickness, ion beam figuring, petal tools, diamond turning or numerically controlled polishing [5]. Further developments in magneto rheologic polishing allowed the production of quasi perfect surfaces of small asphericities [6]. These surfacing techniques are extremely powerful for the generation of aspherical optical components of high optical quality but are limited by slope errors generating *high spatial frequency* (HiF) ripples due to subaperture tool marks, whose diffracting effects shall degrade the resulting image quality. Nowadays, strong efforts are made by the optical fabrication community to solve these problems, with algorithm optimisations and new materials for the tools [7]. However, such intrinsic limitations of all these techniques are drawbacks, especially in the field of high contrast imaging.

Manufacturing aspherical optics using stress polishing is a mature technique [8]. Its principle relies on spherical polishing with a full-sized lap of a warped substrate, which becomes aspherical once unwarped. The main advantage of this approach is the very high optical quality obtained in terms of both form and high spatial frequencies (HiF) errors. Realizing aspherical optics under stress requires minimizing both warping and polishing errors. The correct warping function, corresponding to the exact inverse of the final aspherical shape is obtained using analytical calculations based on elasticity theory. A specific blank geometry and load

configuration is defined [9], and finite-element analysis (FEA) then allows optimization of the blank shape to increase the optical quality of the warping function. Warping the substrate during polishing allows using a full sized lap, avoiding the generation of HiF (or at least minimizes this term), but also allows the simple realisation of superpolishing to get supersmooth surfaces.

Superpolishing means the ability to decrease the roughness of polished surfaces by optimising each parameter of the polishing process such as the type of lap, the polishing slurry, the temperature, speed and time of a polishing run. Leistner et al [10] made extensive analysis for supersmooth flat surfaces using Teflon or pitch laps on several materials using several polishing powders. However, the study was limited to flat surfaces because of the manufacturing process of the Teflon lap [11]. Tin laps are also used for the superpolishing of sapphire, allowing reaching less than 1Å roughness [12]. Our interest here is to focus on the superpolishing of Zerodur: according to Leistner et al, roughness can be decreased down to less than 2Å, using a pitch lap with Aluminium oxide (Al₂O₃) in colloidal slurry.

Our purpose here is to develop a manufacturing method increasing the optical quality of aspherical surfaces often use in optical designs. To reach this goal, we propose here a combination of these two powerful methods. Stress polishing and superpolishing techniques can be combined in a simple way, resulting in a substantial gain on each parameter defining an optical surface and impacting on the final contrast in coronagraphic images.

This combination has been implemented for the manufacturing of the toric mirrors for the VLT SPHERE instrument dedicated to exoplanet direct imaging.

III. VLT SPHERE TORIC MIRRORS

The realisation of the toric mirrors part of the VLT-SPHERE instrument has been achieved in January 2010 with the delivery of these three aspherical components. In order to ensure the better optical quality on each range of spatial frequencies, we optimised in a first time the deformation function: the mirrors are warped during the polishing as shown on Fig. 1 (Left) using two pairs of equal and opposite forces applied at the end of two orthogonal diameters of the substrate. An angular thickness distribution has been calculated from elasticity equations in order to avoid the generation of high order angular terms on the deformation function. After validation using finite elements analysis (FEA) and interferometric software (Fig. 1), this specific geometry is machined on an external thick ring on the Zerodur blank, outside the clear aperture of the mirror. The deformation is applied using a ring attached on two points on the rear side of the mirror (Fig. 2). The complete analytical description has been published in our latest articles [13][14].

Results in terms of surface quality are shown on the interferograms on Fig. 2. TM1 (Ø133mm, F/5, 10µm asphericity) and TM2 (Ø40mm, F/15, 1µm asphericity) surface quality is well better than expected: less than λ/30 rms on form errors (LoF, astigmatism error subtracted), less than λ/200 on MiF (up to the limit of the AO correction) and HiF (errors not corrected by AO). Furthermore we applied the superpolishing technique using the full sized pitch tool, decreasing the roughness down to 0.5nm RMS for TM1 and down to 0.2nm RMS for TM2, measured on a window of 200µm² with a resolution of 1µm. This result is obtained after a finishing run of only 30min using Al₂O₃ polishing agent, and is almost easy to manage thanks to the simple spherical polishing.

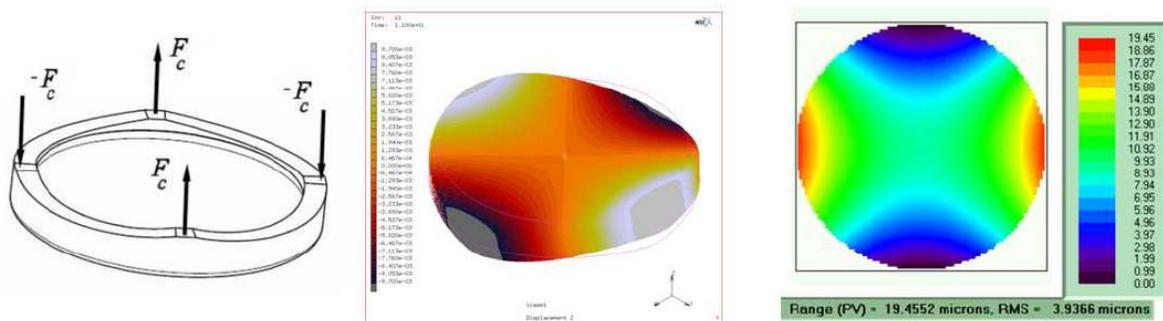


Fig. 1 Left: Rear view of the geometrical design of the TMs blanks. The angular thickness distribution avoids the generation of higher order angular terms. Two pairs of equal and opposite forces are applied on the external thick ring. Middle and Right: FEA and phase map obtained from FEA, used for the characterisation, optimisation and validation of the deformation function.

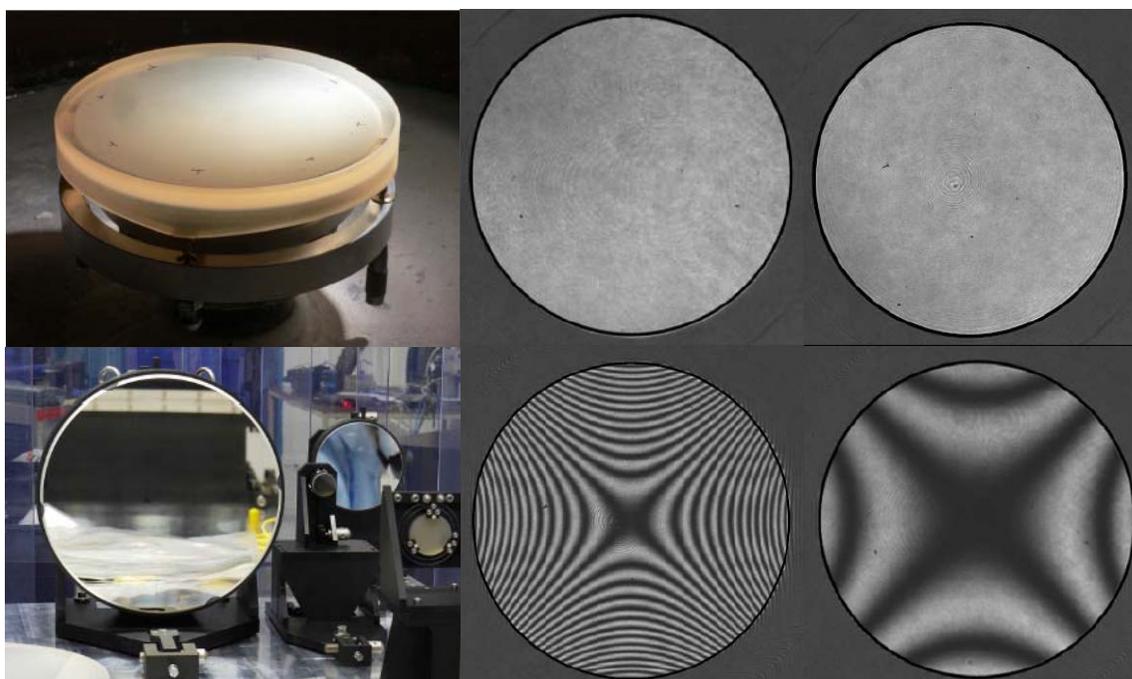


Fig. 2 Left: TM1 on the polishing machine, with its deformation system fixed on the rear side of the external thick ring and view of the three TMs coated and mounted on the SPHERE optical bench. Right: He-Ne interferograms obtained with Fizeau interferometer for TM1, 2 at the end of the spherical polishing (Top) and after removal of the loads (Bottom).

IV. SUPERSMOOTH OFF AXIS ASPHERICS FOR THE ASPIICS PROBA-3 ESA MISSION

A. High contrast imaging with an extended source

Since the study of solar corona using a coronagraph has been proposed by Lyot [15] in the 1930's, strong efforts have been made in the past decades, leading now to dedicated space instruments. ASPIICS [15][17] stands for *Association de Satellites pour l'Imagerie et l'Interférométrie de la Couronne Solaire*. The mission consists in two spacecrafts separated by about 150m to form a giant externally-occulted coronagraph in space permanently reproducing the optimum conditions of a total eclipse of the Sun thus giving access to the inner corona with high spatial resolution and very high contrast around 10^{-9} . High contrast imaging of the solar corona must deal with the fact that sun is a very bright *extended* source. In this case the parameter that dominates the error sources is the roughness on optical surfaces, increasing the *Total Integrated Scatter (TIS)* resulting in a residual halo in the image plane. The optical design described by Vives et al [18] is a three mirrors anastigmat design made of a concave OAA (M1), a convex OAP (M2) and a sphere for the final focusing. In this context, superpolishing of aspherics under stress seems well suited to reach the challenging scientific objectives of this mission. Fig. 3 plots a comparison of 2D-Power Spectral Densities (azimuthal average) showing the obvious gain given by supersmooth surfaces.

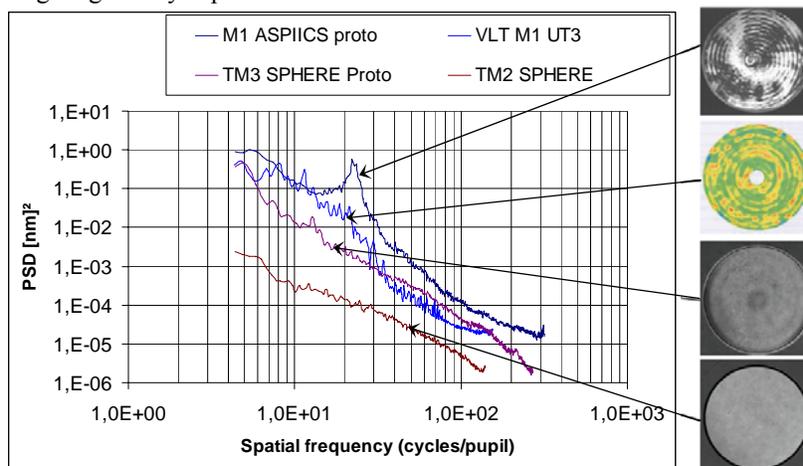


Fig. 3 Azimuthal average of 2D-PSD. Comparison between VLT UT3 primary mirror, the actual M1 ASPIICS prototype, the actual VLT/SPHERE-TM3 prototype, and the actual supersmoothed VLT/SPHERE-TM2.

B. Proposition

The demonstration of superpolishing has been made on the toric mirrors, which surface combines a sphere plus astigmatism. In the case of off axis parabolas (OAP) and off-axis aspherics (OAA), the optical surface is not only a sphere and a simple mode, but combines several modes depending on the parameters defining the surface: the F-ratio of the parent aspheric and the OAA, the off axis distance and the conic constant in case of an OAA. Lubliner & Nelson [19][20] described the analytical equations giving the asphericities or Zernike modes to be generated on a sphere versus these parameters, in the frame of the manufacturing of Keck's primary mirrors segments. Two times 36 segments plus spares have been manufactured with this technique and then finished using Ion Beam (IBF) in order to remove the final HiF on the surface. Optimized designs, called *Vase form Multimode Deformable Mirror* (VMDM), have been proposed by Lemaître [21] (2001) in order to avoid the transmission of local deformation to the optical surface, by using a rigid outer ring clamped at the edge of the mirror's meniscus. This double-thickness design called *vase form mirrors*, present a strong advantage: forces and bending moments are applied as far as possible from the optical surface (Fig. 4), so that quasi-pure optical modes are transmitted to the meniscus (Lemaître & Wang [22]). This warping harness generates N forces applied on the arms, forces corresponding to N influence functions on the mirror, leading to N eigen modes (Laslandes et al 2010 [23]).

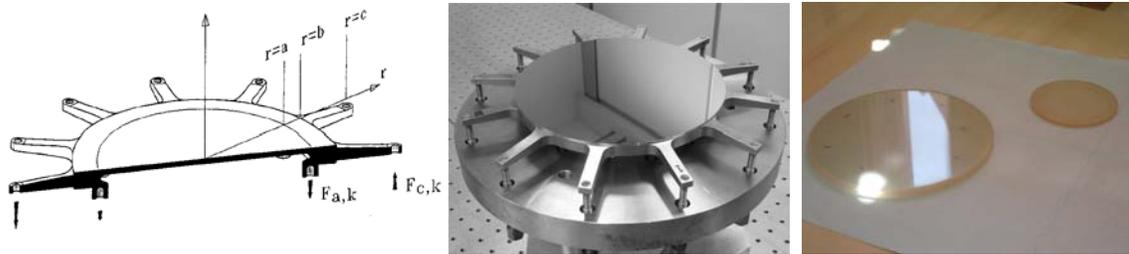


Fig. 4 Left: Mechanical design of a 12-arms MultiMode Deformable Mirror, allowing the generation of 24 optical modes onto the thin central meniscus. Middle: 12-arms MMDM prototype made by Lemaître [21] that must be adapted for the bending of Zerodur mirrors. Right: M1 and M2 Zerodur blanks.

Our proposition here is to develop an OAA prototype using this design, starting from the optical figure of OAA in the TMA design of ASPIICS Proba-3 ESA mission. Fig.5 draws the M1 interferogram to be obtained on the OAA (M1). While M2 is easily feasible, M1 is a challenge considering the amount of aberrations to be generated by elasticity on such a small clear aperture ($\varnothing 110\text{mm}$). The amount of stress into the material is computed using FEA to allow a fine tuning of the deformation system parameters in order to ensure that the material will work down its elastic limit. Results plotted on Fig.5 show that the deformation function is obtained for a level of stress lower than 7MPa, close to the breakage limit. However, the optical quality of the deformation is better than 15nm RMS WF on form errors, and better than 2nm RMS WF on MidF-HiF, validating the mechanical designed proposed.

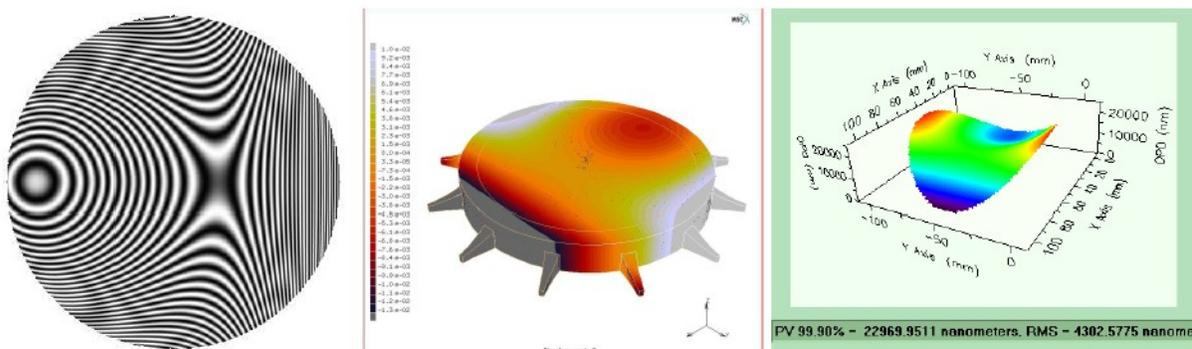


Fig. 5 Left: Numerical He-Ne interferogram of M1 to be obtained on the optical surface by elastic deformation, thanks to the MMDM design. Middle: Finite Element Analysis of the deformation system for the primary mirror, showing the deformation function obtained on the optical surface. With a level of stress lower than 7MPa, the material is working close to its breakage limit. Right: The 23µm deformation PtV is obtained with an optical quality better than 15nm RMS WF on form errors, and better than 2nm RMS WF on MidF-HiF errors.

V. VARIABLE OAP FOR SPACE APPLICATION

The design presented beyond, even if well suited for the stress polishing, requires 12 pairs of actuators for the correct control of the mirror shape even on low order modes. A lot of applications, especially the generation of OAPs, only requires 2 or 3 modes (Astigmatism, Coma, sometimes Trefoil). Having 24 actuators for the generation of only 3 modes, means that the system is able to generate at least 21 parasite modes if the system is not well monitored.

We identify the need to work on the minimisation of the number of actuators in order to obtain smart systems able to generate one single optical mode per actuator. For that, the work is focused on the shape of the influence functions of each actuator. Optimising the shape of an influence function requires a strong effort on the mechanical system transmitting the shearing forces and bending moments to the mirror. Our first demonstration has been made on the astigmatism mode in 2008 [13]. We are now converging on Coma and Focus, and the linear combination of these influence function. Fig. 6 shows the prototype we made for the astigmatism generation: two beams are attached at the end of two orthogonal diameters of a circular plate. A single actuator acting between these two beams will directly transfer two pairs of equal and opposite forces. The shape of the mirror has been optimised in order to avoid generating high order harmonics.



Fig. 6 View of the prototype realised at LAM optical laboratory, allowing generating variable third order astigmatism. Two beams are placed under the thick ring and attached to it via solid links. The angular modulation is achieved via *mechanical bridges*, avoiding the $\cos(6\theta)$ component of the deformation. The differential micro screw located between the beams acting as a mechanical actuator can be replaced by any other type of actuator for a servo control.

Advantages of this concept are clear. The reduction of the number of actuators also reduces the mechanical integration, the control/command system, the weight of the overall system, the calibration time in an instrument. It also excludes any differential amplitude of the forces, avoiding parasite Tip/Tilt errors. It is a gain in time, reliability and cost.

The use of these systems will reduce the complexity of future space mission such as giant formation flying satellites holding OAPs. By adjusting in situ the shape of OAPS, such systems can eventually reduce the positioning precision and then increase the life time of space crafts, and also allow any change of the pupil configuration.

VI. CONCLUSION

We demonstrate, through the realisation of VLT-SPHERE toric mirrors, the possibility to obtain supersmooth aspherical mirrors and their impact on the final contrast of high dynamic instruments such as planet imagers or solar instruments. The stress polishing method provides high quality aspheres, exempt of MidF or HiF errors classically due to subaperture tool marks. By avoiding the generation of these errors, this technique reduces the level of the residual quasi-static speckles in the image plane and limits the scattering effect, reducing the residual halo in the image plane. Our work is now focused on the manufacturing of OAPs and OAAs, through the realisation of two prototypes for the ESA ASPIICS/Proba3 mission. Results will be delivered at the end of year 2010. We are also developing *smart warping systems* in order to generate OAPs with a minimal number of actuators, typically one actuator per optical mode. A patent is pending on this technique.

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