FIRST STEPS IN ELT OPTICS POLISHING

OECD CONFERENCE CENTER, PARIS, FRANCE / 6–8 FEBRUARY 2018

R. Geyl, D. Bardon, R. Bourgois, N. Ferachoglou, E. Harel, C. Couteret

Safran Reosc, avenue de la Tour Maury, 91280 Saint Pierre du Perray, FRANCE,

KEYWORDS: ELT, Large optics, optical manufacturing

ABSTRACT:

Green light for the construction of the 39-m aperture giant Extremely Large Telescope (ELT) was given by the European Southern Observatory (ESO) council on Dec 4th, 2014. Procurement of the key elements was immediately initiated by ESO team and Safran Reosc was awarded all the key optical polishing and testing contracts since that time:

- 2015-07: contract for the Adaptive Optics M4 mirror thin glass petals,
- 2016-07: contract for the 4-m M2 convex mirror,
- 2017-02: contract for the 4-m M3 mirror.
- 2017-05: contract for polishing and intergation of the 931 1.45-m hexagonal segments for the giant 39-m M1 mirror assembly

This paper is dedicated to highlighting the various challenges linked to these various optical fabrication projects and reporting about the progress of our work so far.

1. The ESO ELT project

The ELT is the last major optical telescope project conducted by ESO for the benefit of the astronomic community of all its member states.

ELT will be the largest optical telescope ever built with its 39-m segmented primary mirror aperture. The scientific return shall be major thanks to the big step in aperture since the last telescope generations of 8-m monolithic, e.g. the ESO Very Large Telescope (VLT), or 11-m segmented, e.g. the Gran Telescopio Canarias (GTC). Beyond cosmology and deep universe science the ELT shall allow soon to directly observe nearby exoplanets and to hopefully detect some blue color that would be the direct proof of presence of water and extra-terrestrial life.

Installed on the Cerro Armazones montain in Chile, the ELT will be an integral part of the Paranal observatory already hosting the VLT. This site at an altitude of 3046-m is of exceptional quality with more than 300 clear nights a year and very stable weather conditions. The dry atmosphere offer good IR transmission and UV ligh can also be collected. The drawback of this site is the rather high seismic activity, but ESO has gained solid experience in handling these events in the observatory.

The ELT telescope total budget is 1.1 B€, including first light instruments and some contingency.

Figure 1. Artist view of the ELT *(Credit ESO)*

2. An innovative optical configuration

The ELT is a compact telescope featuring an innovative optical design as shown below.

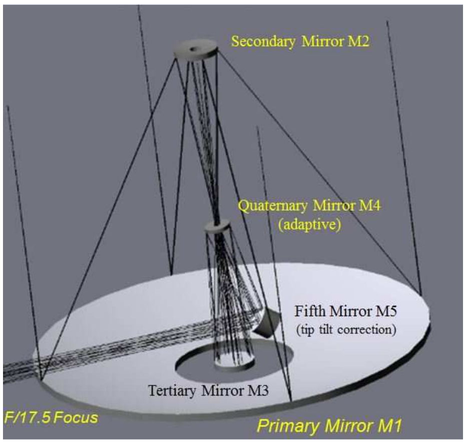

Figure 2. The ELT optical design *(Credit ESO)*

The first three mirrors M1, M2 & M3 are aspheric and constitute a state-of-the-art Three Mirror Anastigmat system (684-m focal length!) offering perfect image quality over a 2-m wide focal surface. The convex M2 and concave M3 have nearly 4-m diameter.

The second innovation of the ELT is that Adaptive Optics is directly integrated in the telescope with two folding flats: the AO deformable M4 and the image stabilisation M5.

The M4 is a giant 2.4-m diameter AO mirror with a thin glass shell of 2 mm thickness only, actuated by nearly 5000 actuators operating at 1 kHz frequency. The mirror is however split into 6 petals in order to give redundancy and not constitute a critical single failure point of the whole system.

The M5 is a large elliptical contoured mirror of 2100x2700 mm. It shall be solid, stiff and lightweight to perform the image stabilization. At this date this optics has not be contracted for fabrication by ESO.

Let's now report the to-date contribution and progress of Safran Reosc for the various M1 to M4 mirrors, in the contract award chronological order.

3. Thin glass shells for the M4 Unit

The Italian consortium Adoptica is responsible for the development of the M4 Unit shown on figure 3.

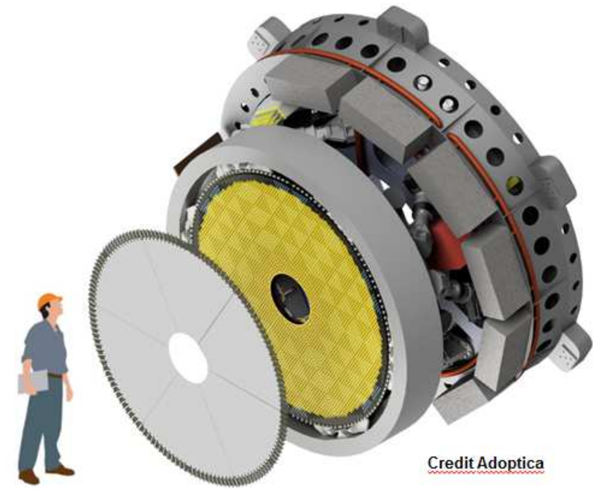

Figure 3. The ELT M4 Unit

A large hexopod system is adjusting the position of a large stiff structural part made from Silicon Carbide holding the 5000 actuators, with their electronics, to which the 6 thin glass petals are attached, constituting the AO deformable M4.

The glass petals produced by Safran Reosc have the following main specifications:

Size	1-m x 60° sector
Thickness	1,95 mm
Thickness uniformity	< 15 µm
Reflected WFE	< 14 nm RMS
Quantity	12 (2 sets of 6)

To meet these requirements Safran Reosc is adopting the successful technique of "thinning & cutting after polishing". This means that we procure a round Zerodur substrate of 40 mm thickness, polish it to the very smooth specification, block it on a body and thin it to the final thickness. Finally the part is cut to the 60° sector shape.

The most critical manufacturing step of these thin glass shells is the release from the blocking body without breaking the part. This technique is now fully mature and was developped for the production of 2 aspheric thin shells for the VLT M2 AO facility [1]. During prototype activities we also demonstrated to ESO our capability to produce the full size 2.4-m thin shell in one single piece.

At the date of the conference the first ELT M4 thin shall has been produced sucessfully and delivered to Adoptica. This is in fact constituting the first delivered optical hardware of the numerous optical components of the ELT telescope. The production of the 11 pieces remaining is now continuing at a rate of nearly 2 pieces / year.

A specific transport container has been developed to securely transport the pieces through Europe.

Figure 4. The first ELT M4 shell blank accepted at Schott

Figure 5. The M4 shell transport container

Figure 6. The first ELT M4 shell acceptance

4. M2 and M3 mirrors

The M2 and M3 mirrors are both near 4-m in diameter and in the shape of a thin meniscus of only 100 mm thickness and have a small central hole used for alignment purpose.

M2 is convex and with a high asphericity of 1,8 mm due to its relative aperture of F/1.1.

M3 is concave and much less opened at F/2.6 only and will therefore be rather easy to polish and test.

Both mirrors will be installed in an 18 points passive wiffle-tree support system designed by ESO and delivered to Safran Reosc for integration and final optical testing of each mirror.

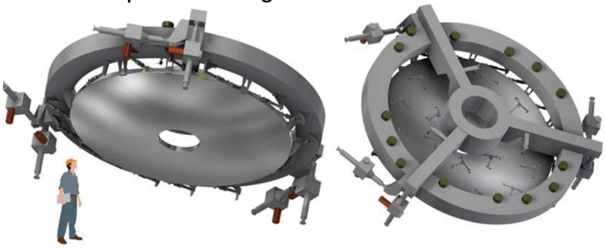

Figure 7. The ELT M2 in its support system

Tripods similar to those developped by Safran Reosc for the VLT will be again used for the ELT M2 and M3. Therefore the two optics are in fact supported by 54 support points for reduction of the gravity induced print-through. Laterally, each mirror is attached to the cell with 14 jacks. The global positionning of each M2 and M3 units is performed with a large hexapod device.

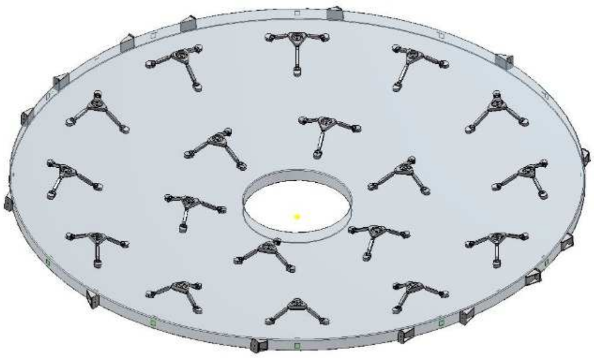

Figure 8. The ELT M2 mirror with pads and tripods

Safran Reosc is also responsible for the fabrication of the lateral pads and tripods and their bonding to the mirror bodies.

In term of optical fabrication and testing, the critical optics is definitively the M2 mirror due to its high aspheric departure and convex shape.

4.1. A new 4-m class polishing facility

The optical fabrication of ELT M2 and M3 will take place in our former VLT optical shop but the shop organization will be completely upgraded to accommodate the production of these two optics in the most effective manner. The figure 9 below shows the shop layout with:

1_ Storage area
2_ Optical processing machinery
3_ 3D CMM
4_ Station for inspection, washing, bonding
5_ Integration are in ESO cell
6_ Optical test station below test tower

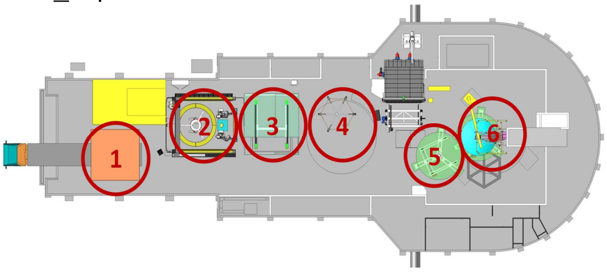

Figure 9. Organisation of the 8-m shop for ELT M2/M3

The new 4-m class optical processing machinery has been entirely designed by Safran Reosc process team and will include several features aimed to make this challenging optical fabrication more precise and productive.

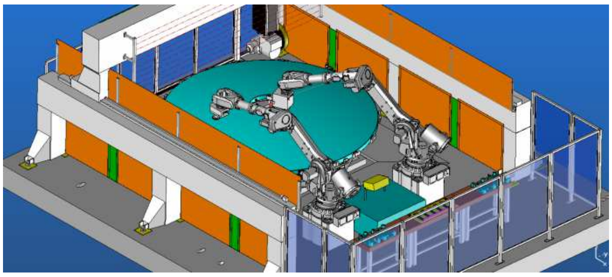

Figure 10. New 4-m class optical machinery

The machinery include a rotating table supporting the mirror resting on its laboratory pneumatic active support system and is fitted with 2 robots undertaking some of the manufacturing steps with the capability to operate at the same time, thus speeding the processing time by a factor of 2. Such dual robotic system seems to have never reported previously in the optics community and we are sure it will be for Safran Reosc a solid schedule consolidation disposition in order to produce M2 and M3 in due time for the project.

The machinery also includes a gantry structure that will operate other processing heads combining their specific processing efficiency with the one of the robot systems for the most rapid obtention of smooth, accurate and to the closest to the edge optical shape for ELT M2 and M3.

In this early 2018 civil work has been done and the machinery is to be installed by mid of 2018. The first 4-m Zerodur blank for the M2 has been cast by Schott mid of 2017 and will be delivered to Safran Reosc begin of 2019. M2 and M3 mirror shall be delivered to ESO before 2023.

4.2. The M2 mirror test bench with its reference plate

The optical testing of the large, convex and highly aspheric M2 is one of the key challenges of ELT optics. The optical specification set-up by ESO for this mirror allows some relaxation on the low order astigmatism and trefoil but it rapidly tightening the specification value when going to mid and high spatial frequencies of the residual RMS WFE errors:

Low Freq	Astig 1000 nm, Trefoil 100 nm
Mid Freq	40 nm RMS
High Freq	25 nm RMS
VHF	20 nm RMS
Roughness	2 nm RMS

The optical configuration selected by Safran Reosc for the M2 mirror optical testing is a sector shaped sub-aperture Fizeau testing with an off-axis aspheric reference plate as shown on the figure below:

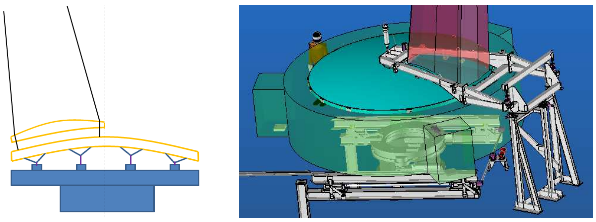

Figure 11. The ELT M2 test bench concept

The mirror is resting on its support on a vertical axis rotation table. An off-axis triangular concave aspheric reference plate, the negative of the mirror, is approached to the mirror and the Fizeau fringes are observed as some distance, in the height of the test tower, thanks to the converging (aspheric) rear surface of the aspheric reference plate. Through rotation of the mirror, several 30° sector-shaped sub-apertures of the optical surface are evaluated and a global map is reconstructed through a stitching process. The concave surface of the aspheric reference plate is measured from below at its center of curvature with a CHG. For this the reference plate is to be lifted 4-m in height.

The various challenges linked to this test bench are a) the stitching accuracy, b) the effects of the birefringence within the aspheric reference plate on the measurements, c) the proper evaluation of the low and high spatual frequency defects, d) the mounting effects and gravity effects on the aspheric reference plate and its calibration, e) the measurement time.

The sector reference aspheric plate is the critical part of the test bench. Its concave surface is the negative of the aspheric M2 mirror and shall be polished to the highest optical quality as it acting as the reference for the measurements. But its convex surface is also aspheric, freefrom in fact, with a very high amplitude of 3,9 mm on the useful area (6,4 mm in total). However, its polishing quality is relaxed because its function is simply to re-image the interference fringes towards the interferometer's head. It remains that this large, aspheric sector test plate is probably the most challenging optical test component ever produced.

A high quality Zerodur blank has been procured from Schott with best internal quality (bubbles, inclusions, birefringence, striae, etc.) in order to not affect the fringe re-imaging function of the reference plate.

At the date of the conference, the plate in undergoing its first runs of robotic lapping and polishing as shown on the image below.

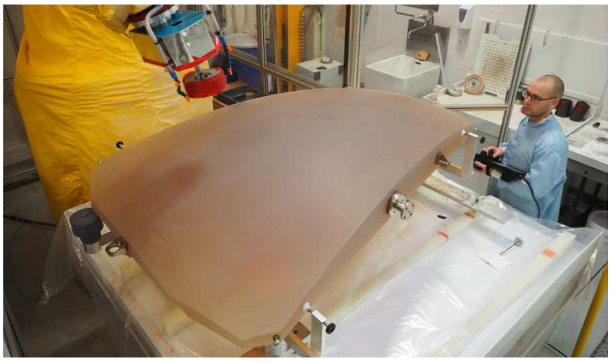

Figure 12. The M2 sector aspheric reference plate installed for first robotic lapping cycles.

The reference plate is to be finished and calibrated by begin of 2019 in order to be used for the first measurements on the M2 at this time.

5. The M1 segments

The ELT segmented M1 mirror is made of 798 hexagonal off-axis segments as shown on the figure 12. This is the result of 133 different segment types arranged with a six-fold symmetry. In addition ESO is asking for one more set of 133 spare segments to be processed. Therefore the contract for the M1 segments polishing and integration is representing by far the largest volume of activity for Safran Reosc with a total 931 1.5-m class optics to be processed through the next 5 year, with 3 years full rate production.

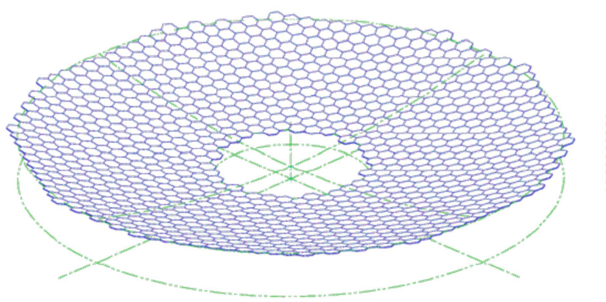

Figure 13. The ELT segmented M1 (798 segments)

The segments are thin meniscii of 50 mm thickness and of hexagonal contour with 1.45-m peak to peak dimension.

The ELT M1 is a fast mirror with a base radius of curvature of 68,685 meters, i.e. F/0.9 relative aperture. The aspheric shape is close to a parabola, in fact an ellipse, with a -0,996573 conic constant value. With these parameters ESO has set the amount of aspheric departure from the closest sphere similar to the one of the Gran Telescopio Canarias 42 M1 Segments polished by Safran Reosc in the period 2003-2005.

This similarity with the GTC segments and the demonstration with 7 proto ELT segments polished by 2010 make Safran Reosc fully confident in achieving the required optical performances:

WFE	< 15 nm RMS (goal 10)
Edge effect	< 200 nm PTV / 10 mm
Radius match	< 50 nm RMS in WFE

The last activity to be performed by Safran Reosc on the ELT M1 segments is their integration on their wiffle tree support systems delivered by ESO to us. It is known that this integration process does generate a tiny deformation of the mirror. Therefore a final figuring run might be conducted after integration and each segment will remain attached to its support during its whole life, i.e. even during transportation and periodic cleaning and coating operations.

Figure 14. First ELT proto segment integrated on its support (in 2010)

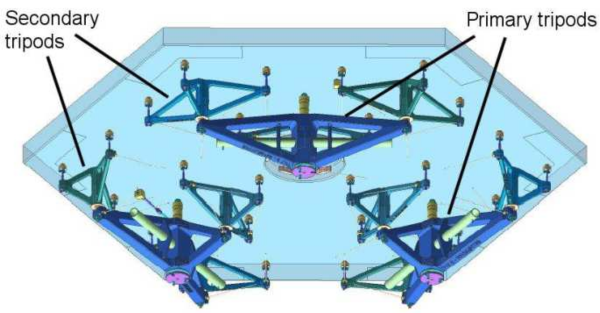

Figure 15. The 27 point wiffle tree support

5.1. Industrialization of the M1 segments optical processing

As stated above, the ELT M1 segments are similar in term of optical difficulty to the one of the GTC. The similarity is also found in the process chain we intend to apply for the production of these parts shown on the figure below.

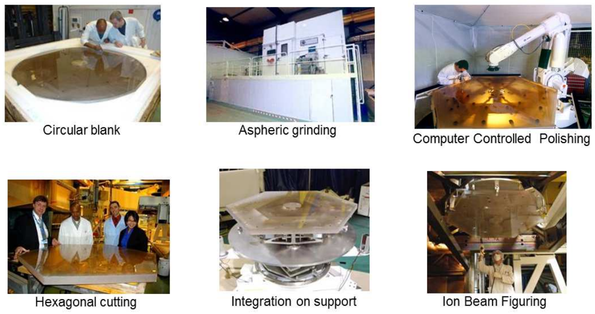

Figure 16. The process sequence for the M1 segments

The real challenge for Safran Reosc is now linked to the industrialization of these processes and their real implementation within an existing facility made available for the project by SAFRAN in the plant of Poitiers. For this we are getting the full and efficient support of SAFRAN since the tender phase: black belt experts for industrial process analysis and optimization, civil engineering team for the building preparation and modification, purchase team for the many procurements, IT workforce for the production management system, etc. No less than 50 employees will operate there quite a hundred of equipment, with more than 40 of them beeing robotic or automatic.

Most of the machinery has been defined and is under procurement at this date. The facility will be fully fitted by 2019 to start producing the the first segment, then enter low rate production and later accelerate to full speed production of one ELT M1 segment per day during the years 2020 – 2023.

5.2. The M1segments test bench

Again the optical test bench is representing a critical part of the project. All the 931 segments will undergo several optical test sequences during the production. The related challenges are:

- Coping with the 133 different types of segments
- Performing the measurement in short time, our target beeing set to less than 2.5 hours.
- Measuring segment integrated on its support.
- Delivering a high accuracy below 10 nm RMS WFE along with a high spatial sampling of 512x512 pixels min.
- To be operated in a quasi-automated manner by non expert production technicians.

The concept of the test bench is based on a spherical convex reference plate covering the full aperture of the segment and placed to the segment surface. Various CGH and an innovative optical configuration of fringe acquisition allow the testing each of the different 133 segment types.

The bench is arranged vertically within a short tower as shown on the sketch below.

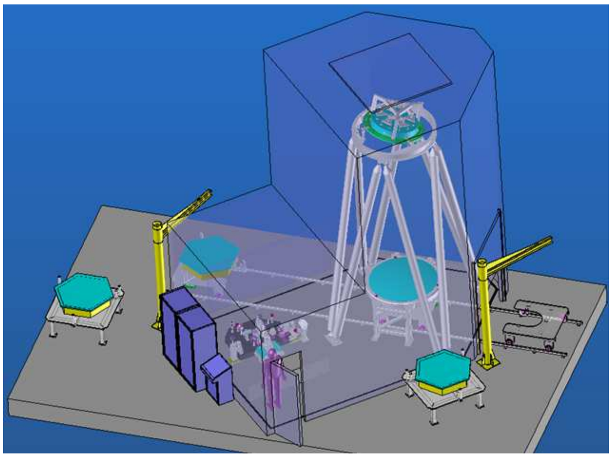

Figure 17. The M1 segments test bench

At the date of the conference the reference plate substrate material is under procurement and the bench still under engineering and design.

5.3. Pads bonding

Last but not least, Safran Reosc is responsbible of all the Invar pads bonding operations onto the Zerodur substrates. There are on each M1 segments 27 axial pads, 12 edge sensor pads and 6 lateral pads. The M2 and M3 are each equipped with 54 axial pads and 14 lateral pads. This leads to a total of nearly 50.000 pads to be bond on glass during the next 5 years of the project.

Safran Reosc holds again a solid heritage on the subject with 1500 pads bonded on the VLT mirrors and 1900 pads on the GTC segments but difficulties encountered on the Keck segments since some years makes our customer ESO particularely concerned about the quality of these bonding operation and the 30 years lifetime expected for these operations.

Therefore the ELT project also includes a deep qualification process of this bonding operation as well as its industrialization to be compatible with the production rate of 1 segment / day. Again, SAFRAN specialists on the subject are helping us to combine our successful VLT/GTC heritage with aerospace serial production methodologies.

Today a detailed bonding qualification plan has been prepared for ESO and wil be developped in the coming months.

6. CONCLUSION

The Extremely Large Telescope has entered in its construction phase and Safran Reosc has been awarded the contracts for the optical polishing, testing and integration for the M1, M2, M3 and M4 mirror units.

The gain of these majors contracts is the logical follow-on of the successful conduction of the ESO VLT 8-m and the GTC M1 segments polishing contracts as well as accurate demonstrations of capability made for ESO with thin shells and prototype ELT segments.

Safran Reosc is benefiting from full support from SAFRAN to run these various projects. 40 engineers and technicians are hired at Saint Pierre du Perray to conduct all the engineering, machinery definition, procurement and installation and the M2, M3 and M4 contracts.

In the industrial SAFRAN site of Poitiers, the facility for the mass production of the M1 segments is under preparation to receive in 2018 all the machinery and test equipment for the project. Then, up to 50 engineers and technicians will be hired and trained to run the optical polishing, testing and integration of these unique optics with progressive production rate acceleration up to 1 ELT M1 segment per day. Observing the unique acceleration of aircraft motors production undertaken by SAFRAN presently we have no doubt that Safran Reosc will also succeed in its similar challenge in the domain of precision optics for astronomy.

Our management is puhing these project while preserving, and developping, our company power in the other domains of space, laser, defence and thin films.

We thank ESO for its confidence placed in the company and in the SAFRAN Group. We thank the various Safran Reosc engineers and technicians who have prepared for more than 10 years the company for catching these four ELT challenging and exciting projects, still and again in the pionneering spirit of our founders Henri Chrétien and Charles Fabry, 80 years ago.

7. References

(1) R. Geyl & al, Safran Reosc, “Thin glass shells, a new type of optical component”, EOS conference on Manufacturing of optical component, Munich, May 2013.

(2) J. Rodolfo & al, Reosc, “Segment polishing & testing for the ELT primary mirror”, SPIE Astronomy & instrumentation, Amsterdam, 2012.

(3) R. Geyl & al, Safran Reosc, “ELT critical optics technology readiness”, AOMATT conference Harbin, 2014.