

ICSO 2016

International Conference on Space Optics

Biarritz, France

18–21 October 2016

Edited by Bruno Cugny, Nikos Karafolas and Zoran Sodnik



Monomorph deformable mirrors: from ground-based facilities to space telescopes

Raphaël Cousty

Tania Antonini

Marie Aubry

Hélène T. Krol

et al.



icso proceedings



International Conference on Space Optics — ICSO 2016, edited by Bruno Cugny, Nikos Karafolas,
Zoran Sodnik, Proc. of SPIE Vol. 10562, 1056231 · © 2016 ESA and CNES
CCC code: 0277-786X/17/\$18 · doi: 10.1117/12.2296247

MONOMORPH DEFORMABLE MIRRORS: FROM GROUND-BASED FACILITIES TO SPACE TELESCOPES

Raphaël Cousty, Tania Antonini, Marie Aubry, H el ene Krol, Aur elien Moreau
CILAS, 8 Avenue Buffon, CS 16319, 45063 ORLEANS Cedex 2, FRANCE
cousty@cilas.com

INTRODUCTION

Since 20 years, the bimorph deformable mirrors developed by CILAS and their most recent generation called “monomorph” demonstrated their powerful ability to correct the optical aberrations and optimize the performances of numerous ground-based facilities from astronomical telescopes to high-power laser chains. Thanks to this unequalled heritage, its exceptional performances and its unfailing reliability, the monomorph technology rationally became an ideal candidate for in-flight wavefront correction of next-generation space telescopes.

In the frame of OTOS (Observation de la Terre Optique Super-R esolue), a CNES technological program preparing next generation of Earth observation satellite, CILAS is developing a monomorph mirror which could be located in the telescope exit pupil to compensate primary mirror shape defaults. Thanks to this deformable mirror, the imaging resolution is increased while the telescope compactness is improved, which represents a considerable advantage for the agility of the satellite and for the size and cost of the launcher. The design of this spaceborne deformable mirror was achieved in 2015 and the manufacturing of a Qualification Model is currently under progress to achieve TRL6 at the end of its full-qualification planned in a few months.

I. THE MONOMORPH TECHNOLOGY

A. Introduction

Pioneer in adaptive optics, CILAS started to develop deformable mirrors (DM) in the early 1970’s. After few years dedicated to the study of adaptive optics systems for the French Defense procurement agency, CILAS started a very fruitful collaboration with the astronomy community in the mid-1980’s. The first major success of this collaboration was obtained in 1989 with the first light of COME-ON (Cge, Observatoire de Meudon, Eso, ONera). The results obtained with this Adaptive Optics (AO) prototype constituted the first demonstration in astronomy of atmospheric turbulence real-time correction [2]. Such as many other AO systems from ESO (European Southern Observatory), this first system was equipped with a piezoelectric deformable mirror designed and manufactured by CILAS (formerly CGE).

After this successful demonstration, CILAS continued to develop years after years numerous of innovating and high-performance deformable mirrors. These mirrors were dedicated to fast correction of atmospheric turbulences for ground-based telescopes (field of adaptive optics) but also for quasi-static correction of very low thermal drifts, for instance in high-power laser systems to optimize the focusing of the optical beams (field of active optics). Since 1996 and the first light of PUEO [2], CILAS is proposing a time-tested technology with performances meeting the requirements of these two fields of correction (active and adaptive optics): the bimorph technology and its most recent and most powerful generation, the monomorph.



Fig. 1. Left: 60-element bimorph installed on VLT early 2000’s. Right: recent monomorph mirror
Proc. of SPIE Vol. 10562 1056231-2

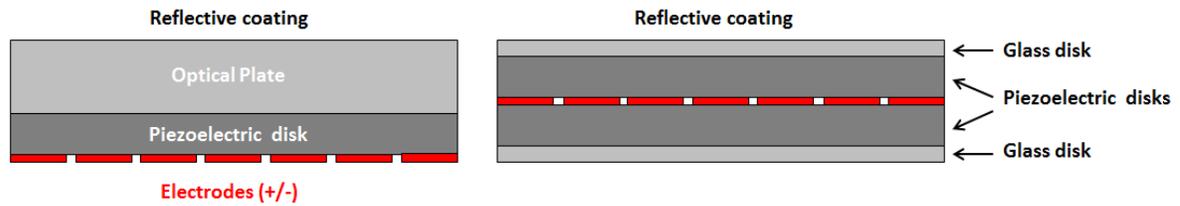


Fig. 2. Left: architecture of the monomorph technology. Right: former bimorph technology

B. Architecture and main characteristics

The architecture of a monomorph deformable mirror is very simple (figure 2). The mirror is made of two main components bonded together: a piezoelectric disk and a glass plate which is polished and covered with a reflective coating. The piezoelectric disk is composed of several electrodes (figure 3): when a voltage is applied on an electrode, the electrical field induces a local in-plane elongation (or contraction) of the piezoelectric disk. The bimetallic effect between the piezoelectric ceramics and the optical plate then generates a local bending of the optical surface. The shape of the mirror can be completely controlled by applying different voltages on each electrode to generate numerous shapes (focus, astigmatism, spherical aberration, trefoil...).

The former bimorph mirrors dating from the late 1980's used the same functional concept based on the piezoelectric transverse effect but their architecture were much more complex. These mirrors were made of two piezoelectric disks encapsulated between 2 glass plates. The local curvatures of the optical surface were at that time generated by the opposite elongation of the two piezoelectric disks. As the electrode layout was located at the interface between the two piezoelectric plates, the electric contacting was very critical. In addition, this previous architecture also imposed very thin glass plates to achieve sufficient stroke: for comparison, the optical plate of a monomorph mirror is 10 times thicker than the ones of a bimorph to generate the same stroke.

The following paragraphs will illustrate the unequalled heritage of the former bimorph mirrors since 20 years. We will also present the major improvements obtained with the new generation of monomorph mirrors though their 10-year of return of experience in ground-based facilities. These improvements concern the performances (optical quality, stroke, bandwidth: see table 1) but also the reliability: during this last decade, no major or minor failure has been noted by the users of monomorph mirrors implemented and operating in ground-based facilities.

Regarding the dimensions, monomorph mirrors are compatible with clear aperture from 25 to 250 millimetres. The number of electrodes is usually limited to tens to a few hundreds, which is quite sufficient to correct with accuracy the wavefronts of the most common applications. The layout (number and shapes of the electrodes) can be easily adapted to optimize the correction performances according to specific requirements. Typical performances reached with monomorph DM are:

- High stroke of $\pm 60 \mu\text{m}$ PtV wavefront ;
- Excellent optical quality after flattening (better than 10 nm RMS wavefront) ;
- Very fast response time response ($\sim 100\mu\text{s}$) ;
- High bandwidth (from 500 Hz to a few kHz depending on dimensioning and customer requirements).

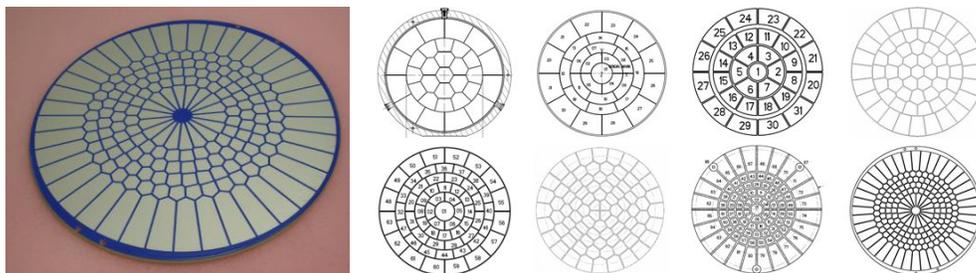


Fig. 3. Example of electrode layouts designed and manufactured by CILAS

Table 1. Left: Performances obtained with former bimorph mirrors (example of BIM60-60 installed on VLT early 2000's) compared to the performances of new generation of monomorph mirrors.

Parameter	BIM60-60 ESO-VLT	MONO60-60
Clear aperture diameter	60 mm	60 mm
Number of electrodes	60 elements	60 elements
Optical quality	20 – 30 nm RMS WF	< 10 nm RMS WF
Maximum stroke	< 30 μm PtV	> 30 μm PtV
First mechanical frequency	200 - 300Hz	1.5kHz

B. Heritage through ground-based telescopes

CILAS deformable mirrors operating on ground-based telescopes are used to compensate in real time spurious effects of the atmospheric turbulences. The DM usually operates in closed-loop combined with a wavefront sensor (WFS). For these applications, very fast response time ($\sim 100 \mu\text{s}$) and large bandwidth ($> 1 \text{ kHz}$) are commonly required, which is well adapted to the performances reached by the monomorph technology.

The first bimorph from CILAS operating on the sky was developed for the AO system known as “PUEO” [2]. It was installed on the 3.6-meter Canada-France-Hawaii Telescope (CFHT), located near the summit of Mauna Kea on Hawaii's Big Island at an altitude of 4,204 meters. PUEO system is composed of a 19-electrode bimorph mirror and a curvature wavefront sensor. Extensive results collected since the first light of PUEO in 1996 demonstrates significant gains of performances thanks to AO.

After the success of PUEO, other famous large telescopes were equipped with CILAS bimorph mirrors. Let's mention for instance the Subaru Telescope, the 8.2-meter optical-infrared telescope also located in Hawaii and operated by the National Astronomical Observatory of Japan (NAOJ). First AO system installed on this telescope was composed of a 36-electrode DM from CILAS, providing its first light in 1999. Seven years after, the 36-element system was upgraded with a much-improved 188-element system which gave its first image in 2006. The 188-electrode bimorph of this system was also developed by CILAS.

During the same period, several AO systems were developed and installed on the Very Large Telescope (VLT) from ESO (European Southern Observatory). Four of these systems were installed at the Coude foci of the VLT unit telescopes to feed the VLT Interferometer [3]. The system used 60-elements DM developed by CILAS (clear aperture of 100-mm diameter) with curvature WFS using avalanche photodiode as detectors. The correction performances of these systems allowed to reach a 60% strehl ratio in the K-band (2.2 μm wavelength), which is an excellent performance for this relatively low (60) order system. The AO systems were installed at the observatory in Chile in the early 2000's and have been in routine operation since then, feeding all VLTI instruments at the Paranal Observatory. The deformable mirrors never experienced any failures and ESO has undertaken actions in order to extend the lifetime for which the systems were designed beyond the nominal 10 years. Besides VLTI, ESO also installed during the same period two other smaller 60-elements DM (clear aperture of 60-mm diameter) at the Cassegrain and Nasmyth foci of Unit telescopes [4] [5]. These mirrors remain in a successful, flawless operation.

More recently, the Swedish 1-meter Solar Telescope (SST) benefited from the optimal performances given by the monomorph technology. This telescope was installed in 2002 on La Palma in the Canary Islands and is commonly considered as the world leading ground-based solar telescope. In 2013, a new adaptive optics system gave its first light: this upgraded system is composed of an 85-electrode monomorph mirror (specifically designed and manufactured by CILAS) which is controlled by an 85-subaperture Shack-Hartmann WFS. Since 2013, the AO85 system is used approximately 10 hours per day from beginning of April to end of October. The 85-electrodes mirror has led to an impressive enhancement of the image quality of the SST. This is obvious in part from the strongly enhanced contrast of solar images at all wavelengths and in particular as a strongly increased fraction of near diffraction limited imaging at wavelengths around 400 nm. The improved image quality is mostly attributed to the exceptional optical quality of the DM, reaching 3 nm RMS mechanical surface after flattening. Regarding the temporal performances, the update frequency is set at 2 kHz to reach a 0 dB closed loop of approximately 120 Hz. Scientific observations cannot be made without a properly functioning adaptive optics system and the SST fully benefited of the powerful performances of the monomorph technology since 4 years.

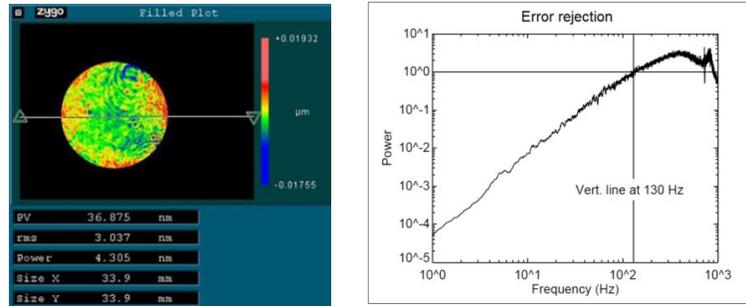


Fig. 3. Performances obtained with 85-element mirror operating on SST. Left: Optical quality after flattening (3 nm RMS mechanical surface). Right: error rejection response of SST AO system.

C. Heritage through high-power laser chains

Since many years, the users of high-power lasers require deformable mirrors to optimize the focusing of their systems. These active devices are positioned in the path of the beam in order to control the distortions. For these systems, the correction is limited to the compensation of the low order aberrations (first Zernike modes) and the deformable mirrors operate at very low temporal frequency (< 1 Hz). This kind of correction defines the field of active optics.

For years, piezoelectric mirrors are used to optimize the quality of laser beams, first with former bimorph technology, then with new generation of monomorph mirrors. This last technology immediately provided a major improvement of the correction performances when it was installed and tested in laser systems 10 years ago: the optical surface of a monomorph mirror does not show any “print-through” on the optical surface during operation, whereas former bimorph mirrors sometimes show this kind of defects (electrode layout “visible” on the optical surface). This point is critical for laser systems as print-through can create “hot spots” which can degrade the optical components located in the laser chain after the deformable mirror. The demonstration of this unequalled optical quality without print-through (see figure 4) was first demonstrated by LOA (Laboratoire d’Optique Appliquée), a French laboratory specialized in ultrafast lasers and their applications [6]. For more than 15 years, CILAS deformable mirrors (both bimorphs and monomorphs) equipped femtosecond lasers from this famous laboratory. Among the DM used by LOA, let’s take the example of a 61-electrode monomorph with a clear aperture of 75-mm diameter: this mirror is operating in vacuum at 10⁻⁵ mbar and is submitted to 200 shots per day (1 shot every 1 or 2 minutes) since several years. During the shots, the mirror is driven in open loop without requiring any recalibration of its shape. No print-through effects and no laser induced damage have been observed, and the deformable mirror allows obtaining a wavefront measured at lambda/20 after correction. This DM is considered by LOA as an essential device to optimize the laser beam quality.

The Orion laser facility operated by the Atomic Weapon Establishment (AWE) is another example of the contribution of the monomorph technology [7]. This 2PW-class laser is equipped with two 63-electrodes monomorph mirrors with clear apertures of 85-mm. The mirrors were installed in 2010 and have been used continuously and reliably since that time. The systems are used in conjunction with a Shack-Hartmann WFS. The system uses CW alignment beams for closed-loop operation and readily corrects the aberrations of the laser system (a few microns peak to valley) to around 50 nm peak to valley. Before a laser shot, the mirrors are driven in open loop during a few minutes: no drift of the mirror shape is then observed. These mirrors have enabled the Orion laser facility to achieve its potential in terms of focal intensity.

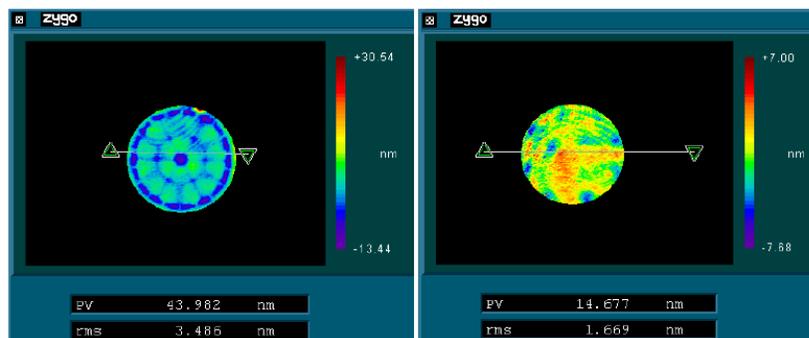


Fig. 4. Optical quality of former bimorph mirrors (left) and new monomorph mirrors (right)

II. SPACE TELESCOPES

A. Introduction

Previous chapter gave an illustration of the use of monomorph mirrors operating in ground-based facilities. On high-power lasers and ground-based telescopes, this type of deformable mirrors became an essential device to reach the full-performances of the instruments. Numerous advantages are highlighted by the users of CILAS mirrors through 20 years of return of experience. Among these advantages, let's mention the exceptional optical performances or the unfailing reliability.

In order to implement deformable mirrors for in-flight correction of space telescopes, other characteristics of the monomorph present considerable advantages, such as the simplicity of the architecture, the lightweight, or the absence of internal heat dissipation during operation. To mitigate aberrations caused by thermal deformation and gravitational release, next generation of large space telescopes will require in-flight active optics systems implementing deformable mirrors. Thanks to the addition of a monomorph DM in the telescope exit pupil, primary mirror shape defaults could then be corrected with an excellent efficiency.

For this reason, CILAS is currently developing a mirror compatible with the performances and the environments required for these upcoming space programs. These developments are conducted in the frame of OTOS technological program from CNES preparing next generation of Earth observation satellite. In the scope of this program, the manufacturing of a Qualification Model is currently under progress to achieve TRL6 at the end of the qualification tests in a few months.

B. Early studies (phase A)

Before the start of OTOS program, early studies preparing in-flight correction with a monomorph mirror were carried out in the frame of CNES "CXCI" activities (2012-2013). These studies included an early design and mechanical dimensioning done by CILAS, to mitigate one of the most critical issues for a space deformable mirror: the safety of the mirror during the launching phase.

Among the other early activities, an experimental characterization of the monomorph mirrors was realized by CNES [6]. The optical setup included a Shack-Hartmann wavefront sensor and a 63-electrodes monomorph mirror with a clear aperture of 85 mm. Figure 5 shows a representative result obtained by CNES, demonstrating an efficiency of correction of 99.6% thanks to the MONO63-85 mirror provided by CILAS.

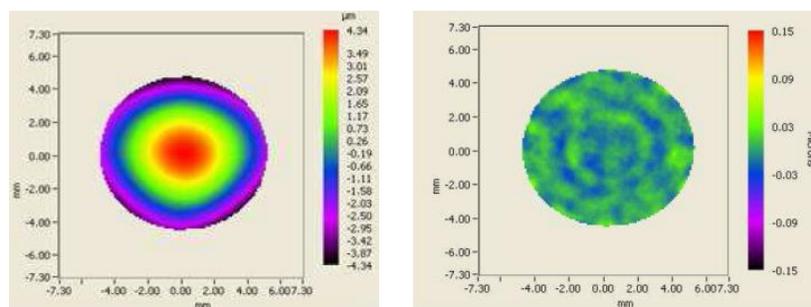


Fig. 5. Experimental results obtained by CNES with 85-electrode monomorph. Left: before correction (3 μm RMS). Right: after reflection (11 nm RMS).

Beyond these performance measurements, a technological evaluation was done by CNES to characterize the robustness of the technology on about twenty samples specifically produced by CILAS. Numerous tests were performed by CNES (table 2), showing very high security margins on all the parameters between the limits of the technology and the requirements of upcoming Earth observation space programs.

Endurance tests performed by CNES (> 1 billion cycles) complete the return of experience from CILAS on monomorph mirrors operating in ground-based facilities. Figure 6 gives an overview of relative security margins between ground-heritage and OTOS requirements (125,000 cycles):

- x50 for laser systems,
- x1,000 for astronomical telescopes,
- x10,000 for endurance tests in CNES premises.

Table 2. Results of the preliminary technologic evaluation done by CNES

Test	Conclusions
Electrical reliability	Security margins x10 on the coercive field (depolarization of the piezoelectric material) and x17 on the breakdown voltage
Humidity	Test successful at 80% RH during more than 1300 hours. No criticality is noted on the reliability for operation in clean room humid conditions
Mechanical tensile strength	Security margins higher than x10 (no damage noted at 10 times the nominal deformation)
Endurance	Cycling at resonance frequency up to 1 billion cycles with no failure

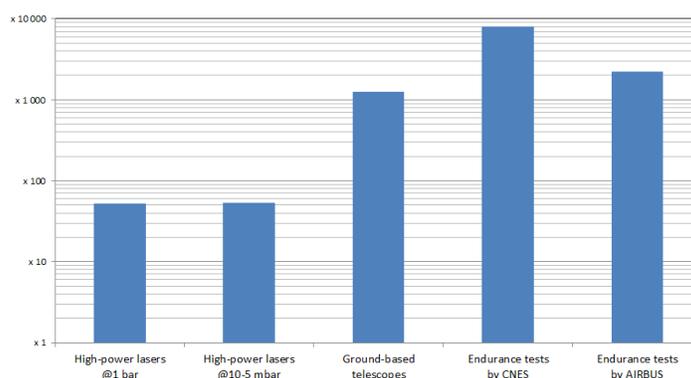


Fig. 6. Lifetime of monomorph mirrors operating in ground-based facilities (number of cycles): security margins between the return of experience and the requirements for OTOS program.

B. Preliminary and critical design (phases B/C)

The design of the spaceborne deformable mirror was done in accordance with ESA standards (ECSS) and the technical requirements provided by AIRBUS. The mirror is made of 63 electrodes for a clear aperture closed to 90-mm diameter. The overall volume is included in a cylinder of 240-mm diameter and 100-mm height.

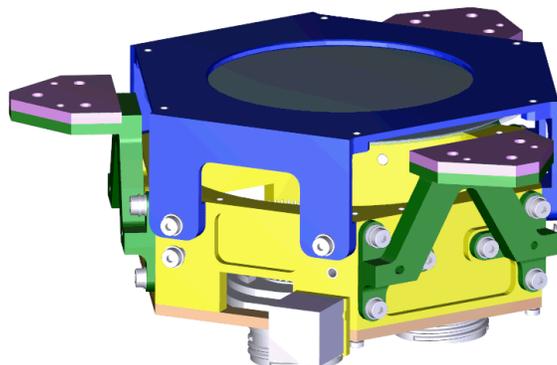


Fig. 6. Overview of the spaceborne monomorph design (CAD)

During the phase of design and dimensioning, each elementary process (gluing, coatings, electrical contacting...) was qualified on numerous samples according to a rigorous test plan including thermal cycling tests, vacuum, humidity, vibrations... Low-outgassing materials compatible with space environments were selected according to criteria of table 3. At least, concerning the molecular and particular contamination, typical requirements of Earth observation programs were taken into account across the cleanliness plan defined for the manufacturing of the mirror.

Table 3. Outgassing criteria for material selection

Mass of material	CVCM (%)	RML (%)
> 100 grams	< 0.01%	< 1 %
10 – 100 grams	< 0.05%	< 1 %
< 10 grams	< 0.1%	< 1 %

The mechanical dimensioning was realized with numerical models by rigorously applying ESA rules regarding the security factors and associated margins. Finite Element Models allowed an optimization of the overall design, especially the mass, the first eigen frequency and the robustness in regards to the random vibration environments. Final design presents a total mass lower than 2 kg and a first mechanical eigen frequency higher than 600 Hz.

The mechanical simulations show significant security margins regarding the vibration environments (table 4). These environments cover the European launchers, including Vega, Ariane 5 or Soyouz. The numerical results were confirmed by tests on two representative breadboards, showing consistency better than 3 % between measured and calculated frequencies (without recalibration of the models). At least, shaker testing was successfully realized to validate the random vibration environments on a representative breadboard at scale 1:1 of all the critical components (materials and processes) of upcoming qualification model.

Table 4. Random vibration levels

f (Hz)	PSD (g ² /Hz)	lope (dB/oct)	gRMS (g)	f (Hz)	PSD (g ² /Hz)	lope (dB/oct)	gRMS (g)
20	0.008089	6		20	0.004044	6	
100	0.200000	0	2.57	100	0.100000	0	1.82
400	0.200000	-12	7.75	500	0.100000	-12	6.32
2000	0.000327	0	5.15	2000	0.000398	0	4.06
Overall Lev 9.65g RMS				Overall Lev 7.73g RMS			

Regarding the thermal environments, non-operational temperature range was fixed to -15C / +50C and the operational temperature specified at 20C ± 2C. These operational temperature values do not represent a limit for the monomorph technology as the functional properties of the selected piezoelectric ceramics were characterized by test at CILAS, showing extremely stable properties in the range in the range of -30C / +30C.

The dimensioning of the mirror considers maximum voltages of ±150V to drive the mirror. This limit is not intrinsically imposed by the monomorph technology but by the associated space electronic driver (which is deported) in order to limit its volume, mass and dissipation. This space electronics is under development by AIRBUS. The mirror itself does not include proximity electronics and is not submitted to any internal heat dissipations during operation.

Regarding the performances, the response time of the mirror is very fast (typically a hundred of μs) with a bandwidth limited by the first mechanical eigen frequency (higher than 600 Hz). The instantaneous maximum stroke at ±150V is closed to ±25 μm PtV. These parameters (stroke and temporal performances) were validated by tests on a representative breadboard, showing a perfect coherence with expectations and theoretical models. Ultimate correction ability in closed loop is given in figure 7.

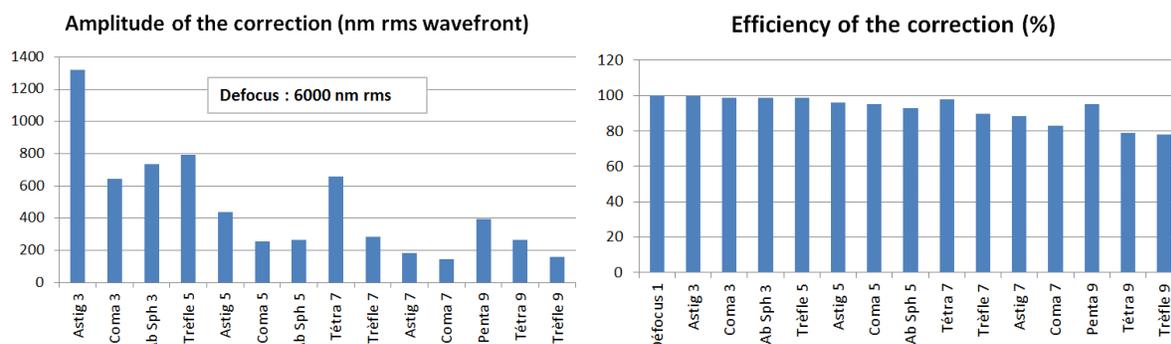


Fig. 7. Right: instantaneous amplitude of the correction in closed loop. Right: efficiency of the correction.

In-flight performance budget was set thanks to numerical simulations, taking into account the customer requirements (instrument aberrations before correction) but also the flattening of the deformable mirror. This flattening takes into account a shape at rest of the DM which combined all the following parameters:

- Deformations induced by all DM manufacturing steps (evaluated by experimental measurements);
- Integration of the mirror on the customer mounting plane (worst case evaluated by FEM);
- 0g/1g effect (FEM);
- Thermal evolutions of the mirror shape at rest in the operational temperature range (FEM).

The simulations show that in-flight correction of the instrument aberrations can be corrected by the deformable mirror with a residual error better than 10 nm RMS wavefront (flattening of the DM included). This correction requires voltages lower than 100V.

To complete the analyses, a Failure Modes Effect Analysis (FMEA) was also carried out, showing that all single points of failure (SPOF) were addressed during the design phase. No risk of failure propagation was identified.

C. Manufacturing and qualification (phases D)

Last phase of the project is currently under progress. It includes the manufacturing and the formal qualification of a Qualification Model (QM) aiming to reach at least TRL6.

The manufacturing of the QM is done in accordance with the final design ratified at end of phase C. The model implements all the elementary process and components previously qualified during the design phase.

Formal qualification tests will include performances, environmental testing (thermal cycling, random vibration) and endurance test. This phase will be finished in a few months. The deformable mirror will then be delivered to AIRBUS for additional tests coupled with their space electronic driver which is under development in order to drive the spaceborne mirrors from CILAS.

ACKNOWLEDGMENTS

CILAS would like to express its gratitude to the following organizations for sharing their return of experience with our deformable mirrors: the European Southern Observatory (ESO), the 1-meter Swedish Solar Telescope (SST), the Laboratoire d'Optique Appliquée (LOA) and the Atomic Weapon Establishment (AWE).

CILAS is also very grateful to CNES and AIRBUS for their fruitful collaboration, trust and confidence expressed through the developments under progress for space-telescopes.

REFERENCES

- [1] Rigaut, F., Rousset, G., Kern, P., Fontanella, J. C., Gaffard, J. P., Merkle, F., "Adaptive optics on a 3.6-m telescope - results and performance" *Astronomy and Astrophysics*, vol. 250(1), 280-290 (1991)
- [2] Arsenault, R. ; Salmon, D. ; Kerr, J. ; Rigaut, F. ; Crampton, D, et al., "PUEO: the Canada-France-Hawaii Telescope adaptive optics bonnette I: system description", *Proc. SPIE 2201, Adaptive Optics in Astronomy*, 833 (1994).
- [3] Arsenault, R., Donaldson, R.; Dupuy, C.; Fedrigo, E. ; Hubin, N., et al., "MACAO-VLTI adaptive optics systems performance", *Proc. SPIE 5490, Advancements in Adaptive Optics*, 47 (2004).
- [4] Bonnet, H. ; Conzelmann, R. ; Delabre, B. ; Donaldson, R. ; Fedrigo, E., et al., "First light of SINFONI AO-module at VLT", *Proc. SPIE 5490, Advancements in Adaptive Optics*, 130 (2004).
- [5] Paufigue, J.; Biereichel, P. ; Donaldson, R. ; Delabre, B. ; Fedrigo, E., et al., " MACAO-CRIRES: a step toward high-resolution spectroscopy ", *Proc. SPIE 5490, Advancements in Adaptive Optics*, 216 (2004).
- [6] Gilles Cheriaux et al., "Monomorph large aperture adaptive optics for high peak-power", *Proc. SPIE 6584, Adaptive Optics for Laser Systems and Other Applications*, 658405 (May 16, 2007)
- [7] Nicholas Hopps et al., "Overview of laser systems for the Orion facility at the AWE", OSA publishing, *Applied Optics*, Vol. 52, No. 15, 3597-3607 (2013)
- [8] Costes, V., Laubier, D., Darré, P., Perret, L., "Optical design and active optics for next generation space telescopes," Presented at the SPIE Conference on Optics + Photonics, San Diego, California, USA (2013).