# Specifications and design of the E-ELT M4 adaptive unit

Elise Vernet[a], Marc Cayrel[a], Norbert Hubin[a], Michael Mueller[a], Roberto Biasi[b], Daniele Gallieni[c], Matteo Tintori[c]

[a]European Southern Observatory, Karl Schwarzschild strasse 2, D-85748 Garching, Germany; [b]Microgate, Italy; [c]A.D.S. International, Italy

## ABSTRACT

A 40 meters class telescope does require adaptive optics to provide few milli arcseconds resolution images. In the current design of the E-ELT, M4 provides adaptive correction and has also to cancel part of telescope wind shaking and static aberrations. The 2.4 meters adaptive mirror will provide as well Nasmyth focus selection.

We will present the main design drivers and the main specifications quaternary mirror will have to meet. We will discuss what the challenges are in term of stability and performance of the associated key technologies. We will finally describe the current baseline design and the required schedule and work plan to adequately manufacture the E-ELT quartenary mirror.

**Keywords: Adaptive Optics, E-ELT, Deformable Mirrors, voice coil actuators.**

## 1. INTRODUCTION

The future European Extremely Large Telescope (E-ELT) is a 40 m class optical, near and mid-infrared ground –based telescope. The telescope will have control system allowing real-time adjustments of its optical surfaces to compensate for errors sources including atmospheric turbulence. The telescope designed for a minimum lifetime of 30 years, will be located in a dry site (Cerro Armazones, in Chile). The project initiated in 2006 has gone through extensive concept studies.

The telescope current baseline design (Figure 1) incorporates:

- A segmented primary mirror made of 798 hexagonal off-axis aspheric segments; M1; the primary mirror segments are mounted on active position actuators allowing these mirrors to be phased in real time on the basis of error signals provided by position sensors located at the inter-segments boundaries. The overall primary mirror has an f/D ratio smaller than 1.
- A 4.2-m class convex secondary mirror supported by 120 force actuators.
- A 4-m class concave actively supported tertiary mirror which can be relocated axially to refocus the telescope
- A 2.4-m class flat deformable mirror mounted on a positioning system providing a first stage large stroke low frequency mechanical tilt, a two dimensions rigid body decentering degrees of freedom and a focus selector.
- A 2.6-m class flat mirror providing fast-steering correction to compensate for image motion at frequencies up to a few Hz.

A more detailed description of the optical units is provided in Cayrel[1].

The telescope main structure holds the mirrors M1 to M5, supports two Nasmyth platforms and the scientific instruments and provides the altitude and azimuth kinematics. It also holds the pre-focal stations, which will contain the on-sky metrology required to monitor the wavefront delivered by the telescope. The telescope structure provides as well kinematics to compensate for field rotation, and hold the sixth mirror and its kinematics. The telescope will be protected against adverse weather conditions by a co-rotating dome. During daytime the dome will be thermally controlled to ensure that the thermal environment inside the telescope chamber remains as close as possible to the projected conditions of the following night.

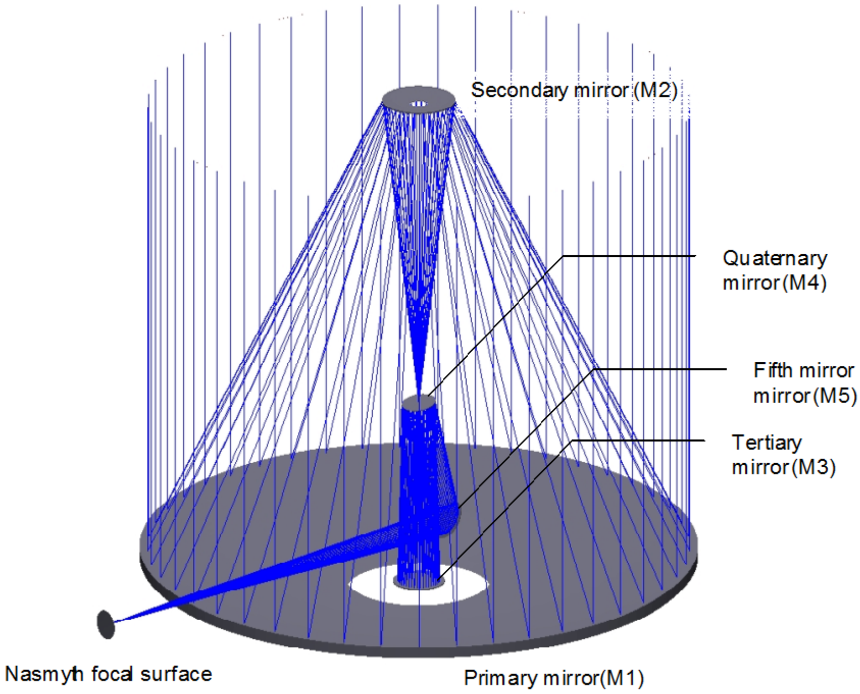



Figure 1: Optical layout

## 2. CORRECTION REQUIREMENTS FOR THE M4 ADAPTIVE UNIT

### 2.1. Functional requirements and product characteristics

The M4 Unit provides the real-time correction capability to the telescope. The adaptive mirror inclined by 7.75 degree is able to switch between two symmetrical orientations to allow the beam propagation towards either Nasmyth foci of the telescope. The M4 unit includes a lateral (in-plane) centering and tip-tilting system allowing canceling relatively large and slowly varying pupil centering and/or tip-tilt of the light beams which may occur as a result of gravity and thermal effects.

The M4 Unit being located in the middle of the telescope, above M5, M3 and M1, it shall ensure its own integrity and safety hardware, software and human safety under all conditions and includes safety mechanism if required without reducing required performance during normal operation; it shall as well includes on-line and off-line remotely operated functions to provide housekeeping feedback as to its health and integrity.

The M4 Unit will provide in addition to the M4 Adaptive Subunit itself mounted on the telescope a series of handling and maintenance tools, all the necessary test equipment and the required spares for the 30 years lifetime.
The M4 Adaptive Subunit is composed of three subsystems: the M4 mirror, the M4 kinematic support and the M4 Local control system.

The M4 Mirror is the deformable mirror slightly elongated with a maximum external optical diameter of 2387mm. The inner optical diameter is 540mm while the M4 must provide a 520mm free central hole.
It provides real-time shaping and fast steering capabilities to compensate for wavefront errors caused by atmospheric turbulence and telescope perturbations allowing optimization of the telescope performance. Low order terms can be off-loaded to other mirrors (via the telescope control system) to prevent stroke saturation. The E-ELT intermediate focus

being located inside the M4 central hole, the M4 unit includes all the functions to limit at maximum heat dissipation and thereby contains local air turbulence around the unit.
Preliminary studies have shown that only adaptive mirrors using thin shell and voice coil technologies can provide the necessary stroke required by the E-ELT.

## 2.2. Performance Requirements

### 2.2.1. General requirements

As any sub-system of any telescope the M4 Adaptive Subunit is designed to withstand - without subsequent performance degradation - all the telescope positions, speed and accelerations during its entire lifetime.

Overall dimensions in term of mass, maximum volume, maximum cooling, and first Eigen frequency of the system have been settled to fulfill interface requirements with the telescope. The M4 Adaptive Subunit is indeed in a crowded place of the telescope limited in size by the optical beam and other subsystems interface.

Standard optical quality requirements have also been specified in term of surface quality and reflectivity. Shell optical quality has also been specified as for the previous adaptive secondary mirrors [2],[3].

With the intermediate focus placed inside M4 central hole, the thermal management becomes even more important than for the previous Adaptive Secondary Mirrors. A thermal management is essential to avoid any thermal disturbance at the intermediate focus. A detailed analysis has been required with the objective to have the outer non optical surface temperature not varying more than ±1.5ºC with respect to the ambient air.

As the operation of such telescope need to be optimized, time constrains have been defined for any transition (in term of software and also during focus switch) to maximize the efficiency of the telescope.

### 2.2.2. Kinematic support requirements

The M4 Adaptive Subunit is mounted on a positioning system providing a first stage large stroke low frequency mechanical tilt, a two dimensions rigid body decentering degrees of freedom and a focus selector.

Forty millimeters stroke displacements have been foreseen for realignment of M4 with respect to M1 during observation and initial stroke needed during integration on the telescope.

The tip-tilt range of four arc-minutes will allow correcting quasi-static perturbations due to thermal loads and gravity effects. All the degree have been specified with stringent cross coupling requirements (limited by the system resolution for small displacements and tip-tilt) and good positioning accuracy (~400 times smaller than the total stroke) to allow a reliable and efficient alignment during preset.

### 2.2.3. Wavefront correction requirements

The main function of the M4 Adaptive Subunit is to correct for both low and high spatial frequencies wavefront errors. The errors contribution is coming from different sources and has therefore different temporal frequency ranges:

- A quasi static stroke budget needed to correct at low frequency (<1Hz) wavefront errors due to misalignment of the different mirrors with gravity. A budget of 10 micron PtV wavefront has been foreseen to correct for the first 20 Zernike quasi-static aberrations.
- Stroke to correct for wavefront errors due to wind load on the telescope structure, M1 and M2. The errors are mainly the low spatial contributions such as tip/tilt, defocus, astigmatism and coma.
- Stroke to correct for atmospheric disturbances.

The two last entrances are the most demanding items in term of stroke. On such a telescope like the E-ELT, the wind load induces vibrations these vibrations have been thoroughly analyzed by the E-ELT project and the M4 Subunit (as well as the M5 fast steering mirror) has been specified to cancel the wavefront error coming from the wind load. While the fast steering M5 Unit takes care of the low temporal frequency tip-tilt, the remaining tip-tilt errors as well as the focus, astigmatism and coma disturbances need to be cancelled by M4.

In operation, the system will have to correct for typically 35 micron PtV WFE due to wind load while in functional mode the disturbance will rise up to 160 micron PtV WFE.  Only degraded performance is required in functional mode with the worst seeing: the system is required providing 0.5arcsec FWHM corrected image.

The M4 Adaptive Subunit being in the telescope, it has to withstand all type of atmospheric conditions (even if for the worst cases, degraded performance is accepted). With a median seeing of 0.85 arscec the system will provide a residual fitting wavefront error smaller than 145 nm rms (with a goal at 110nm rms). In bad seeing conditions (1.1 arcsec), the residual fitting wavefront error is required to be smaller than 180 nm rms.
The total stroke and temporal response is derived from all the real-time shaping requirements. Previous study has demonstrated a stroke capability of ~120 microns.

The telescope wavefront control will drive the M4 Adaptive Subunit. A clear interface defines all the information to be transmitted by the M4 subsystem which will need to be able to act as an actuator: the system is not informed of the telescope "mode", it has just to react to the telescope control command at whatever frequency in the [0,1000] Hz range.

## 3. BASELINE DESIGN FOR THE M4 UNIT

The main requirements have been presented in Section 2. In this section, the short summary will explain how the baseline was defined before describing the design itself.

### 3.1. Project Historical background

Already in 2006-2007, first studies of M4 were made by different companies. It was then decided to launch two competitive contracts for the next phase till preliminary design review.
Between 2008 and 2010, two contracts with Microgate/ADS/SAGEM and Cilas/AMOS were run in parallel with the objective to provide a preliminary design for the 42 meter telescope E-ELT. The two contracts have provided two different designs in term of technology [4],[5] and performance.
End of 2010, the E-ELT design baseline was finalized selecting the Microgate/ADS/SAGEM design. In 2011, two delta studies have allowed to reduce risks on the reference body material, capacitive sensor stability and cooling aspects.

### 3.2. Baseline M4 Adaptive Subunit for the 39 meters telescope

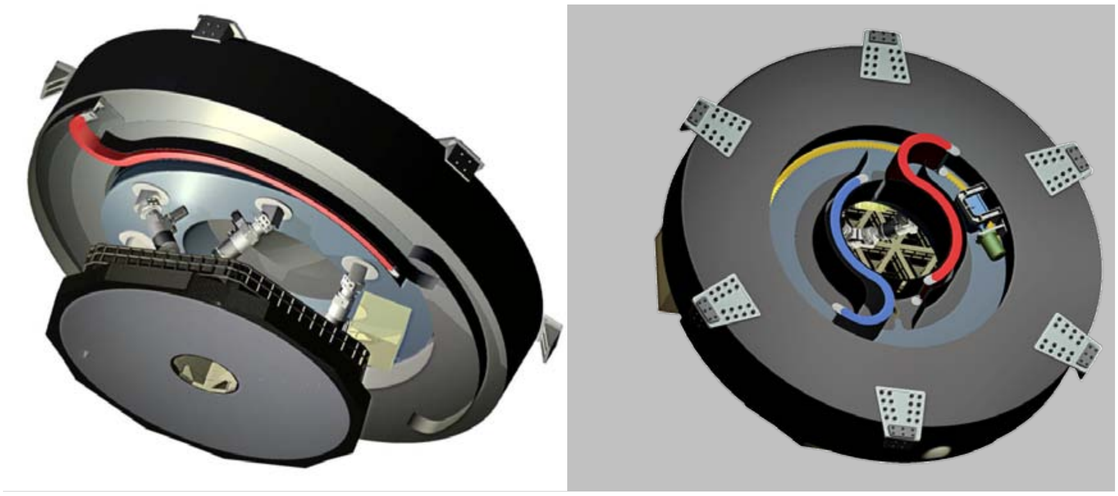
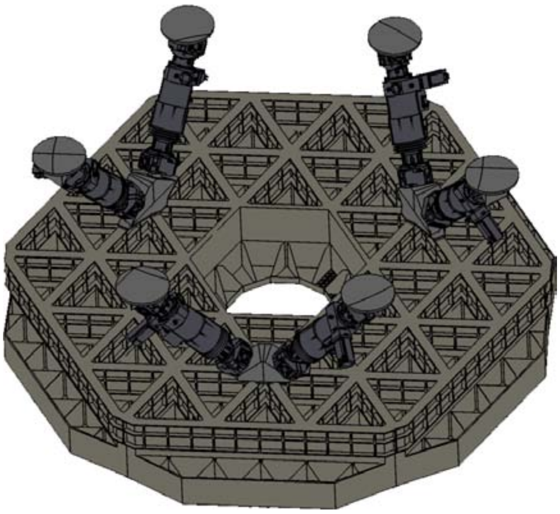


Figure 2: M4 Baseline design. The M4 Mirror is visible on the left figure as well as the hexapods while the cable wrap and fixation interface to the telescope is visible on the right figure.

The M4 Adaptive Subunit baseline is the assembly of a 2.4-m deformable mirror using voice coil technology and co-located sensors, a hexapod and a rotating system to feed the two Nasmyth (Figure 2). This design has been developed by Microgate and A.D.S. International in collaboration with INAF for the Optical test bench.

The hexapod design has already been validated in the frame of another contract in term of stroke but there is still some validation analysis to be done in term of cross-coupling requirements. A rotator has been selected for the Nasmyth focus selection to avoid any additional stroke request on the hexapod. It is one positive aspect of this design since it use flexure joint which cancel any risk of friction.



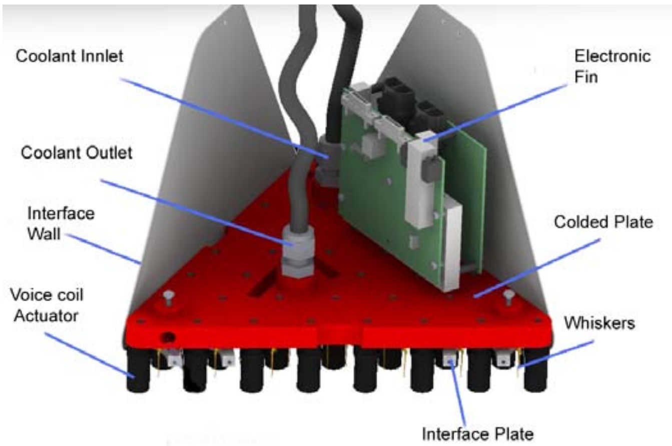



Figure 3: Left: reference body structure. It is the reference surface for the thin mirror shell. It need optical surface quality in term of flatness and must be stable with gravity and temperature. Right: Bricks: mechanical structure supporting ~30 actuators, the associated electronics and used to cool down the system.

The M4 mirror is composed by a reference body (Figure 3 left), a thin mirror shell, actuators and associated electronics. The thin Zerodur mirror is a six petals mirror, 1.95mm thick to cover an optical surface with inner diameter 540mm and 2400 outer diameter.

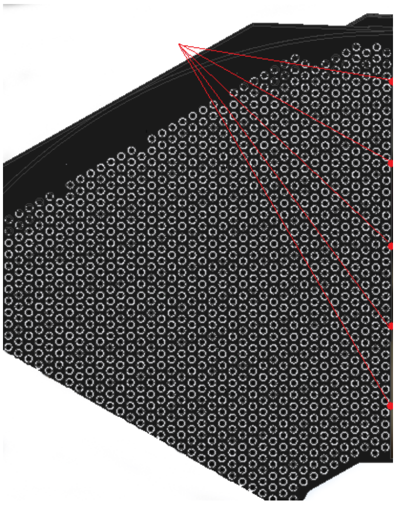


Figure 4: Sixth of the reference body seen from the front side: all the actuators holes are visible. Sixth of the reference body seen from the back side: the triangular structure of the reference body as well as the bricks is visible.

Each mirror shell segment is deformed by 985 voice coil actuators (829 on the optical surface of each segment) for a total of 5910 actuators (4974 on the optical surface). The 6 segments thin shell mirrors are laterally restrained by membranes fixed on their external border.

The reference body is a metallic structure with triangular cells and as many holes on its front surface as actuators are present in the design. The actuators are on a triangular pattern separated of 31.5 mm except at the segment border where the pattern is reduced (Figure 4).
A maximum access is provided to the back surface of the reference body to allow a telescope on-board maintenance. It is indeed foreseen that only maintenance related to mirror shells (like re-coating) and extraordinary maintenances shall need the dismounting of the unit from the telescope. The M4 unit design provides maintenance paths and its design allow to exchange electronics and voice coil actuators.

The brick concept (Figure 3 right, Figure 5) has been developed in the frame of M4 studies to easier the maintenance concept: with almost 6000 actuators, it is essential to be able to do such maintenance without removing the unit from the telescope. As for LBT and VLT secondary mirrors the voice actuators rely on contactless concept with in addition permanent bias magnet to handle the shell when the mirror is in stand-by. By grouping actuators in bricks, the maintenance is simplified: when it is decided to exchange a brick, the engineer need to remove the brick and replaced it by a spare one already calibrated.

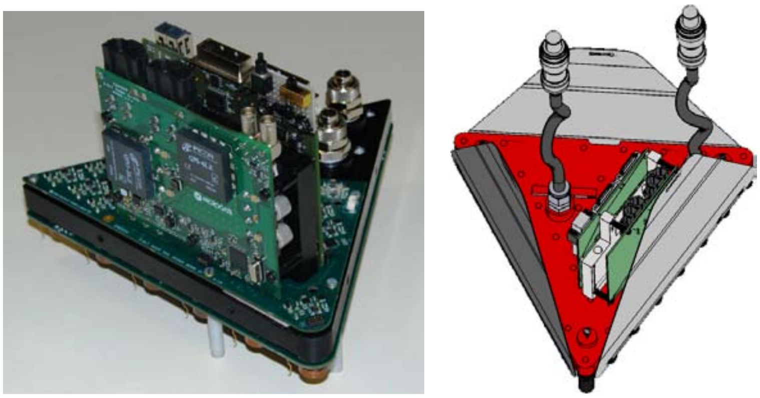


Figure 5: Left: First brick prototype designed in the frame of the previous contract. The extensive test of the Demonstration Prototype allowed Microgate and A.D.S. International to improve to design in term of mounting on the reference body, improving as well the cooling and updating the electronics design. Right: Baseline brick design. The three material plates allow a better alignment of the brick in the reference body structure and make the maintenance easier.

In addition to the bricks concept, several key new elements have been developed specifically for the M4 Adaptive Subunit:

- The cophasing sensors to have the six segments perfectly cophased: co-located differential sensors with a specific shape allow to measure at the same time the gap between the reference body and the two shell segments, in addition to the information already provided by the sensors co-located with each actuator. With several cophasing sensors placed along the border of two shells segments, one can easily cophase the two shells.
- The external membranes due to stringent requirement on the inner hole in term of space: as the intermediate focus is located in the central hole of M4, the hole need to be large enough to avoid vignetting on the field of view but it must be as well small enough to avoid a too large inner hole reducing the quantity of photon coming from the sky. The space provided for M4 subunit is too small to allow having a central membrane. The concept of external membrane was successfully demonstrated during the previous design phase.
- The use of gas for coolant: M4 subunit been located in the middle of the telescope above M5, M3 and M1, alternative to glycol has been considered to avoid leaks on optical elements. The solution of gas coolant has been extensively analyzed by modeling and experiments in a delta study demonstrating its capability to cool the M4 Mirror as required. Vibrations have also been measured and few additional tests are required to definitively confirm the validity of the gas coolant.

Few aspects remain to be validated in the next year: the reference body material is one aspect. Indeed during previous study SiC was considered in the baseline but it appeared that companies manufacturing such type of material were not ready for manufacturing. A delta study has been done to establish the feasibility of a reference made in CFRP or in other materials measuring in particular the manufacturability in term of flatness and thermal stability.

The design of capacitive sensors is another aspect: previous study have demonstrated the feasibility of a design with Zerodur inserts and small flexible contact arms but the integration and reliability of such system seems need to be consolidated considering the large number to install. Moreover, alternative designs have been proposed and will be tested during the next year.

The last important aspect of the system is its optical test bench which should allow measuring the influence function, calibrating the flat and determining the optical performance of the unit. The bench requires stringent conditions in term of thermal stability and mechanical stability. The baseline design is a 12-meters bench using a ~1-m spherical off axis mirror and a null-lens[6]. Alternative design will be traded-off in the next months trying to reduce the dimension and to improve the easiness of the alignment..

## 4. SCHEDULE AND WORKPLAN

The M4 subunit is a critical item of the E-ELT due to its complexity and since it is one of the items requiring the longest time to manufacture, integrate and test. Nine years are needed to have the system at Cerro Armazones in Chile. The preliminary design update for the 39-m E-ELT M4 will last 18 months. During this phase the final reference body material will be selected and the Demonstration Prototype procured during the previous contract will be re-furbished to have a 100% compliant design with the M4 mirror. The Demonstration Prototype will be tested and the design validated on this 1-m prototype. The following 15 months will be dedicated to the final design.

The thin mirror shells will be procured by ESO and delivered to A.DS../Microgate for final integration. The first mirror segment will be manufactured in 21 months while the sevenths successive segments will be manufactured two by two at a pacing of two shells per year.

The large amount of actuators induces a long time for integration. The ~6000 actuators (plus spares) will have to be integrated, calibrated on the bricks. The same amount of magnets will have to be glued on the mirror shells and the same quantity of capacitive sensors will be integrated on the reference body. One year is planned for the optical testing of the complete unit and one year is foreseen for transport, re-integration and testing in Chile.

## 5. CONCLUSIONS

The contract for the preliminary design study of the M4 Adaptive Subunit for the 39-m E-ELT has been kick-off in May 2012. This is the first step for the manufacturing of the system which should allow placing in 18 months a contract for the final design, manufacturing, integration and test of the 2.4-m adaptive mirror.

The M4 Adaptive Subunit is key element full of powerful technological developments. It will allow the E-ELT to provide enhanced seeing performances in bad seeing conditions and windy situations and will provide diffraction limited images median seeing conditions.

## REFERENCES

[1] M. Cayrel, “E-ELT Optomechanical Overview”, Proc. SPIE Vol. 8444, 8444-69, (2012)

[2] : H. M. Martin; G. Brusa Zappellini; B. Cuerden; S. M. Miller; A. Riccardi and B. K. Smith, “Deformable secondary mirrors for the LBT adaptive optics system”, Proceedings Vol. 6272, Advances in Adaptive Optics II, Brent L. Ellerbroek; Domenico Bonaccini Calia, Editors, 2006

[3]F. Poutriquet, A. Rinchet, J.-L. Carel, H. Leplan, E. Ruch, R. Geyl, G. Marque, “Manufacturing of glassy thin shell for adaptive optics: results achieved”, 8447-89, this conference

[4] E. Vernet, L. Jochum, P. La Penna, N. hubin, R. Muradore, J. M. Casalta, I. Kjelberg, J-C. Sinquin, F. Locre, P. Morin, R. Cousty, J-M. Lurçon, J-J Roland, B. Crepy, E. Gabriel, R. Biasi, M. Andrighettoni, G. Angerer, D. Gallieni, M. Mantegazza, M. Tintori, E. Molinari, D. Tresoldi, G. Toso, P. Spanó, M. Riva, G. Crimi, A. Riccardi, G. Marque, J-L. Carel, E. Ruch, “The field stabilization and Adaptive optics mirrors for the European Extremely Large Telescope”, SPIE volume 7015, N. Hubin, C. E. Max, P.L. Wizinowich Editors, 2008

[5] B. Crépy; S. Chaillot; M. Cola; J. M. Conan; R. Cousty; M. Dimmler; J. L. Dournaux; S. De Zotti; E. Gabriel; R. Gasmi; R. Grasser; N. Hubin; P. Jagourel; L. Jochum; F. Locre; P.-Y. Madec; P. Morin; M. Mueller; G. Petit; D. Petitgas; J. J. Roland; J. C. Sinquin; E. Vernet, Demonstration prototype and breadboards of the piezo stack M4 adaptive unit of the E-ELT, proceedings 7736, Adaptive Optics systems II, B. Elelrbroek, M. Hart, N. Hubin, P.L. Wizinowich Editors, 2010
[6] P. Spanò, A. Bianco, R. Brugiglio, M. Cecconi, L. Miglietta, E. Molinari, M. Riva, M. Xompero, F. Zerbi, Optical calibration and testing of the E-ELT M4 Adaptive Mirror, 8447-134, this conference