Publication Year	2015
Acceptance in OA@INAF	2020-07-21T09:55:56Z
Title	E-ELT M4 Unit updated design and prototype results
Authors	Biasi, Roberto; Gallieni, Daniele; BRIGUGLIO PELLEGRINO, RUNA ANTONIO; Vernet, Elise; Andrighettoni, Mario; et al.
DOI	10.20353/K3T4CP1131718
Handle	http://hdl.handle.net/20.500.12386/26543
Number	1

UCLA

Adaptive Optics for Extremely Large Telescopes 4 – Conference Proceedings

Title

E-ELT M4 Unit updated design and prototype results

Permalink

Journal

Adaptive Optics for Extremely Large Telescopes 4 – Conference Proceedings, 1(1)

Authors

Biasi, Roberto
Gallieni, Daniele
Briguglio, Runa
et al.

Publication Date

2015

DOI

10.20353/K3T4CP1131718

Peer reviewed

E-ELT M4 Unit updated design and prototype results

Biasi Roberto [a], Gallieni Daniele* [b], Briguglio Runa [c], Vernet Elise [d], Andrighettoni, Mario[a];
Angerer Gerald[a], Pescoller Dietrich [a], Manetti Mauro [a], Tintori Matteo [b], Mantegazza Marco [b],
Lazzarini Paolo [b], Fumi Pierluigi [b], Anaclerio Vincenzo [b], Xompero Marco [c], Pariani Giorgio [c],
Riccardi Armando [c], Cayrel Marc [d], Dierickx Philippe [d], Hubin Norbert [d], Kornweibel Nick [d],
Pettazzi Lorenzo [d]
[a] Microgate Srl, via Stradivari, 4 – 39100 Bolzano-Bozen (BZ) – Italy
[b] A.D.S. International Srl, via Roma, 87 – 23868 Valmadrera (LC) – Italy
[c] Istituto Nazionale AstroFisica – Italy
[d] ESO, Karl-Schwarzschild-Str. 2 - 85748 Garching bei München - Germany

ABSTRACT

We present the current design of the E-ELT M4 deformable mirror consolidated at the conclusion of the Preliminary Design activity. The most prominent features of this system are the SiC Reference Body now mounted to the positioner by a whiffle-tree and cell structure, actuators bricks, capacitive sensors layout and new cooling concept. All this allowed achieving the challenging stability requirements demanded to the M4U, as proved by analysis and test results measured on the Demonstration Prototype, which has been updated to implement the current design. The final design and construction contract is now on-going: Final Design Review is planned on mid 2017 and delivery to site by late 2022.

Keywords: E-ELT, adaptive optics, deformable mirror

1. INTRODUCTION

The M4 is the adaptive optics corrector in the main optical chain of the E-ELT. It provides adaptive optics correction and partially compensates for telescope wind shake effects and optical aberrations.

The Final Design and Construction contract for the E-ELT M4 Unit has been signed in June 2015 between ESO and AdOptica, a consortium of Microgate and A.D.S. International. The contract covers the full design, manufacturing, testing, calibration, transport and re-integration in Chile. INAF, Arcetri and Milano-Brera observatories, is subcontracted for the AO scientific advisory and to support the optical tests. Mersen Boostec has been subcontracted for the manufacturing of the SiC Reference Body. The thin mirror shells will be delivered for integration to AdOptica directly by ESO that contracted the manufacturing to Safran-Reosc.

The supply will be completed by a number of auxiliary systems, the most notable being the Optical Test Tower to allow the calibration and complete verification of the M4 Unit before being installed on the telescope.

2. M4 UNIT MAIN FEATURES

Within the M4 Unit we can distinguish the following main components:

- the **M4 Mirror**, which is the Deformable Mirror itself including the embedded power and control electronics;
- the **Kinematic Support**, which active components are the hexapod for fine positioning of the M4 mirror and the Nasmyth Switcher, a rotating unit that allows to point the M4 towards the two telescope foci;
- the **Local Control Unit**, placed in the control rooms of the telescope, performing the global control functions that transform the modal command from the ESO Real Time Reconstructor into position and force commands for the M4 Mirror, including a smart saturation management. Besides that, the Local Control Unit provides also all states machines, diagnostic, telemetry and safety functions required for system operation.

---

* gallieni@ads-int.com; phone 39 0341 201950; fax 39 0341 201950; ads-int.com

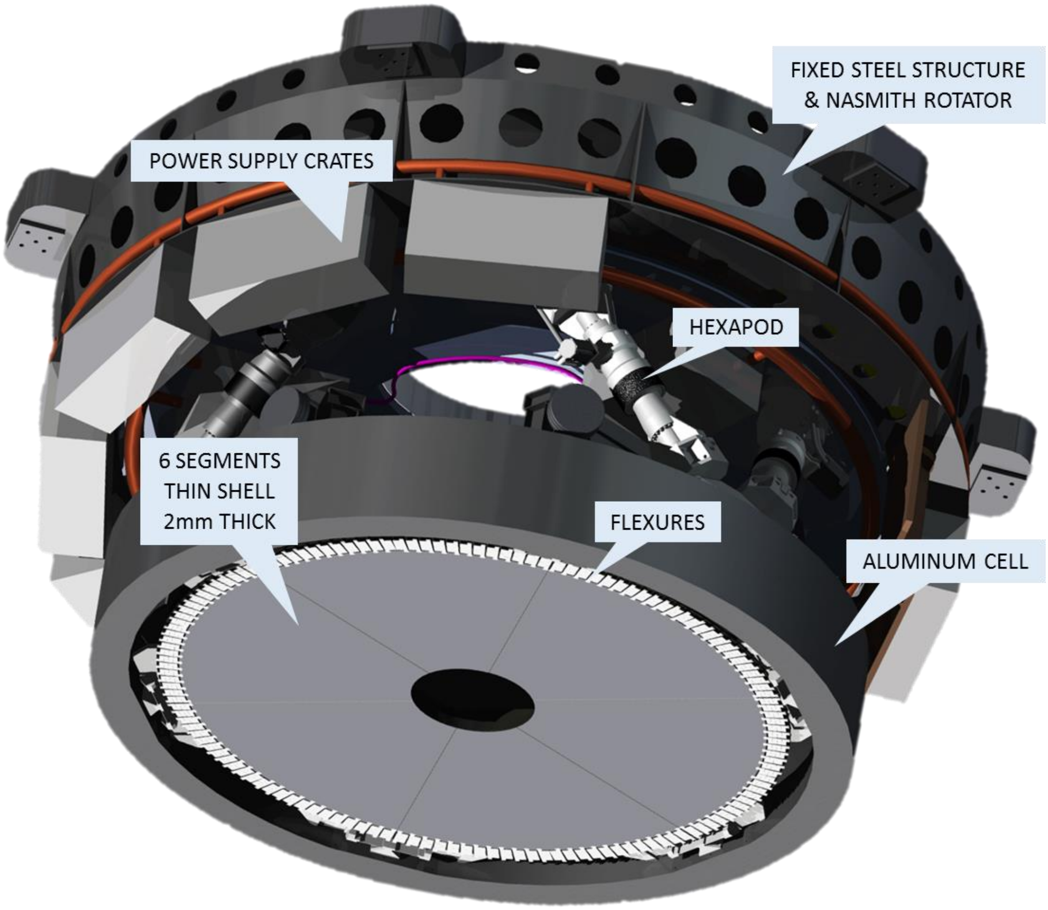

Figure 1. The E-ELT M4 Unit layout as consolidated at the end of the Preliminary Design phase.

The M4 Mirror is a 2.4 m diameter flat surface made by 6 petals; each one is a 2mm thick Zerodur shell. The deformable shells are controlled in position against a reference structure by 5316 contact-less voice coil actuators and capacitive sensors, while the in-plane restraint is defined by a set of flexure elements placed on petals external diameter. Permanent magnets are glued on the back surface of the shells, facing the voice-coil actuators. As all deformable mirrors built by AdOptica, the shell is free-floating and there is no fixed axial constraint between the mirror and the actuators, making such system by nature fail safe against actuators possible failures.

The Reference Body is an ultra-stiff SiC open-back structure providing at same time the reference surface for the control of the thin shells and the mechanical support for the actuators. This is instead a novel design feature compared to previous DMs by AdOptica, where the actuators are fixed to a separate structure.

The SiC Refrence Body is held into an aluminum cell by 12 axial supports arranged in a whiffle tree configuration plus 6 lateral ones.

The use of SiC together with the support design allow achieving the tight requirements on the passive stability of the M4, when the mirror shape shall be set and kept in absence of optical feedback from the telescope WFS.

The actuators are grouped in “bricks”, which are aluminum plates carrying from 28 to 36 voice coils each. Each brick embeds all the control, communication and supply functions needed by the adaptive mirror local control and safety.

The bricks are interfaced to each other by means of power, data and cooling quick connectors, allowing its replacement when the M4 Unit is installed aboard the telescope; they are mounted on the M4 Mirror from the rear side, thus they can be serviced and replaced without dismounting the mirror shells. Three locking mechanisms attach each brick to the SiC Reference Body by flexures; the brick can be installed and operated without the need of alignment and calibration.

The M4 Mirror is cooled by using gas instead of the conventional glycol mixtures. This innovative choice is dictated by the potential catastrophic effects of leakages at M4 location, which could affect other optical surfaces of the telescope, as M1 segments and M3. The gas cooling system has been successfully tested on the Demonstration Prototype.

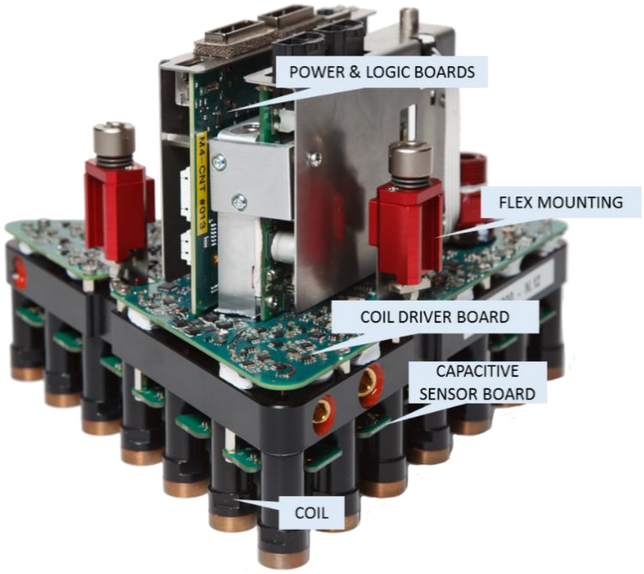

Figure 2. M4 Mirror brick mounting 28 voice coil motors with their power and control electronics. The mounting plate is cooled by gas.

The following table reports the most prominent data to summarize M4 Unit facts and predicted performances.

Table 1. M4 Unit in numbers

Optical Diameter	Int.	0.56 m	
	Ext.	2.4 m	
Mass		10.2 tons	
1st structural mode		25 Hz	
Shell thickness		1.95 mm	
# of shell segments		6	
# of actuators		5316	
# of control bricks		180	
Optical control rate		≤ 1kHz	
Actuators control rate		80 kHz	
Control bandwidth		> 600 Hz	
Settling time within 5%		< 1.4 ms	
Position sensor noise		~3nm (0..40kHz)	
Differential position stability		0.8nm/°C	
Seeing @ λ 0.5µm	*0.5”*	*0.85”*	*1.1”*
Power	6.5 kW	7.8 kW	8.2 kW
WF error RMS	106 nm	152 nm	193 nm

3. DEMONSTRATION PROTOTYPE TEST RESULTS

A Demonstration Prototype was built already during Phase B of the project [1][2][3]. More recently, during the advanced preliminary design phase (aka Phase 1) the Demonstration Prototype has been completely renewed to be representative of the final unit. In particular, the Reference Body manufacturing and the control electronics have been developed to a pre-production level. This new unit is equipped with 10 electronics bricks, capable of controlling 280 actuators, 222 of which control two slender shells simulating the segmentation of the final mirror.

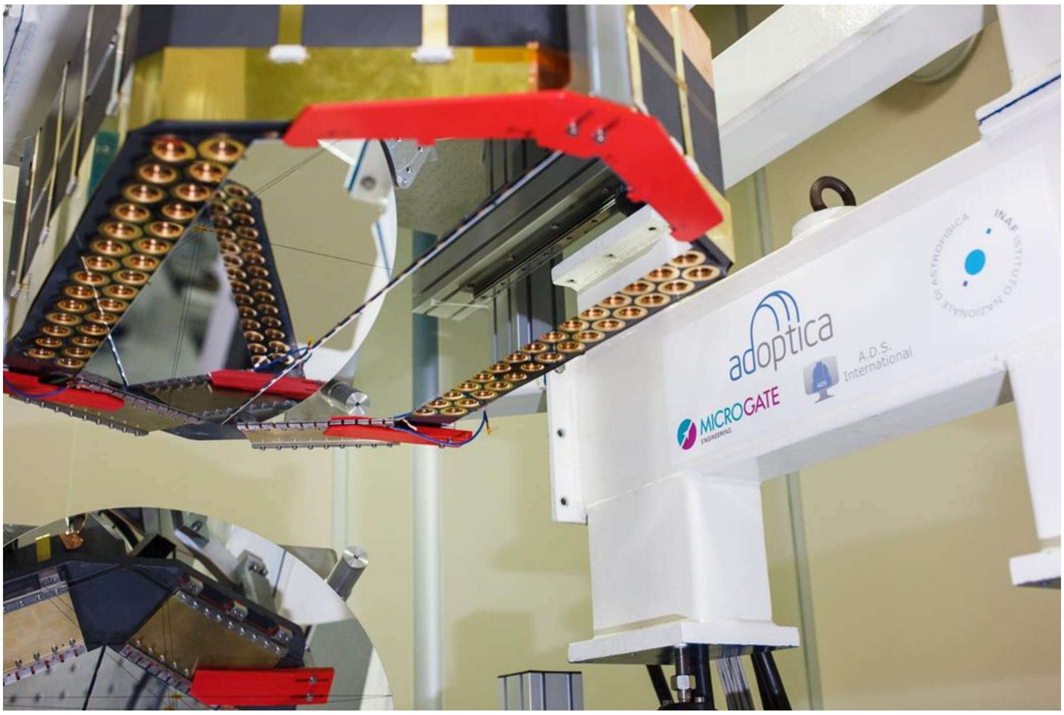

Figure 3. View of the two shells segments mounted on the Demonstration Prototype; some actuators are not covered by the shells, which are undersized because re-used from the previous smaller version of the DP.

The prototype unit has undergone a full test campaign, including electromechanical tests to characterize system dynamics and optical tests. The results of the latter are reported extensively in [6]. The electromechanical tests have been carried out according to a test plan that will be eventually adopted as baseline also for testing the final M4 Unit. More specifically, the tests comprised:

- Safety tests, aimed to characterize and verify the safety features implemented on the unit to protect the thin shells against external disturbances, like wind and earthquakes, excessive commands and possible control system malfunctioning. Most of the safety protections are implemented in the brick-level embedded control system and operate on a fully autonomous base, so to remain active even in case the main communication between telescope control and M4 Unit is interrupted. A backup battery is foreseen on the final M4 Unit (not present on the Demonstration Prototype) to guarantee the safety functions also in case of power cut off. The performed tests simulate the various failure modes and verify the expected intervention of the safety mechanisms.
- Preliminary system calibration, including the electromechanical calibration of the capacitive sensors over the whole motion range, on base of the shell continuity assumption, and measurement of the interaction matrix between actuator forces and capacitive sensor readout, also known as feedforward matrix. Such matrix is essential for the control strategy [4] and also to determine the modal base used for the dynamic tests.

- Performance tests, covering both system dynamics and other various aspects, like the verification of the maximum stroke, the assessment of power consumption in various operating conditions and EMC tests. System dynamics is measured through modal step test, through measurement of the following error while 'playing' simulated turbulence time histories in different seeing conditions and through transfer function acquisition. An additional important goal of this activity has been the matching between the sophisticated numerical model of the mirror dynamics, including control, structure and fluid-dynamics [5] and the experimental data.

The step response results are summarized in Figure 5. The settling time is very uniform and below 0.8ms for all modes beyond the first 15. The low order modes settling time is longer, up to 1.4ms, but still in specification, due to some overshoot that requires longer time to settle within 5%, while the rise time performance is very compatible with all other modes. This different behavior depends mainly on the effect of the membranes and of the slender shells of the M4 Demonstration Prototype. Figure 4 presents the step response of mode 40 and the excellent matching between the experimental results and the numerical ones, adopting the same control parameters for both cases.

The following error tests has validated the new *clipping* saturation concept introduced for the M4 mirror control. Since our mirror technology is mainly limited in force rather that in actuator stroke, it is not possible to apply position patterns requiring a static force exceeding the maximum actuator force capability. So far, in all existing adaptive mirrors based on our technology, such commands were simply *skipped* holding the shape commanded at the previous step. On the M4, the modal commands will be *clipped* autonomously by the system reducing the number of high order modes actually applied to the mirror. This requires that the commands modal base is made available to the M4 control system, and that the number of actually applied modes is fed back to the Real Time Reconstructor. The whole control and actuation system is dimensioned to limit the intervention of the *clipping* mechanism to seldom events in bad and worst seeing modes. Table 2 reports the results measured on the prototype. The increase of error in the worst seeing conditions depends on the *clipping* intervention on some of the commanded steps.

The transfer function has been measured by commanding each individual mode with a chirp signal. Figure 7 presents the system bandwidth derived from both the *command* and *disturbance rejection* transfer functions, as a function of the modal number. The 'modes' considered here are the eigenvectors of the Singular Value Decomposition of the interaction matrix between Demonstration Prototype actuators forces and capacitive sensor reading, also referred as *electromechanical modes*. The results refer to one single shell, controlled by 111 actuators; results of the other shell are substantially identical. The command transfer function benefits of the open loop control contribution (feed-forward), on top of the closed loop control part, to enhance system responsivity to the commands; conversely, the disturbance rejection transfer function in measured activating only the closed loop control without feedforward. The command transfer function bandwidth is >600Hz for all modes, while the disturbance rejection bandwidth is >300Hz for the large spatial scale modes, up to mode 15, and then drops significantly due to the moderate stiffness of the control compared to the structural one. It shall be remarked that the expected disturbances, in particular wind and support structure vibrations, mainly excite the shell very large spatial scale modes, so we are not interested in obtaining a high rejection to disturbances having small spatial scales.

Table 2. Following error rms including the data transfer and computational latencies.

Seeing conditions	**Error nm rms wavefront**
Good seeing (outer scale 25m, 0.50" @ λ=0.5µm)	11
Median seeing (outer scale 50m, 0.85" @ λ=0.5µm)	21
Bad seeing (outer scale 100m, 1.1" @ λ=0.5µm)	55
Worst seeing (outer scale 100m, 2.5" @ λ=0.5µm)	145

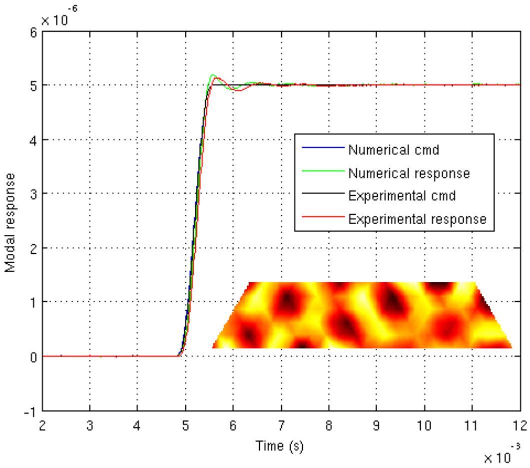

Figure 4. Mode 40 step response. Comparison between numerical and experimental results.

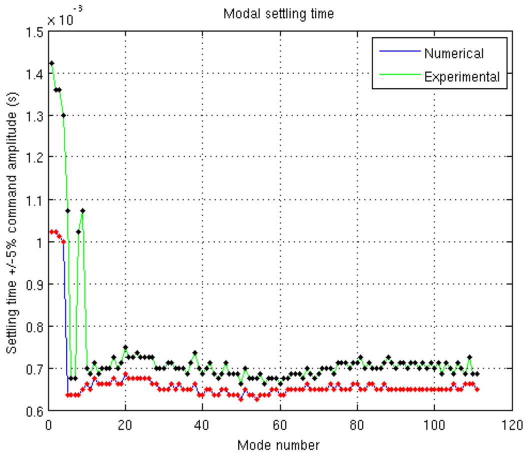

Figure 5. Modal settling time within 5% of command.

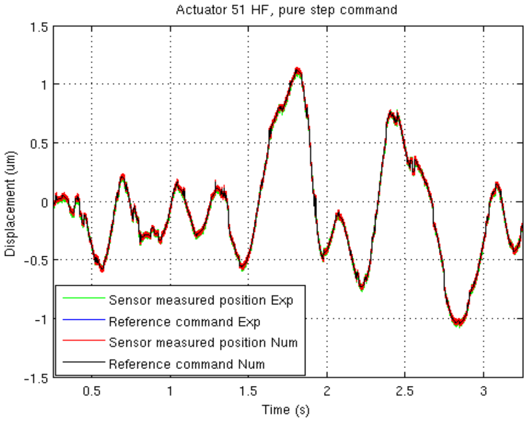

Figure 6. Following error test, worst seeing

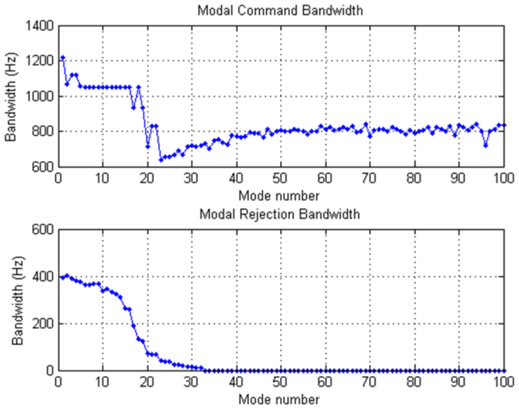

Figure 7. Command and rejection bandwidths

4. FINAL DESIGN, MANUFACTURING, ASSEMBLY, INTEGRATION AND TEST OF THE M4 UNIT

The final design process, including some further validation through dedicated prototyping, will be completed by mid 2017. System integration will begin in 2020; from mid 2020 until April 2022 we will carry out a thorough test campaign including electromechanical and environmental tests and full optical calibration. Transport to Chile will follow, and the final on-site delivery of the re-integrated and re-tested unit is planned for mid 2023.

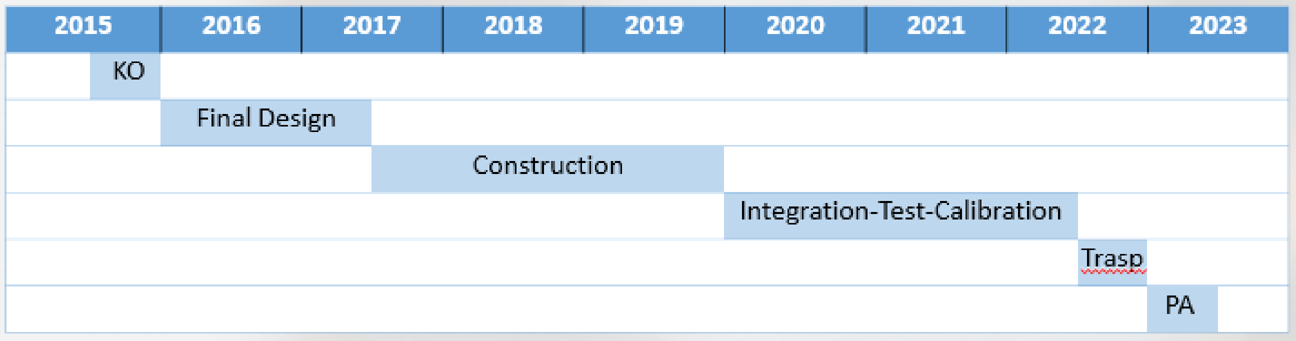

Figure 8. M4 Unit Final Design and MAIT schedule.

REFERENCES

[1] Vernet, E., .Cayrel, M., Hubin, N., Biasi, R., Gallieni, D., Tintori, M. "On the way to build the M4 Unit for the E-ELT" Proc. SPIE 9148, 2014, id. 914824, doi: 10.1117/12.2056281

[2] Briguglio, R., Xompero, M., Riccardi, A., Biasi, R., Andrighettoni, M. "Optical calibration of capacitive sensors for AO: strategy and preliminary results" Proc. SPIE 8447, 2012, 84474E, doi:10.1117/12.926820

[3] Molinari, E., Tresoldi, D., Toso, G., Spanò, P., Mazzoleni, R., Riva, M., Riccardi, A., Biasi, R., Andrighettoni, M., Angerer, G., Gallieni, D., Tintori, M., Marque, G "The optical tests for the E-ELT adaptive mirror demonstration prototype" Proc. SPIE 7736, 2010, 773632, doi:10.1117/12.857188.

[4] Manetti, M., Morandini, M., Mantegazza, P., Biasi, R., Gallieni, D., & Riccardi, A., (2010b). Modeling and control of massively actuated, magnetically levitated, adaptive mirrors. In IEEE international conference on control applications (CCA) (pp. 860–866)

[5] Manetti, M., Morandini, M., Mantegazza, P., "Servo-Fluid-Elastic Modeling of Contactless Levitated Adaptive Secondary" Computational Mechanics 50 (1), 85-98 (2012).

[6] Briguglio, R., Pariani, G., Xompero, M., Riccardi, A., Andrighettoni, M., Tintori, M., Biasi, R., Gallieni, D., "Optical calibration of the M4 prototype toward the final unit" in this conference.