ASM:
a scaled down Active Segmented Mirror for the Active Phasing Experiment

Christophe Dupuy*
Frédéric Gonté, Christoph Frank,
European Southern Observatory, Karl-Schwarzschild-Strasse 2, 85748 Garching bei München, Germany

ABSTRACT

The construction of extremely large telescope is only possible with a segmented primary mirror. The phasing of the primary mirror due to its size and its number of segments is a main concern at the European Southern Observatory. The European Southern Observatory has developed a test bench called Active Phasing Experiment to study new phasing technology and new telescope control system. The key subsystem of this experiment is a scaled down Active Segmented Mirror (ASM) composed of sixty-one hexagonal segments of seventeen millimeters side to side. Each hexagonal mirror can all be controlled in piston, tip and tilt. The integration of this jewel piece of opto-mechanic started after the successful results obtained with the manufacturing of a prototype composed of only seven modules.

Keywords: ESO, ASM, APE, ELT, hexagonal segments, development, scaled down, active optics, Claraluna.

1. INTRODUCTION

Segmented primary mirror is mandatory for the design of the future **E**uropean **E**xtremely **L**arge **T**elescope (E-ELT). Such facility needs a new type of telescope control system taking account of the phasing of the primary mirror. The **A**ctive **P**hasing **E**xperiment[1] (APE) has been developed to explore future technologies for the phasing sensors (different optical principle) and study new telescope control systems.

The **A**ctive **S**egmented **M**irror (ASM) has been fully developed, designed and built at ESO to simulate primary segmentation in APE by imaging on it the VLT pupil over a diameter of 130 mm.

The Active Segmented Mirror is composed of 61 hexagonal segments that have piston tip tilt capabilities. The size of each segment is 17 mm side to side which means approximately 100 times smaller than of an ELT segment. Each segment of this key subsystem is controlled with a resolution of the order of a few nanometers by means of three piezo actuators having a stroke of 30 µm. It is required to use a range displacement of the segments of 15 microns during the Active Phasing Experiment. It imposes an opto mechanical manufacturing alignment of all the front hexagonal mirror surfaces better than 15 microns peak to valley at rest.

Each module is assembled, glued and integrated from standard (piezo-actuators) and custom-made (mirrors, mechanics) parts procured from industries. Specifications, designs, assembly, tools, hand work skills, electronics, software, control algorithms and test procedures are the field of competences required to obtain in the end a “plug and play” product. A previous proceeding[2] was describing the results obtained on a prototype composed of seven modules. This one describes from concept to test, how we built the full ASM, a jewel piece of opto-mechanic. Figure 1 shows the full Active Segmented Mirror before integration in its mount

*e-mail: cdupuy@eso.org

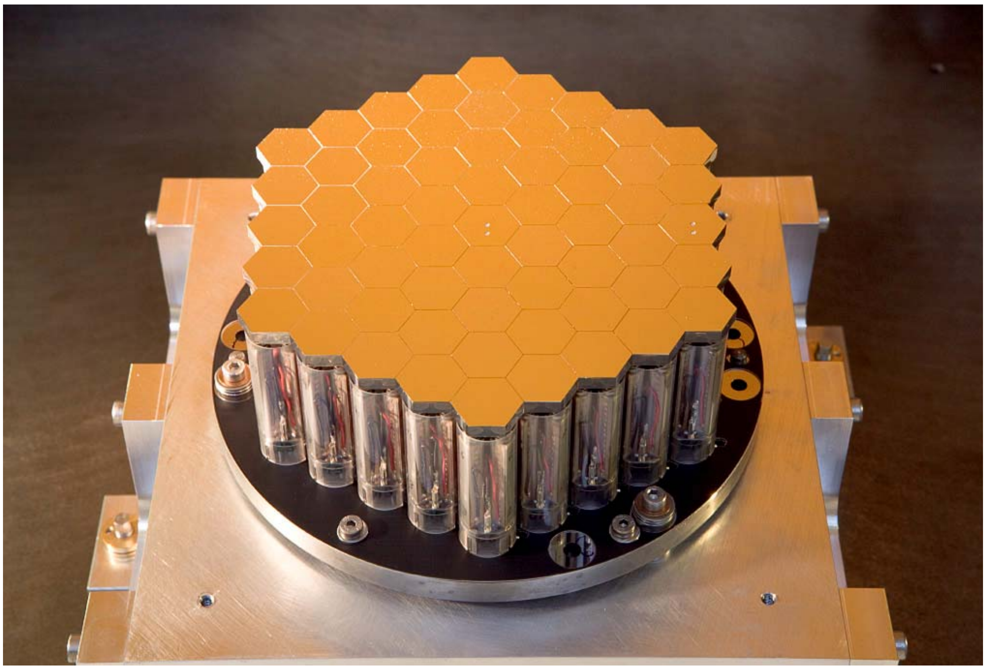


Figure 1: the Active Segmented Mirror before integration in its mount

2. REQUIREMENTS

The key requirement for the ASM is to be representative to an ELT, at a scale affordable for laboratory testing in Garching, and on sky on the VLT-UT nasmyth platform. The requirements are:

⬣ The ASM price shall be within the allocated budget.

⬣ Free optical aperture of a diameter of 130 mm. This value is to limit APE bench optical components to reasonable sizes.

⬣ The 61 flat mirrors are made of Zerodur® with a surface flatness better than 15 nm RMS after coating and integration. The quantity, the coating and the material are representative of an E-ELT segmented primary mirror.

⬣ The segments are fully coated (no jig lip) with protected aluminum. This standard coating type reduces the risk of premature aging mainly due to sharp edges.

⬣ Segments have hexagonal shape; they are 17 mm width side to side, and have sharp edges. The sharp edges are mandatory to fulfill the scaling down with respect to chamfer sizes foreseen on ELT segments.

⬣ The gap between two segments is comprised between 70 to 150 µm. In addition of respecting the scaling down, this range is to provide reasonable mounting and width segment manufacturing tolerances.

⬣ The active control requires a maximum range of 15 µm for Piston, Tip and Tilt. This value is defined in order to split the piezo stroke in two ranges. First half is used to phase the mirror and compensate module integration and assembly errors. The second half is used by the active control of the ASM.

⬣ Frequency response shall be greater than 10 Hz.

⬣ Used in laboratory and at telescope environment.

⬣ Strong follow up by the ESO people of the ASM manufacturing in the field of integration, engineering and design.

3. CONCEPT

The selected approach was finally in-house ASM design, development and integration. It presented with respect to received industrial offers, the advantage of having interchangeable modules, control of the whole building process, possible size expansion, some experience gained regarding manufacturing of segmented mirror cells. Last but not least, the proposal from the industries was also more than twice higher than the allocated budget.

The baseline was:

- To design as far as possible simple, efficient and reliable interfaces, to ease the exchange of modules in case of whatever failure.
- Address at a very early phase the design of assembly tools to assure their modularity and efficiency with respect to final requirements.
- Each module is composed of one interface base, three piezo actuators, three mirror support elements (spring shape), three adjustment screws, one mirror. All parts are cemented with epoxy type glue.
- Two modules are equipped with monomode fibers used as point source for later ASM alignment.
- All modules are interfaced on an invar polished disk used as main interface with respect to the outer world.
- All assemblies are validated by FEM analysis

3.1 Concept of the ASM into the Active Phasing Experiment

The ASM is the heart of the APE experiment and is located close to the center of a 3 x 2 m optical table. The Optical axis is at 230 mm height. It defines the APE pupil plan and will be on site conjugated with the one of the VLT. It faces a 200 mm off axis parabola. **Figure 2** shows the ASM at the center of the APE bench. It can be seen that two optical beams are reflected onto the ASM. The first one (red) comes from the VLT or from the turbulence generator. The second optical beam (green) comes from the Internal Metrology[3] and is used for the ASM control.

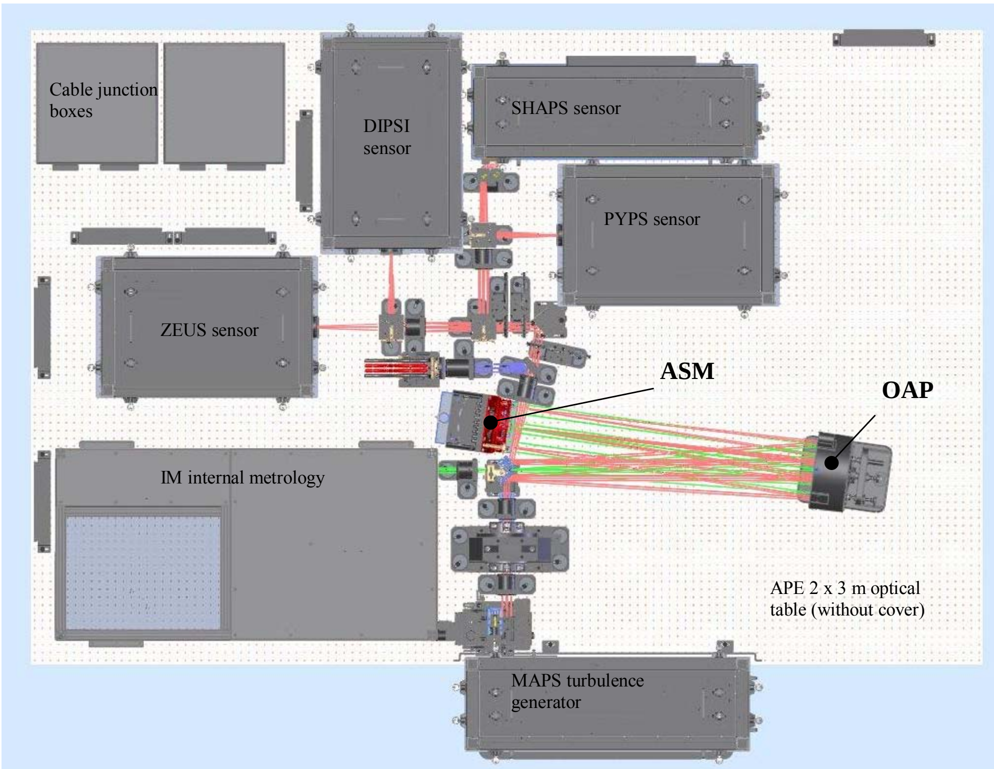


Figure 2: ASM on APE bench (top 2D view)

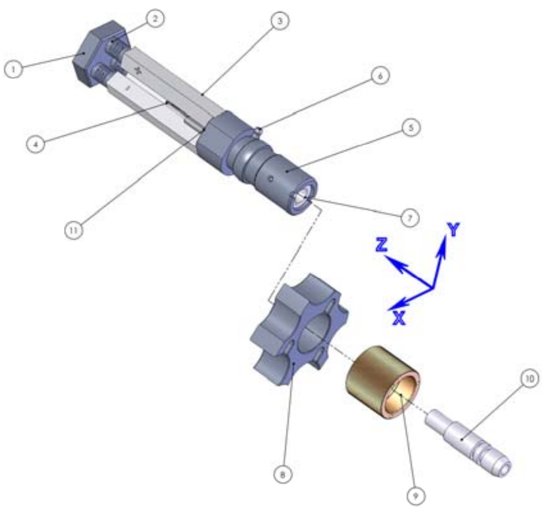
The monomode fibers inserted in the ASM central and extreme side segments are used for three different purposes:

- ASM alignment, lateral, height and along the optical axis of the APE bench
- APE system aspect; plate scale verification, pupil distortion, ASM orientation
- Optical phasing sensor and Internal Metrology alignment.

The ASM can be replaced at anytime by a monolithic flat mirror (called dummy) for alignment of APE and also for the calibration and alignment of the optical phasing sensors. We can this way considerably speed up the general system alignment steps. All these ideas were already addressed during the general APE concept phase.

3.2 Module concept

The ASM is an assembly of 61 clone modules. Two of them are specific ones equipped with custom monomode fiber patch cords. The module principle is based on a stack of glued parts. The mirror position in space, is this way, directly linked to the base as shown in **Figure 3**. Additional translucent tubes visible on **Figure 1** are glued on the base to protect mechanically the piezo and also for safety issues related to high voltage control.



1. Hexagonal mirror (1x)
2. Spring element (mirror support) including height and tilt adjustment screw (3x)
3. Piezo (3x)
4. Removable piezo grounding connector (3x)
5. Base (1x)
6. Base orientation key (1x)
7. Female module connector (1x)
8. ASM interface disk (partial view) (1x)
9. Nut (1x)
10. External male connector (1x)
11. Electrical pin piezo grounding (3x)

Figure 3 : 3D module exploded view

3.3 ASM mount description

A specific mount (**Figure 4**) is used to hold and align the ASM on the bench. Tip and Tilt of the ASM are done with rotating axis located above the main base and as close as possible to the optical surface to respect the gimbal principle. Lateral alignment is carried out with adjustable stops on the APE table that will be locked when aligned. Vertical alignment is adjusted once by shims. The front red cylinder in addition of protecting the ASM allows also attachment of masks. The masks can be used to simulate the segmentation on the dummy mirror or to cover the borders of the segments on the ASM. The masks are adjusted once, with respect to segmentation pattern and are glued on dedicated frames. They can be exchanged through two cylindrical pins and clamping grooves with a position reproducibility of less than 10µm.

The disk holding the modules is made of invar to limit the distortion of the ASM due to the temperature. The holes where the modules are inserted, are shaped by wire electrical discharge machining to fulfill the tight tolerances. The cut pattern directly defines the mirrors lateral positioning, i.e that its accuracy has a direct influence on the gaps values between mirror edges. The front disk surface is the main module interface. Its surface is post polished within a micron to reduce the final mirror height and tilt error from one module to one other. The disk is clamped on the mount bracket frame using three pairs of ball and socket washers to avoid deformation. **Figure 4** shows the conceptual design of the ASM mount.

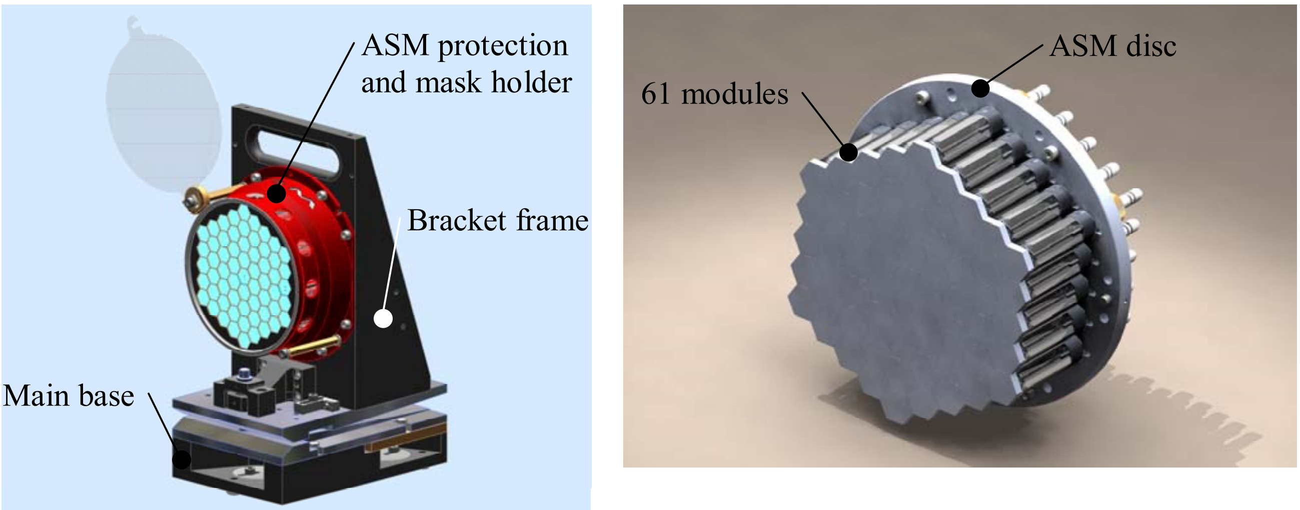


Figure 4 : 3D concept view of the ASM with and without its mount

A second identical mount was designed for the dummy mirror. Both ASM and “dummy” are adjusted inside their respective mount to get both optical surfaces at the same position (over 6 degrees of freedom) with respect to each mount base. The Weight of the whole mount is around 20 kg and can be handled easily for exchange by a dedicated cut directly machined in the bracket frame.

3.4 ASM modules gluing tools

The technology chosen to stack the components of the module is cementing. This choice has been taken due to the lack of space and small sizes of the components. ESO is used to apply this technology even for tight positioning tolerances. This knowledge and experience was necessary for the precision required between base interface and front mirror surface.

The ASM has around 600 glued interfaces. The difficulties were to properly design and optimize the concept of the gluing tools to position and keep parts from moving until handling strength is reached (at least 24h).

The tool is based on playing with interfaces linked each other between pure kinematic and hyperstatic (dependent of machining accuracy). The tool is then composed of a main frame providing three module base interfaces similar to the ones machined on the ASM disk. This quantity was selected as an optimum compromise due to machining accuracy, free space for handling components to be glued, tool stiffness and external sizes. The top of the main frame is machined in a way to receive different kind of modular stages, each one being dedicated for cementing a specific interface. For example; one for the piezos on base, one for springs on piezos, and one for the mirror. Each top stage can be easily repositioned on the main frame within less than few microns.

After the ASM prototype phase, we decided to build four of these tools. This was for a single operator, the best compromise and best optimization between mixed glue lifetime, curing time, time to position and adjust the components.

One very important point was to design and make sure that all theses four set of tools guarantee a relative positioning of the mirrors with respect to the base within few microns (laterally and in orientation). Whatever the mirrors shift is, the value and direction must be the same for all of the 61 modules. We validated the tools at a early integration phase by fully assembling one module per tool and perform extensive checking.

Figure 5 shows the module gluing tool principle

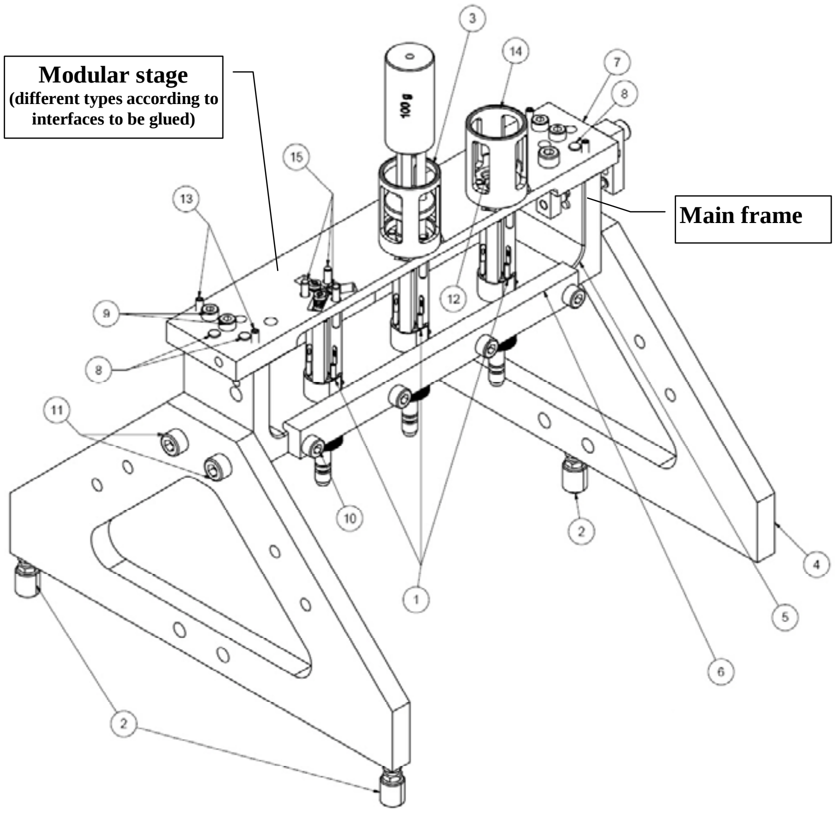


Figure 5 : Gluing tool design

4. PREPARATION AND TEST OF SINGLE COMPONENTS

The ASM is composed of around 900 parts..

4.1 Parts preparation

The first step prior to start the integration was to prepare the parts ready for test and cementing. After marking all critical parts by numbers for traceability, standard cleaning procedures were applied according to components type. We used ultra sonic bath, plasma cleaning or traditional hand cleaning with acetone for the mirrors and interfaces to be glued.

4.2 Test on single parts

All parts have been checked that they were conform to requirements or data sheet. Quick test that they could interact and fit properly together was carried out as well.

Depending on the test already performed by the miscellaneous suppliers, we carried out additional checking in house on a representative number of parts. The list of the most important parameters checked is:

- Mechanical parts dimensions, machining quality, metal blurs.
- Mirrors dimensions and wavefront surface check.
- Mirrors coating performances including adherence, reflectance and cosmetics up to sharp edges as shown in Figure 6.
- Piezo sizes dispersion and electro-mechanical response.

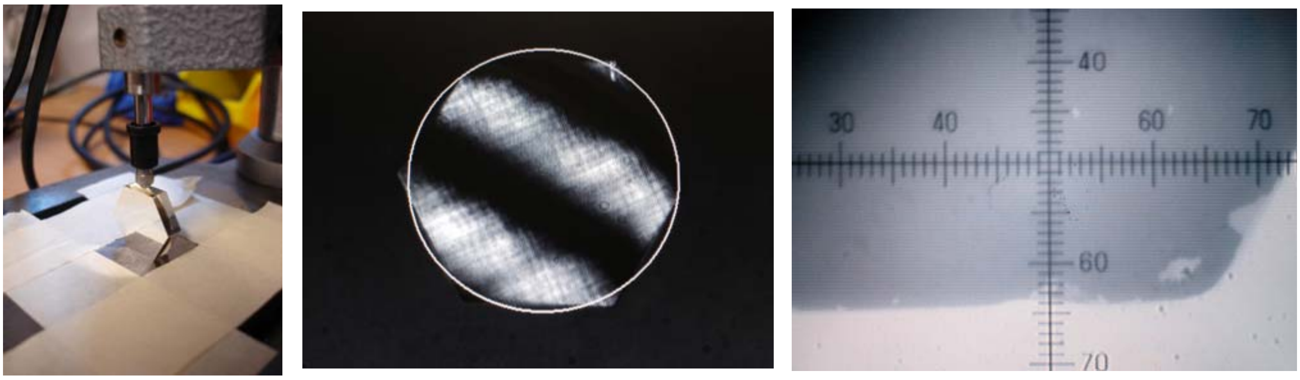


Figure 6 : some of the mirror measurements and checking

5. INTEGRATION

Integration was a key point of the ASM having to position around 600 elements of different natures, shapes, and material within microns. More than following step-by-step procedures, the final result was much more dependent of hand skills, adequate tools, and experience with cementing small components.

From the process validated by the prototype, we could optimize many integration steps and speed up the time required to build a single module.

- First: Well prepare the laboratory environment, working space according to the type of parts to glue.
- Second: Define as optimum, the number of gluing tools for “mass production”.
- Third: Glue the same type of interface in a row for the whole amount of modules.
- Fourth: Perform at the right times, the intermediate verification steps.

From this optimization, we could produce (by a single operator) two modules a day.

5.1 Modules integration

The Table 7 below shows the time we spent for each step, based on building 72 modules (11 spares), including the ones equipped with fibers and the intermediate checking steps.

Interface to be glued	**Remark**	**Amount of base ready per day**	**Total time (days)**
Orientation key on base	1x key per base	12	6
Piezos on base	3x piezo per base	12	6
Springs on piezos	3x springs per base	12	6
Mirror on springs	1x mirror per base	6	12
Translucent tube on base	1x tube per base	12	6
Total time (days) necessary to build all modules			**36**

Table 7 : Module assembly and integration time

Some pictures showing the modules integration steps

Figure 8 : module parts

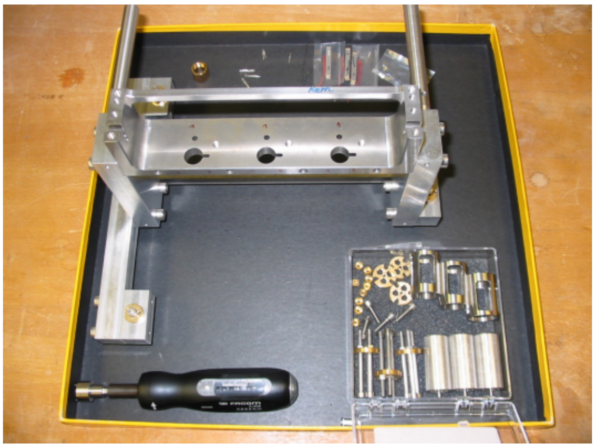


Figure 9 : Gluing tool assembly

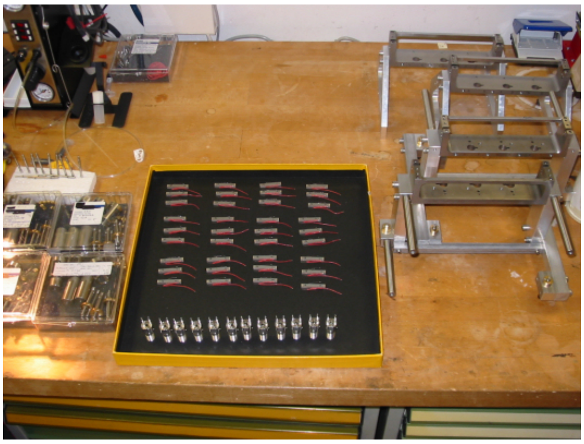


Figure 10 : Environnent preparation

Figure 11 : Glue preparation

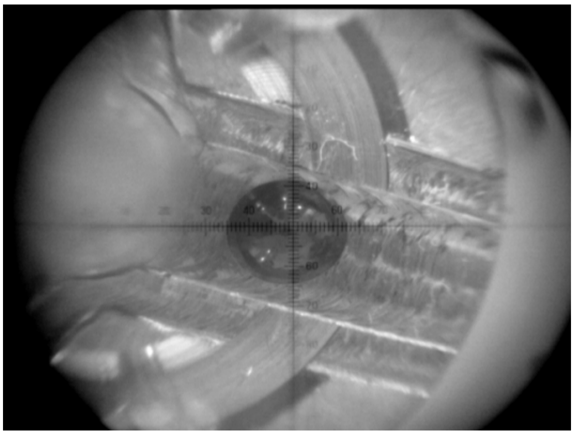


Figure 12 : glue drop applyed on base

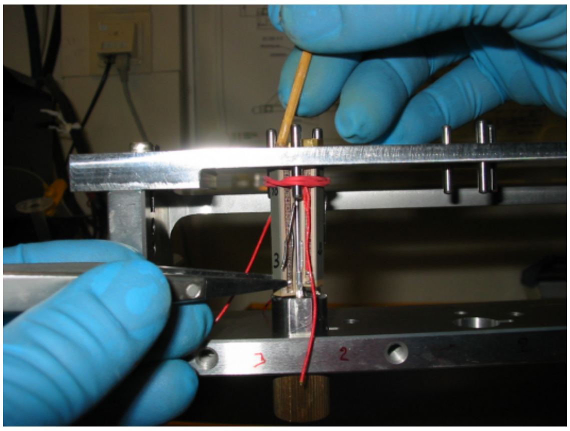


Figure 13 : Piezo on base positioning

Figure 14 : Piezo on base curing

Figure 15 : Work under binocular

Figure 16 : Modules ready for mirror gluing

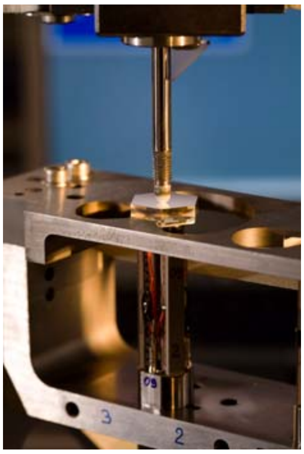


Figure 17 : Mirror adjustment

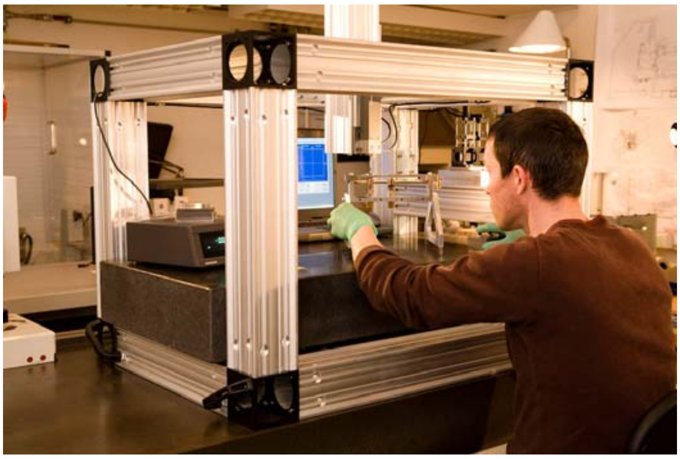


Figure 18 : Dedicated mirror bench alignment

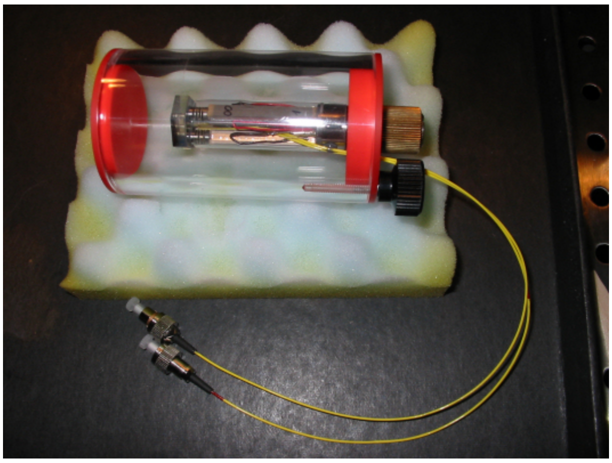


Figure 19 : Full integrated module with fibers

5.2 Modules test

All modules have been checked with values recorded prior to populate the disk. Table 22 summaries the results

Piezo at rest:	Piezo driven (over whole piezo stroke)
⬣ Mirror eccentricity and orientation with respect to base. ⬣ Mirror height and tilt with respect to base.	⬣ Mirror shape. ⬣ Fatigue test on 10 pieces from miscellaneous batches. ⬣ Resonance frequency.

5.3 ASM Integration

After the single modules measurements, we populated the disk by contiguous lines starting from one ASM edge as shown on Figure 20. Modules tightening as shown on Figure 21 was carried out with a calibrated tork key set to 0.8 N.m

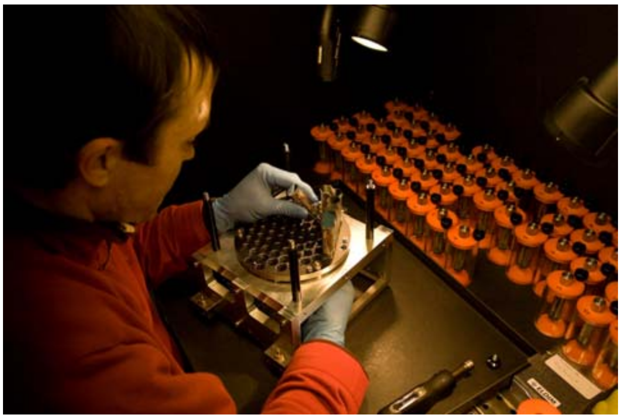


Figure 20 : Disk population by lines

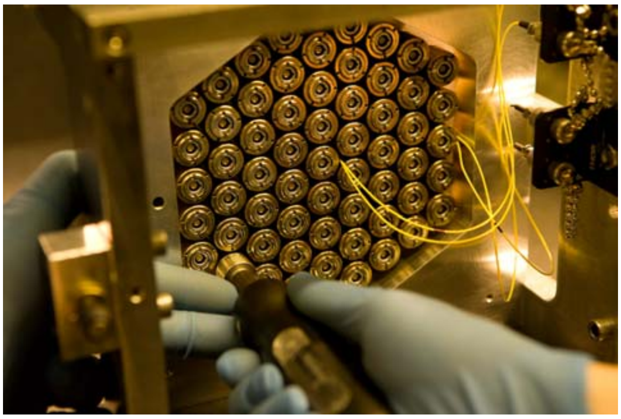


Figure 21 : Modules tightening on disk

6. RESULTS

Many different test setup were prepared to validate the whole ASM requirements. Table 22 provides the results recorded.

Related field	Parameter checked	Measurement	Requirement
Opto-mechanical design, FEM analysis and integration	Mirror eccentricity with respect to piezo base	≤15 µm	≤20 µm
	Mirror height differences (measured at mirrors center)	≤7 µm	≤15 µm
	Mirror angle differences	≤4 arcmin	≤5 arcmin
	Mirror surface form evolution	≤8 nm RMS	≤15 nm RMS
	Gap between segment edges	79 to 115 µm	70 to 150 µm
Control software, electronics and integration	Fatigue test (5 to 15 Hz; 48 H) on all modules prior integration on disk	Successful	No degradation
	ASM surface form error after phasing (open loop)	87 nm Peak to Valley considering dummy as reference	No value, as linked to APE bench optical components quality
	Resonance frequency	800 & 2000 Hz	>> 10 Hz
	Module resolution	≤1 nm	1 nm
	Phasing of ASM in closed loop	≤1 nm RMS	≤5 nm

Table 22 : results obtained on the populated disk

Figure 23 shows one of the gaps measured between three segments under microscope.
Figure 24 is the ASM surface form error recorded on the APE bench over a diameter of 130mm. This interferogram was computed from static fringes using Claraluna. The fringes were captured in open loop after that the ASM was phased by the Internal Metrology. The real ASM surface is even better than 87nm as the value includes the errors of the dummy used as reference.
Figure 25 shows an open loop test demonstrating some of the control capabilities. “ASM” is written through the fringe pattern.
The piston standard deviation in closed loop with the Internal Metrology over 12 hours is better than one nanometre (see Figure 26). We could reproduce many times this record in the laboratory, in standard environment conditions.

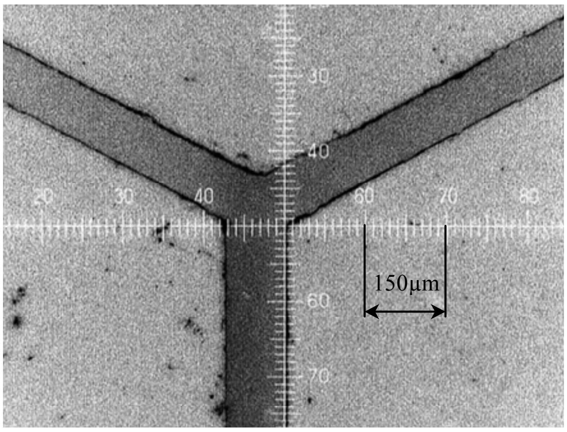


Figure 23 : Gaps measurements

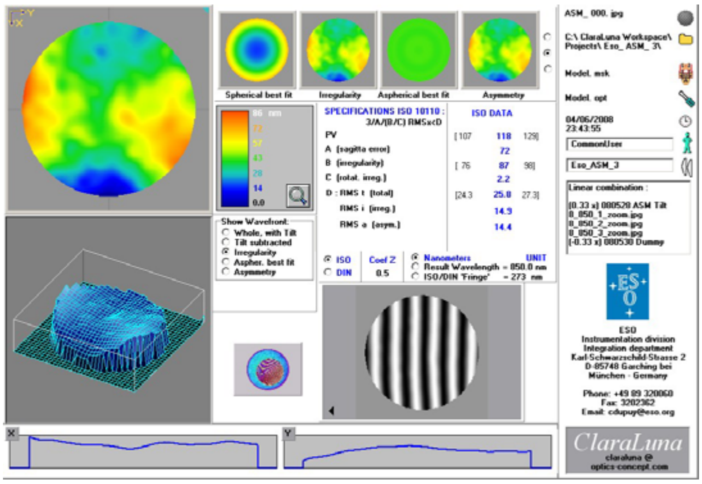


Figure 24 : ASM surface error after phasing

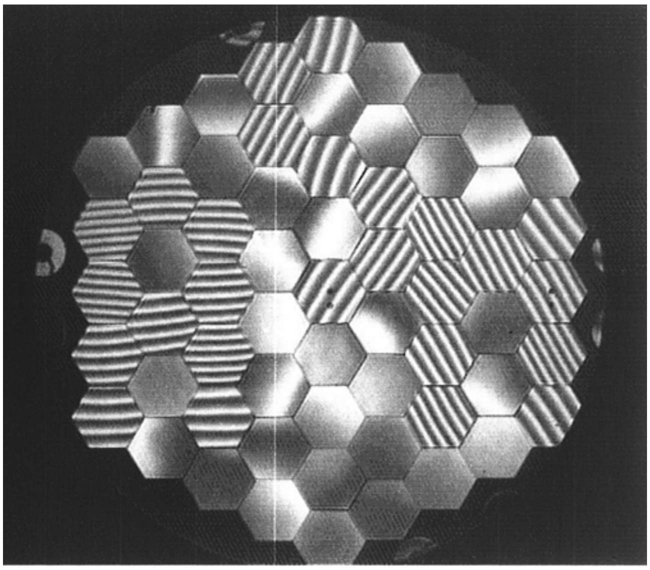


Figure 25 : Open loop test (ASM written)

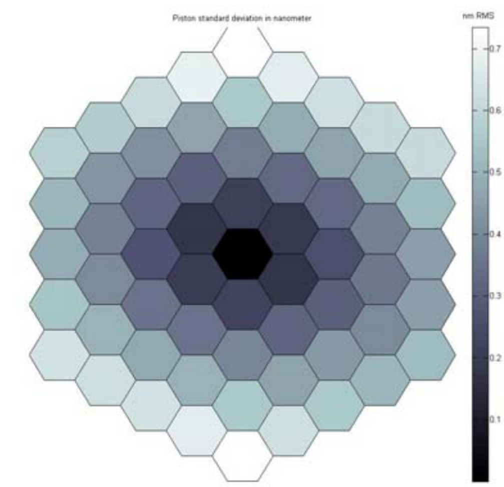


Figure 26 : Piston error in closed loop measurement

Figure 27 shows the dummy and ASM close each other for comparison. Available masks are as well visible.

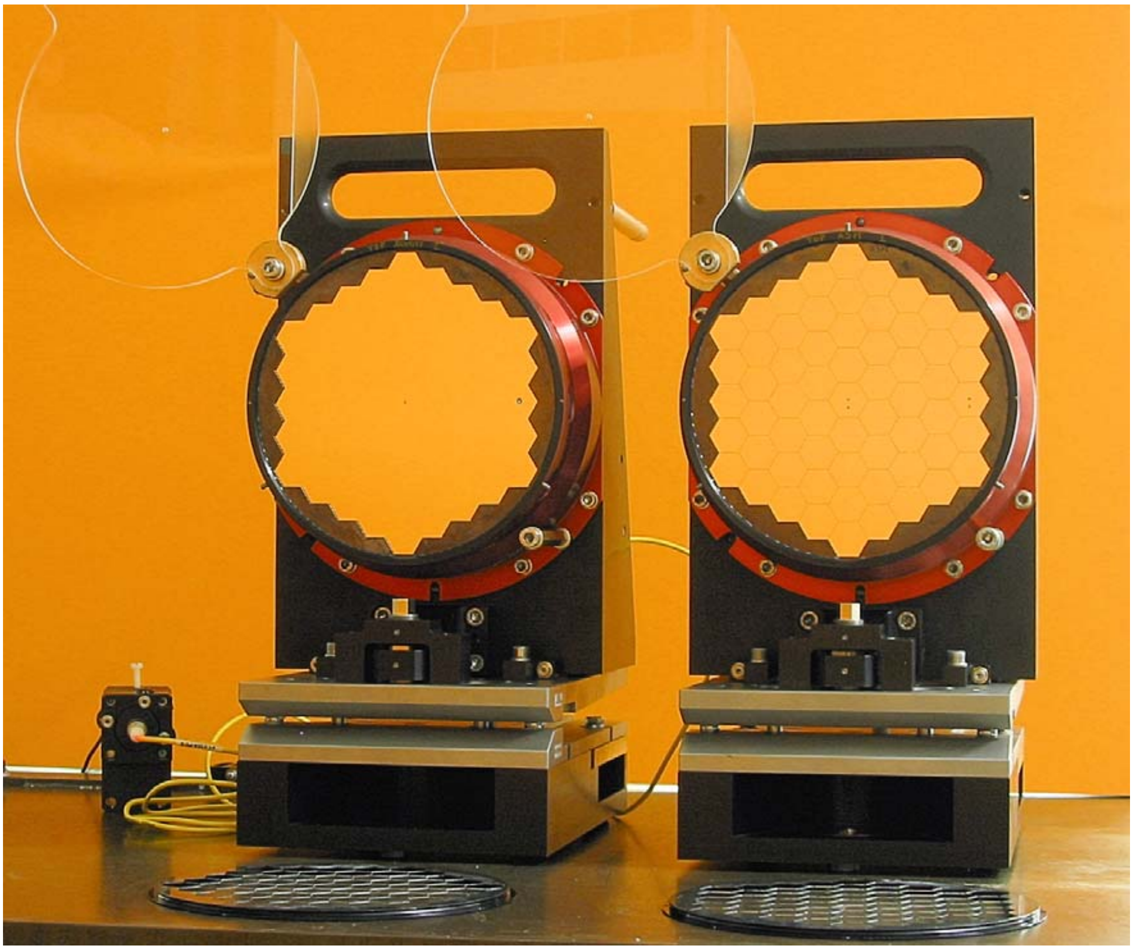


Figure 27: Dummy and ASM ready for integration on the APE bench

7. CONCLUSION

This subsystem was considered as high risk in term of technology and performances. The concept approach and results obtained are directly linked to an excellent communication and ideas exchange between the three authors of this paper, i.e in the field of integration, engineering and design, al of that respecting the dedicated cost budget and time.
The ASM used on a daily basis has a resolution better than 1nm RMS on the APE bench since January 2008. No specific aging or behavior change has been noticed since that. The ASM fulfills totally the whole requirements and much more.

8. ACKNOWLEDGMENTS

The ASM is a subsystem of APE that was financed by the European Union and the European Southern Observatory via the Sixth European Union Framework Program for Research and Technological Development under the contract number 011863.

9. REFERENCES

1. Gonté F.et al. “Active Phasing Experiment: preliminary results”, Proc. 7012-34 (2008)
2. Dupuy C. et al. “ASM: scaled down active segmented mirror developed to simulate a segmented primary mirror”, Proc. 6273 (2006)
3. Wilhelm R., Luong B, Courteville A., Estival S., and F Gonte, “Optical phasing of a segmented mirror with sub-nanometer accuracy: Experimental results of the Internal Metrology”, Proc. 7012-37 (2008)