REOSC contribution to VLT and Gemini

Roland GEYL, Marc CAYREL

REOSC High Performance Optics Department of Sfim – SAGEM Group
Avenue de la Tour Maury 91280 Saint Pierre du Perray, France

ABSTRACT

This paper report the development and production activities performed at REOSC during the years 1989 – 99 related to the VLT and Gemini large telescopes projects.

Key Words : VLT, Gemini, large optics, aspheric, active optics, polishing, testing, lightweight, Beryllium, SiC.

1. INTRODUCTION

During the last 10 years REOSC played a major role in the development of the new generation of 8-m class telescopes to be installed before the end of this millennium :

In 1989, REOSC was selected by the European Southern Observatory (ESO) organization for the polishing of the four 8-m primary mirrors of the Very Large Telescope (VLT) project.

In 1993, REOSC was awarded by the Association of Universities for Research in Astronomy (AURA) with the contract for the polishing of the two 8-m primary mirrors of the Gemini project.

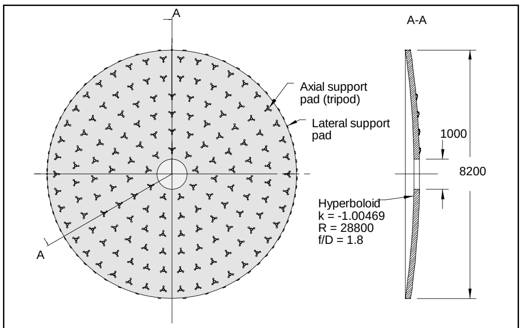
In 1993, REOSC was selected by DASA-DORNIER for the design, fabrication and polishing of the first 1.12-m VLT secondary mirrors in Beryllium. In a later contract directly with ESO, REOSC produced the last three M2 mirrors.

Also to be noticed is the activity performed by our parent Division Sfim, in cooperation with Giat Industries, on the design, fabrication and test of the VLT M1 mirror passive and active supporting system.

In this paper we will briefly present these two projects and their primary mirror specifications. Developments conducted to set up our 8-m polishing facility and validate the transportation containers will be presented. Results and project status at the date of February 1999 will be reported. The M2 mirror specifications and material problematic will also be briefly presented as well as the associated specific design activity and optical test set up installation.

2. THE VERY LARGE TELESCOPE PROJECT

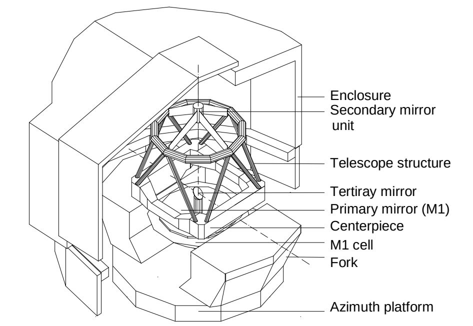
The Very Large Telescope (VLT) project is an array of four 8m telescopes installed on top of Cerro Paranal in Chile. They will be operated either independently or in interferometric mode. Unit telescopes are of the Ritchey-Chrétien type, with the pupil on the secondary mirror. The primary mirrors are 175 mm thin menisci. Their shape is actively controlled by means of 150 axial force actuators, driven by the wavefront sensors located off-axis on the image surface. Laterally, the mirrors are maintained by 64 lateral pads.



VLT 8 meter Primary Mirror

The 23 tons VLT primary mirrors are in Zerodur produced by Schott Mainz (Germany).

The blanks have been delivered to REOSC in 1993, 94, 95 and 96.



VLT Unit Telescope in its enclosure

The VLT M1 mirrors optical specifications : The optical figuring specifications of the VLT primary mirrors take into account the presence of an active mirror support and the effects of atmospheric turbulence. REOSC shall therefore use the active support during final tests within a limit of ± 120 N to remove some low spatial frequency figuring errors. In addition, the first three natural modes are limited in peak-to-valley amplitude.

The high spatial frequency errors are specified by the Central Intensity Ratio (CIR) higher than 0.82 after a perfect active correction with the 16 first natural modes. The CIR can be calculated by a convolution of the diffraction pattern in a vacuum with the atmospheric Point Spread Function. The main optical specifications are summarized here :

Radius	: $R = 28800 \pm 100$mm	Conic constant	: $\varepsilon = -1.00469$
Force variation	: < 120 N	CIR	: > 0.82 ($\lambda = 500$nm, $r_0 = 500$mm)
Micro roughness	: < 20 Angstrom RMS	Cosmetic defects	: scratch dig 80/60

The mirror huge flexibility can be assessed by the fact that no more than 1.6 Newton force can induce 4 microns wavefront PTV astigmatism.

3. THE GEMINI 8.2 M TELESCOPE PROJECT

Gemini is a project of two twin 8.2 m telescopes conducted by the Association of Universities for Research in Astronomy (AURA). The first is telescope is installed on top of Mauna Kea in Hawaii. The second will stay in the southern hemisphere on top of the Cerro Panchon in Chile.

The unit telescope is of Cassegrain type with all instrumentation installed behind the primary mirror. The primary mirror blanks are made from Corning Ultra Low Expansion (ULE) material and have been delivered to REOSC in 1996 and 97. The blank thickness is 200 mm, slightly more than VLT, but leading to a similar flexibility due to a ULE Young Modulus lower than Zerodur.

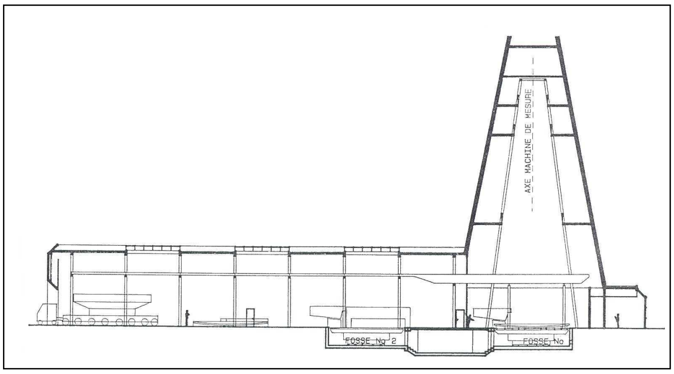
The primary mirror support is a combination of a large air pressure supporting system uniformly sustaining 80% of the weight of the piece and a set of 120 axial pads to achieve active shape error correction.

The Gemini M1 mirror optical specifications: The critical item of the Gemini mirror optical specification is expressed in terms of encircled energy and amplitude of satellite images around the central PSF. The main optical specifications are :

Radius	: $R = 28800 \pm 30$mm	Conic constant	: $\varepsilon = -1.00376$
Force variation	: < 100 N	Encircled energy	: 80% light in 0.1 arcsec diameter
Micro roughness	: < 20 Angstrom RMS	Cosmetic defects	: similar to scratch dig 80/60

4. THE OPTICAL SHOP AND ITS MACHINERY

Within the three years that followed VLT contract award (1989), REOSC designed, built and equipped a dedicated optical shop. It is located in the city of Saint Pierre du Perray, about 45km southern Paris and close to the Seine river to reduce transportation problems.



The building erection was achieved in April 1992. The shop is a 70-meter long building of about 1100m² total floor area with a 35-meter high tower at one end above the polishing machine. The shop also includes a grinding zone, a storage zone and a downloading zone. Offices are placed around the polishing zone.

A key feature of the shop is the presence of **two identical surfacing machines** : one for grinding and one for polishing. This allows to process two 8m class mirrors in parallel enabling a maximum production rate of two mirrors a year.

The turntables : Each machine comprises a 5-meter diameter large turntable capable of handling 100 metric tons. These are hydraulically driven, fully computer controlled and installed 1 meter below the ground so that the mirror surface comes to a comfortable 75cm height.

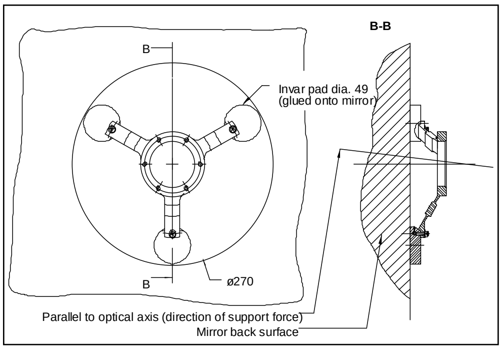
A milling bridge can move from the grinding to the polishing zone and is used to generate the curve, to help accurate setting of the axial supporting actuators and to the handling of the spherometer for mechanical measurement of the optical surface.

The surfacing arms drive the lapping and polishing tools over the mirror surface. The arms are hydraulically driven for smooth and precise movement and are fully computer controlled through encoders located at the « shoulder », « elbow » and « hand » articulations. In combination with the turntable control, the machine driving software is able to monitor the position, speed and time spent by the polishing tool over the mirror surface at any moment. In addition, an hydraulic actuator located at the hand of the arm allows the application of a downward positive or negative force to control the polishing pressure or to lift up the tool once the polishing run is over.

The traveling crane is used to move the 24 tons mirror and the various tools through the 70m long and 12m wide shop. Precise tip tilt adjustments and load transfer of the part are monitored through indicators.

Internal view of the optical shop

5. DEVELOPMENT OF THE VLT MIRROR TRIPODS



REOSC optimized, in cooperation with ESO, the interface between the axial actuators and the mirror blank. This is a tripod assembly which, by inducing local bending moments, reduces by a factor 3, down to 16 nm RMS, the 50 nm RMS wavefront high spatial frequency print through obtained otherwise with a simple point like support.

Our first task for VLT is therefore to bond, with less than 0.1 mm error, 3 Invar pads per actuator, i.e. 450 pads in total, on the rear face of each blank. Then, the tripods are fixed to these three pads.

Another use of the tripods is to act as a fuse protecting the fragile piece of glass in case of any failure or error within the active support system.

6. HANDLING AND TRANSPORTATION MEANS

REOSC is in charge of taking the huge and fragile blanks from the glass manufacturer's plant to the polishing shop and, for Gemini, of the delivery on site. Safe handling and transportation of the mirrors was therefore a critical issue that drove most of the engineering work of the project. The key parameter is the glass acceptable internal stress level fixed by Schott to the value of 5 MPa. It is to know that, resting on 3 points at its periphery, the glass blank develops internal stresses up to 20 MPa and is therefore very likely to break under these conditions.

The handling tool is designed to handle the mirror quickly and with minimum risk. 15 C clamps take the mirror's weight around its periphery and in the center hole with a wifle tree system. The stress stays below 1.3 MPa.

The transport container has been subject to a detailed dynamic F.E. analysis in order to ensure the highest safety level for the blank under all the road, boat, dock cranes loads. A dummy concrete mirror has been fabricated and used to run a dummy transportation in order to verify the computations assumptions. The mirror stays on 24 thick rubber pads and is laterally maintained by a strong central plug. Inclinations up to 45° are allowed.

7. ACTIVE METROLOGY MOUNT

ESO and AURA have asked REOSC to present the mirror to final acceptance on a mount precisely representative of the true active cell of the telescope. Both lapping and polishing machines have been equipped with a set of 150 pneumatic actuators, located at the specified position and driven in force to an accuracy better than 2 N. Uniform pressure or partial active correction can then be applied to the mirror in real time during the tests.

Of course, when the shop switched from VLT to Gemini mirrors, the metrology mount was re-arranged with only 120 actuators and fitted with the air pressure supporting system required by AURA.

These active mirror mounts have been used daily since 1993 and were in fact the world's first 8-m class active support ever built.

8. OPTICAL FIGURING AND TESTING

Computer controlled figuring technique The REOSC computer controlled figuring technique uses flexible laps of various shapes and dimensions ranging from 1 to 4-meters. They are driven by the surfacing arm in a ρ,θ like configuration. The table rotation speed, the arm oscillation speed, amplitude and orientation, combined with the pressure exerted on the tool allow a precise control of the amount of material removed on each point of the surface according to the measured optical error map.

Ground surface testing The ground surface is tested with a REOSC patented bidimensional spherometer. A square, lightweight, stiff CFRP structure holds 3 fixed points and 5 sensors. The zero is taken on a 1.7m diameter reference spherical mirror and the spherometer is moved along several diameters of the surface. The recorded data are processed through a specific software to obtain the radius of curvature and the residual figure error map. An excellent accuracy of 0.5µm RMS over the 8-meter is obtained by the method.

Vibration and thermal insulation of the test tower Particular attention was given to the mechanical and thermal stability of the test tower. A first external structure holds the elevator and the upper floor where technicians can walk. It damps the wind pressure and induced vibrations and ensures at the same time a first level of thermal insulation. A second internal structure only supports the optical bench and preserves it from vibrations. Finally, a conical skirt is suspended over the mirror to further enhance the thermal equilibrium and maintain a stable and axisymmetric vertical air gradient.

IR and visible Interferometry Once installed under the test tower, 10.6 µm interferometry can be conducted through an Offner type null lens with ZnS elements. Once possible, we switch to HeNe visible interferometry. The Offner type null lens used there was designed, toleranced and fabricated with the highest accuracy. A final optimization based on the real index, radii of curvature, thickness and lens spacing values was conducted in order to reach the required wavefront error budget of 30nm PTV.

The interferometric data are processed via our FLow Interferogram Processing (FLIP) technique. This allows to catch the fringe pattern and process it with a high accuracy and dense sampling despite the residual vibrations. Other specific software were developed to average the measurements, compute and extract the mirror natural modes, evaluate the CIR, satellite images intensity, etc. ESO also required Shack Hartman measurements.

Doing a cross test In order to avoid any risk of wrong aspherical departure of the mirror, alternate tests have been run. This is the conventional Hartmann screen test.

9. WORK PROGRESS AND RESULTS

Some key dates for the VLT & Gemini projects

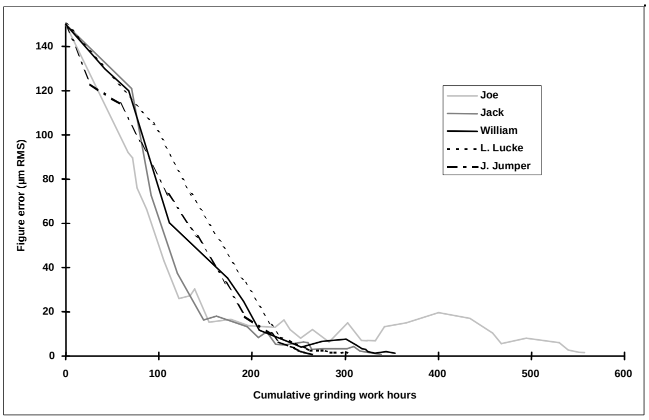
VLT contract date : July 89	Shop inauguration : April 92	Dummy mirror transportation : June 92
Arrival of VLT blank #1 : July 93	Gemini contract date : March 94	

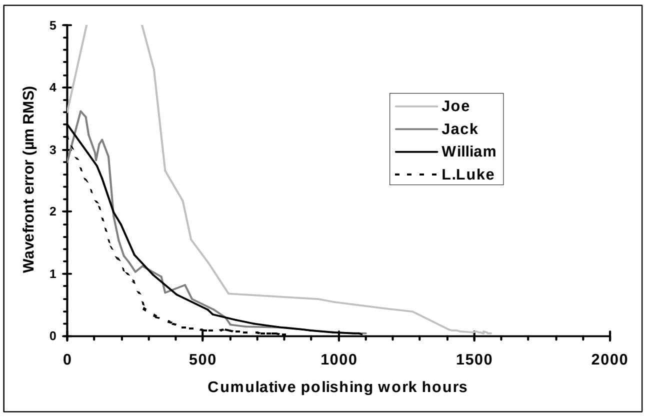
Spread of Technical Acceptance dates :

VLT #1 (Joe)	: Nov. 95	VLT #2 (Jack)	: June 96	VLT #3 (William)	: April 97
Gemini #1 (Lucky Luke)	: Feb. 98	Gemini #2 (Jolly Jumper)	: Dec. 98	VLT #4 (Averell)	: Oct. 99

An average production rate of 1 mirror of 50 m² active area every 10 months appears clearly.

Convergence upon grinding and lapping As it is generally the case, there was a learning effect and results went better and better with less and less production time. Joe was the pathfinder and suffered, after 320 hours, from a severe scratch that required to remove about 0.2mm material. Grinding work was generally stopped at an RMS figure error level around 1.0 µm RMS. Then the lateral pads were bond around the blank periphery.





Convergence upon polishing Once transferred to the polishing machine, polishing was performed with minimum figure loss and final figuring conducted to reach the optical specifications. Again Joe was the pathfinder perturbed by the non uniform angular distribution of the lateral pads that generates some astigmatism.

The final quality of all the mirrors produced was well within the specifications with RMS surface figure errors ranging from 24 nm for VLT #1 down to 15.5 nm for Gemini #1.

10. THE VLT SECONDARY MIRRORS

By end of 1994, the company DORNIER was selected by ESO for the design and fabrication of the four VLT Secondary Mirror Electro Mechanical Units (EMU) with REOSC as subcontractor for the design and fabrication of the first VLT M2 mirror assembly.

The M2 Mirror Assembly specifications The EMU has to ensure Focusing and Centering of the M2 mirror for image quality purpose and fast Tilt for image stabilization in the telescope and chopping for IR observations. This leads to severe optical and mechanical requirements for the mirror assembly. The main are :

Mechanical requirements :		***Optical requirements :***	
External diameter	: 1120 mm	Radius of curvature	: 4553.57 mm ±10 mm
Mirror weight	: ≈ 42 Kg	Conic constant	: -1.66926
Mirror assembly inertia	: < 4.0 N.m²	Useful ext. opt. diameter	: 1116 mm
Mirror assembly 1st freq.	: > 380 Hz	Optical quality	: CIR > 0.98 (r_0 500 mm; λ 500 nm)
Stability	: 25 years		

Mirror material selection Low weight and inertia, high stiffness, high optical accuracy over 25 years are very demanding specifications not fulfilled by many material. Glass being not adequate, there was only the choice between Silicon carbide and Beryllium. But SiC technology was not mature on one meter class at that time (UTOS just disappeared). Beryllium, despite its excellent performances was also seen with some fear about its stability over time and cost.

Many comparisons can be made between these two materials but the real key parameter is in fact the capability to produce the required lightweight structure satisfying size, weight, inertia and stiffness requirements with no or reduced development risks and at attractive costs. SiC was penalized with its high density (ρ ≈ 3) requiring the fabrication of very thin ribs to stay within mass budget. This is a source of fabrication risk for large diameter substrates. The other risk linked to the project is the long term stability and there, despite the fact that no true data was available for SiC at that time, Beryllium was more subject to suspicion.

Decision went in favor of Beryllium. Today, the technology has progressed in the domain of SiC material and the choice might be different but a project like the VLT could not wait long for technology progress.

Beryllium grade selection For optimum cost - performance ratio we selected I220H Beryllium powder grade. This is not an optical grade and therefore a Nickel plating had to be applied in order to allow the achievement of 2 nm micro roughness and to avoid the material toxicity problems during polishing.

Dimensional stability critical analysis Extensive efforts were spent to ensure the best dimensional stability of the blank over time. This is first linked to material homogeneity ensured by Hot Isostatic Pressing (HIP) of impact ground Be powder. Microyelding and microcreeping were mastered by appropriate chemical composition. Internal stresses were reduced by extensive care taken during all the fabrication steps and addition of judicious annealing, thermal cycling and acid etching operations along processing.

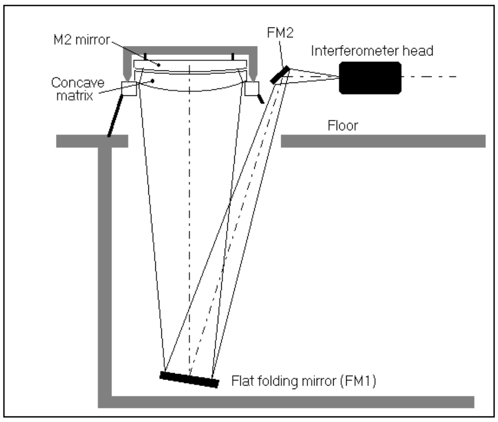
The mirror Nickel plating As explained, the electroless Ni plating is required to achieve the proper microroughness of the optical surface. However, all care had to be taken to avoid all instabilities due to CTE mismatch with the Beryllium and instability of the Nickel layer itself.

A compromise has been found for the phosphorous content, the plating thickness and the post-plating heat treatment temperature in order to achieve low residual stress level and close CTE match. The plating process has been accurately monitored by controlling the bath temperature, pH, phosphorous and Nickel content. Plating both front and rear mirror surfaces minimized the amplitude of the mirror distortion.

The stress in the front surface layer was also reduced thanks to several thermal cycles performed during figuring.

Mirror design The lightweight structure design was optimized with analytical tools and FE computations. Finally a simple plano convex shape with triangular open back cells was chosen. Center thickness was 130 mm. 6 interfaces with the isostatic mounts were machined for using only 3.

Blank machining The first blank was machined at LORAL American Beryllium after careful validation on wax pieces of all critical steps, for example the mount interfaces machining.



The optical test set-up A full pupil optical test set-up was designed and built to test the convex aspherical surface. As shown on the sketch this was done with a 1250-mm diameter Zerodur matrix being the exact negative of the mirror. The fringe pattern is collected by the rear side of the matrix towards the interferometer head at 14 meter distance.

Mirror polishing and performances The mirror was lapped gently in order to not go through the Ni layer and polished with conventional and Computer Controlled Polishing (CCP). An edge lip was cut by Electro Discharge Machining (EDM) to bring mechanical and optical diameters very close but generated some distortion. This was removed with a further CCP run.

A final CIR of 0.982 was reached with less than 9 nm figure error of the optical surface in active mode, i.e. after removal of the first 16 modes of the primary mirror.

Final thermal cycling allowed us to evaluate the long-term stability of the figure to ¼ fringe low spatial frequency defect like focus or astigmatism, easily removable with the primary mirror active optics.

VLT M2 #1 has been delivered in Dec 1996. Mirror #2 in Sept 1998. Mirrors #3 and 4 are today in progress and scheduled for end 99 and end 2000.

11. CONCLUSION

VLT and Gemini were two exciting projects with many difficulties solved with deep engineering and challenging fabrication effort. REOSC is proud to have established on these projects new standards in large optics fabrication and testing. It is worth to notice that all the work presented here was conducted within specification and schedule under firm fixed price contracts spanning over up to 10 years.

12. ACKNOWLEDGMENTS

REOSC wants to thanks ESO and AURA for having given their confidence in the company. Special thanks to :

The ESO representatives for VLT : P. Dierickx, S. Stanghellini, D. Enard and M. Tarenghi.
The AURA representative for Gemini, L. Stepp
J. Espiard, former General Manager, who initiated the project in REOSC and still acts today as a consultant,
J. Paseri, REOSC Chief Engineer, who did most of the conceptual design of the shop, machinery and tools,
R. Paquin and T. Parsonnage (Brush Wellman), who helped to secure the M2 Be blank fabrication, Ni plating and stabilization sequences.
All REOSC engineers and technicians whose dedication to the projects were major contributors to success.

13. REFERENCES

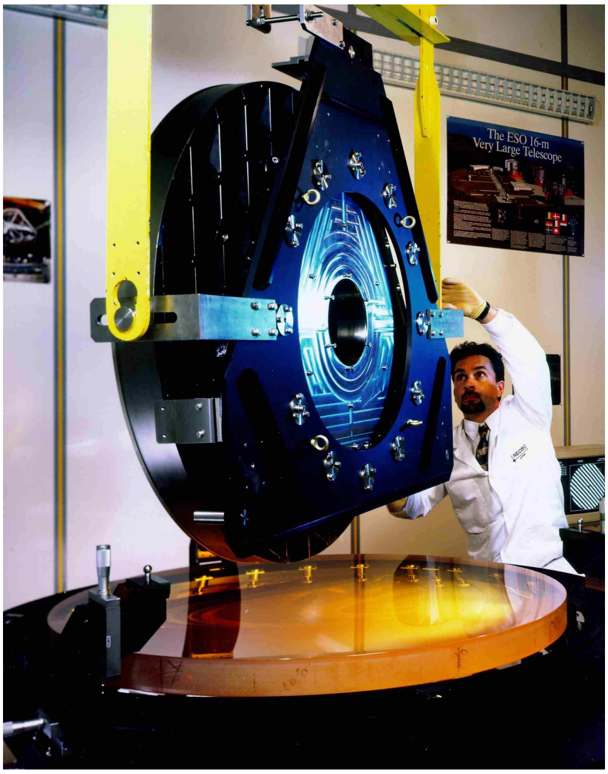
R. Geyl & P. Dierickx, 1995, SPIE Vol 2536 Optical Manufacturing & Testing, p 413-420.

M. Cayrel, "VLT Beryllium Secondary Mirror N°1 - Performance Review" in SPIE Vol 3352, p 721-728.

R. Geyl, M. Cayrel, "The Very Large Telescope Secondary Mirror – A Report" in SPIE CR67.

T. Hovsepian, J.M. Michelin, S. Stanghellini, "Design and Tests of the VLT M1 Mirror Passive and Active Supporting System" in SPIE Vol 3352, p 424-435

A VLT mirror under polishing



The VLT M2 mirror placed in front of the matrix