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Electro-mechanical deformable mirror for space application

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ABSTRACT

ACMAS program, in partnership with CNES and DGA, intends to develop an innovative concept of deformable mirror (DM) for next generation space telescopes, to manufacture an engineering model and to test it on optical and mechanical points of view.
The design of this space compatible DM is based on ISP System's technology, and is adapted to space constraints (ECSS) particularly in terms of vibrations and reliability. These electro-mechanical DMs offer some innovative characteristics for space telescopes with low speed wavefront variations.
A specific version of the patented AME actuator is developed for space applications, and tested to TRL6. The deformable mirror's actuators pattern is optimized in terms of quantity and position with respect to the wavefront corrections expected to apply during mission. The DM design is optimized thanks to finite element modeling in order to withstand the vibrations and shocks due to launching, and improve thermo-mechanical stability, and an innovative redundancy method is developed.
The performance of an engineering model is measured using an optical test bench with high resolution wavefront sensor. The correction thermal stability is also measured and the performance with one and two disabled actuators is evaluated. Vibrations are then injected into the DM. All these measures are compared to simulation values and show an impressive correlation..

Keywords: deformable mirror; active optics; actuator; stability; space telescope; wavefront correction.

1. CONTEXT AND AIM OF THE DEVELOPMENT

1.1 ISP System experience in Deformable Mirror

ISP SYSTEM started to develop an actuator for deformable mirror in 2002 for the French Atomic Agency (CEA) in the frame of very high energy laser "Laser Mega Joule" (LMJ). In order to solve the issue of hot spots encountered by the CEA, ISP was asked to look for a new actuation technology capable of deforming a thin mirror without creating any local slopes. ISP SYSTEM developed an astatic force actuator (AME) with a very high resolution and a very low radial stiffness (patent n° FR2847742 A1), which is currently used on all deformable mirrors of the LMJ facility. This AME force actuator is driven by a stepper motor-gear, and the rod translation is transformed into static push or pull forces thanks to a spring system.

Then the actuator was miniaturized in 2007 in order to increase the actuator density and apply the technology to intense lasers with smaller beam aperture. ISP System's DMs can be compatible with high vacuum and can correct beams from 20 to 500mm diameter. Lots of intense laser facilities are using the deformable mirror from ISP System all over the world.

1.2 Context

Future high resolution space telescope will need very large M1 mirror. In order to limit the weight of these M1 mirror, their thickness will be reduced as much as possible, generating a risk of deformation due to thermo-mechanical and gravity effects. For these reasons the use of deformable mirror embedded in HR space telescopes seems to be a very good solution. This solution could also induce a reduction of the constraints on M1 mirror specifications on term of polishing quality, and at the same time secure the manufacturing schedule of such large optics.

1.3 ACMAS program

In 2014, ISP System started a new Research & Development program called ACMAS, with DGA funding and CNES technical support. One of the objectives of this program is to develop space qualified actuators and deformable mirrors embedded in space telescopes. CNES provided a technical specification corresponding to their current imaging needs. The main requirements are listed in Table 1.

Table 1. DM main requirements.

Optical req.	Pupil Area	Ø85 mm
	Wavefront to correct with a residual lower than 15nm RMS	Composed of several Zernikes : - Focus - X and Y Astig and Coma - Trefoil - Spherical Aberration (50nm RMS) - Optional 2nd Spherical Aberration (25nm RMS)
	High focus amplitude	up to 10 µm RMS
	Active flatness	better than 10nm RMS
	Thermal and long term stability	
Other req.	Reliability must be analyzed	Degraded mode possible
	Redundancy must be considered	
Environment	Vacuum and 20°C +/-0.2°C	
Mechanical req.	Mass	< 5kg
	Dimensions	Ø < 185 mm H < 85 mm
	Vibrations	Launch spectrum with 11 gRMS along axis and 7 gRMS on lateral
	Lifetime	10 years on orbit with 300 actuations per day

2. DEVELOPMENT OF THE DEFORMABLE MIRROR

2.1 Actuator design

ISP's space DM is based on the same architecture as current DM for intense lasers: the thin glass membrane is supported on its outer perimeter by a flexible mount and a pattern of AME actuators applying push or pull forces beneath the membrane.

The design of the AME-Space actuator is mainly based on the off-the-shelf space compatible stepper motors smaller than 20mm diameter. In Europe, only 2 manufacturers were highlighted. These motors have very different characteristics as shown in Table 2.

Table 2. “A” and “B” motors characteristics.

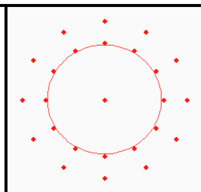
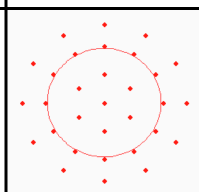
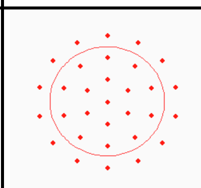
Type	« A »	« B »
Size	Ø19mm	Ø15mm
Weight	100 grams	50 grams
Redundant winding	Yes	No
Output torque	~500 mNm	~ 500 mNm
Output resolution	39 200 steps/turn	7296 steps/turn
Space heritage	+++	+
Price per motor	Very high	High

ISP System decided to go as much as possible towards solution B in order to build a weight and cost efficient solution. It has been necessary to progress through space compliance with the supplier and CNES technical support. However, having no redundancy in the motor winding implies another “degraded mode” strategy to deal with motor failure.
The design of the actuator has then been driven according to the motor capability and the ECSS for mechanical devices, taking in consideration all frictions and motor margin. A breadboard model (BBM) has been built and evaluated in early 2017 in order to validate the design and provide preliminary measurements.
The developed AME-Space actuator can develop up to 12N in push-pull with 0,5mN resolution per motor step. The internal backlash of the gears (70 motor steps) is compensated by movement commands. Repeatability of the actuator force application was measured lower than 1mN RMS on 50mN and 500mN motions. Each actuator weights 100 grams including the motor and gear.

2.2 Actuators pattern and degraded mode

The pattern of actuators has to be optimized with respect to the Zernike polynomials to be generated. ISP System developed a simulation model using a single Finite Elements Modeling (FEM) analysis in order to predict the mirror performance. Lots of patterns can thus be analyzed easily without requiring a complete new FEM model for each version.
Thanks to these simulations, and experimentations, it has been shown that there is a specific way to arrange actuators for generating a defined Zernike combination, depending on the number of concentric rings, and the number of actuators on each ring, center actuator counting as one ring by itself. Axisymmetric Zernikes such as spherical aberration are the most difficult to generate with high fidelity, and require that the number of actuator on each crown is higher than 6. Furthermore, the 2nd Spherical Aberration is the only Zernike of the specification (optional) that requires an extra 4th ring of actuators.
Several patterns were highlighted after a first pass, as shown in Table 3 as examples. We can see the influence on the number of actuators, as well as the influence of their position with respect to the obtained residual for the required wavefront (WF) correction.

Table 3. Description and results with various actuator paterns.

Number of actuators	Actuator pattern		Simulated performance wrt required WF correction	
			Without 2nd Spherical	With 2nd Spherical
25 actuators in 3 rings	N°1 1 central 12 on Ø85 mm 12 on Ø125 mm		13,2 nm RMS	36,8 nm RMS (2nd Spherical not generated)
31 actuators in 4 rings	N°2 1 central 6 on Ø45 12 on Ø85 mm 12 on Ø125 mm		5,3 nm RMS	12,7 nm RMS
31 actuators in 4 rings	N°3 1 central 6 on Ø35 10 on Ø70 mm 14 on Ø105 mm		12,3 nm RMS	25,7 nm RMS

The pattern N°1 has a noticeable similarity with the MADRAS mirror [1] which has 24 actuators in 2 rings and a central ball joint. It covers the requirements, but cannot generate 2nd spherical aberration (optional).

The pattern N°2 was selected, it can generate 2nd spherical aberration and reach a better generation of the required wavefront. Each Zernike has been simulated and the correction quality is listed in the figure XXXX.

Additionally, having 6 extra actuators, the DM can endure 1 or 2 actuator failure without compromising severely its performance. Various failure scenarios have been simulated and showed the reliability of the DM concept, without redundant motor winding. This feature is possible thanks to the AME astatic head which moves with the mirror when forces are applied by other actuators.

2.3 Deformable mirror structure

In order to be compliant with space environment, components of the deformable mirror have been redesigned. For example, space compatible glues were selected, and breadboard models were tested in terms of vacuum compatibility and stress. An innovative membrane flexible support has been developed in order to withstand the vibrational loads. Overall weight was optimized to 4.5kg, and a FEM analysis proved the thermal and vibration behavior of the DM was compliant with the requirements.

3. MANUFACTURING AND QUALIFICATION

3.1 Manufacturing and assembly

An engineering and qualification (EQM) model was built in late 2017. It includes 1x EQM AME-space actuator in its center, and 30x BBM AME-space actuators. Only the central actuator will be qualified to TRL6 level.

All the actuators were assembled in clean room, and embedded into the DM body. A silver coated glass membrane was manufactured with standard polishing quality such as the membranes used on High power laser DMs. Then it was glued on top of the actuators with flexible space compatible glue.

Figure 1. AME-Space actuator and ACMAS Deformable Mirror Engineering Models

A complete process of qualification of the actuator (TRL6) and the deformable mirror (TRL5) is then started.

3.2 Optical performance

The DM is tested on ISP system's optical test bench, in an ISO7 clean room. A high resolution wavefront sensor measures the optical membrane deformation with a nanometric resolution. The noise and fluctuations caused by air turbulence is limited to 2 nm RMS over a 1 minute measurement thanks to a complete cover of the optical path.
Influence function of each actuator is acquired, and the mirror modes are computed. Their aspect is very close to the simulated models. It is interesting to note that the first modes (top-left) are showing similitude with Zernike polynomials. For example the modes measured with the DM are: tilts, astigmatisms, focus, trefoils, comas, spherical. This similarity is intentional, as the actuators pattern was optimized so the shapes that the DM will naturally and easily generate are the required Zernike polynomials.

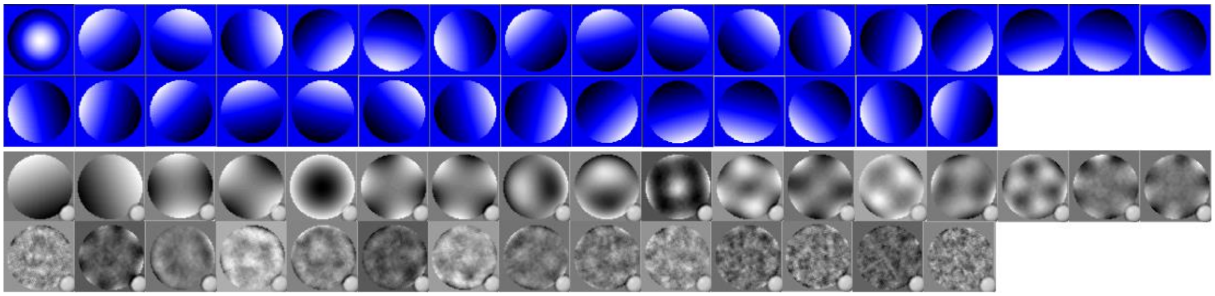


Figure 2. Measured actuators influence functions (top), and mirror modes (bottom)

The DM is then flattened by the actuators and compensates its own aberrations due to membrane manufacturing and integration. The initial wavefront combines several microns of defocus and astigmatism, which are easily corrected, and

300nm of spherical aberration, which induces a minor residual, as shown in figure 3. However, the residual drops to 11nm RMS, requiring less than 10% of each actuator available force range.

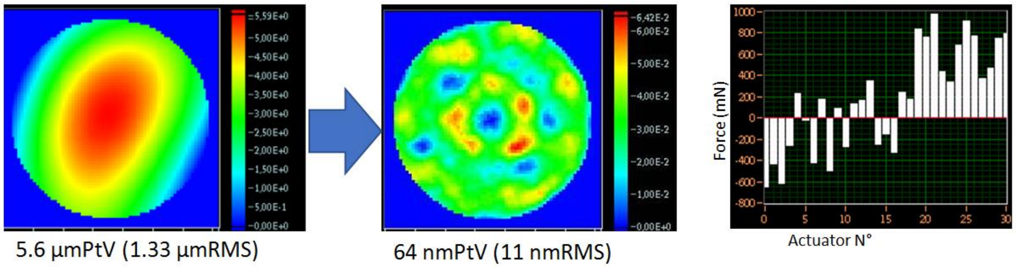


Figure 3. Initial shape, active flatness, and required forces

Manufacturing a membrane with better initial flatness would improve slightly the flatness residual wavefront error (WFE) down to 6-8 nmRMS.
Each Zernike polynomial is generated and the quality is compared to simulation expectations.

Table 4. Description and results with various actuator paterns

Zernike	Generation quality (RMS/RMS) - Measured -	Generation quality (RMS/RMS) - Simulation -	Maximum estimated amplitude (PtV)
Focus	99,6%	99,7%	+/- 50µm
Astig	99,5%	99,9%	+/- 50µm
Astig 45°	99,5%	99,9%	+/- 50µm
Coma X	97,2%	98,4%	+/- 10 µm
Coma Y	98,3%	98,4%	+/- 10µm
Trefoil	96,2%	98,6%	+/- 20µm
Trefoil 30°	96,2%	98,6%	+/- 20 µm
Spherical	93,0%	94,1%	+/- 2.5 µm
2nd Spherical	56%	59%	+/- 0.5 µm

The required wavefront combination is generated with the DM; it includes 50 nm RMS of spherical aberration and 25 nm RMS of 2nd spherical aberration. The measured residual WFE is particularly close to the simulation, and requires about 25% of each actuator force range.

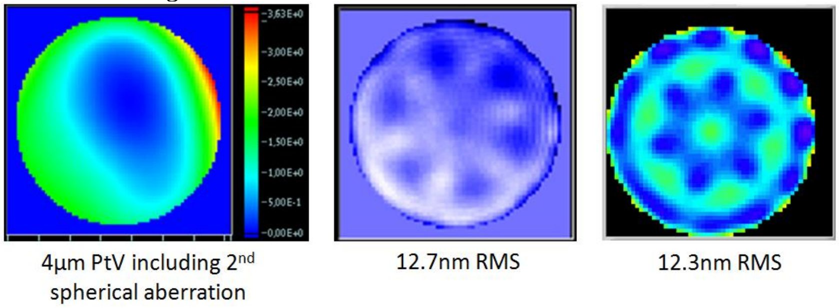


Figure 4. Target wavefront, Simulated residual, and measured residual

3.3 Reliability and redundancy

Several scenarios of failure have been tested on the optical bench. The result of the loss of an actuator is generally the increase of the other actuator required force, up to 50%, and a residual WFE with a higher value, but still acceptable for a failure case. For example an actuator has been offsetted by 1N from his normal working force and then disabled. Then the closed loop tried to converge towards a flat wavefront, as shown in table 5 below.

Table 5. Residual WFE and supplementary actuator force in degraded mode

Failure mode tested	Residual WFE due to failure	Required max force to compensate failure
Central actuator +1N and disabled	16 nm RMS	800 mN
Inner ring actuator +1N and disabled	15 nm RMS	1500 mN
Pupil ring actuator +1N and disabled	8 nm RMS	500 mN
Outer ring actuator +1N and disabled	3 nm RMS	600 mN

For example, if in nominal conditions the residual was 20 nmRMS, and an actuator placed on the inner ring stops working 1N away from his normal position, then the correction residual would reach 25 nm RMS, by quadratic sum of 15 nm RMS to the initial 20 nmRMS. The other actuators force may also increase by 1500 mN (12% of the force range).

3.4 Thermal stability

ISP set a specific study about the DM thermal stability. Materials of each component have been selected thanks to FEM thermal analysis in order to limit the thermal effect on an optical point of view. As temperature raises, the actuators would tend to push and generate defocus, but the radial stress generated by the DM body on the membrane has an opposite effect and tends to generate focus. It is then simulated a thermal stability of 20nm RMS of focus for +1°C.

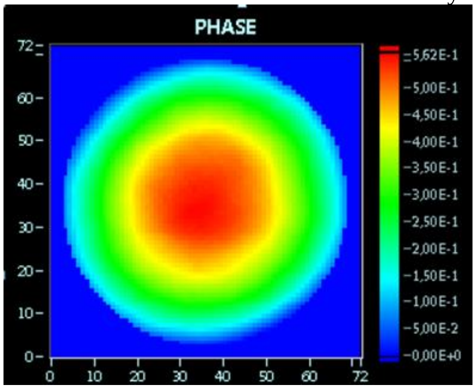


Figure 5. Wavefront measured after a temperature drop of -3.6°C. Wavefront is more than 99% defocus, 145nm RMS.

On the optical test bench ISP measured a thermal effect of 40nm RMS of focus per degree Celsius, without any energy in the actuators. This stability could be even improved by a finer analysis of the FEM thermal model and a better choice of materials.

3.5 Vibrations

The complete DM prototype was mounted on a vibration table. Launch vibrations were applied and accelerations were measured on several specific areas of the DM. All expected Eigen modes were found close to FEM analysis. The whole DM showed a good behavior during the vibrations, and the mechanical response as well as the actuators remained unaltered.

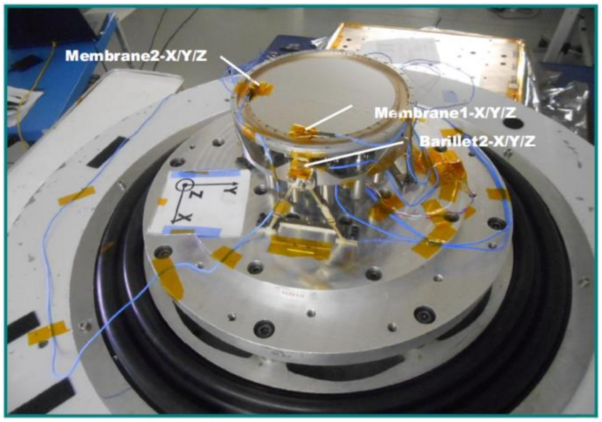


Figure 6. Deformable mirror EM mounted on vibration table, with several accelerometers.

After vibrations, the DM was optically measured on ISP optical bench. Its performance in terms of wavefront correction, as well as the actuator forces were unchanged.

3.6 Lifetime

A complete lifetime test of the central actuator (EQM) mounted in the DM is currently running. More than 80% of the expected lifetime was successfully done, and the actuator does not show any failure.

4. CONCLUSION

ACMAS project has been a successful experience for ISP System. It proved the validity of ISP System's design of deformable mirror with respect to space application. The AME-Space actuator passed a full qualification cycle in accordance with ECSS standards, and reached a TRL6 level. The Deformable Mirror reached a TRL5 level, and showed encouraging results as a first prototype. Optical behavior is absolutely correlated with simulations, and flat performance of 11nm RMS was reached with a standard polishing glass membrane. FEM modeling predicted very closely the mechanical response to vibrations, and the prototype endured the test without any alteration. The Thermal model could be adjusted and material selection could be improved. ISP System's choice to select a non-redundant motor led to a very lightweight and cost-effective solution, and the internal redundancy of the mirror behavior thanks to extra actuators proved to be very efficient.

ISP System wishes now to continue this development with a future qualification model of deformable mirror for a space telescope program, and improve further the current design.