# The Secondary Mirror Units of the VLT: Design Overview and Manufacturing Status

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## Introduction

The M2 Unit, with the secondary mirror and its mechanics, plays a central role in the on-line active control of the optical train of the VLT. The secondary mirror has a diameter of 1116 mm; it is slightly undersized as required for IR observation, and it defines the telescope pupil. The complete mechanical unit is located in the shadow of the secondary mirror, as seen from the telescope focus. The unit is also equipped with a deployable sky baffle.

As part of the active optics loop of the telescope, the M2 Unit will correct two optical aberrations: the defocus and the decentring coma. Both of these are linked to the deformation of the telescope tube and of the optical train under the effect of gravity and thermal espansion. In addition, it has fast steering mirror capability to correct tracking errors outside the bandwidth of the main telescope drives and to perform field chopping during infrared observations.

The design of the M2 Unit and the manufacturing of the aspherical secondary mirror represent a considerable technical challenge. This is, amongst others, linked to the dynamic performance requested from the secondary mirror and to the general requirements of the VLT programme.

After having performed feasibility and development studies, ESO issued in 1993 a call for tender for the procurement of the M2 Unit, with a light-weighted mirror of Beryllium or Silicon Carbide, materials both judged suitable for a mirror with the required performance. In September 1994, following difficulties with the procurement of the initially selected Silicon Carbide blank, ESO awarded a contract to the German company Dornier Satellitensysteme GmbH for the procurement of the four M2 Units and of the first secondary mirror in Beryllium. Dornier retains the overall system responsibility and subcontracted the mirror design and manufacture to REOSC Optique. In June 1996, ESO awarded a contract to REOSC Optique for the procurement of three additional Beryllium mirrors.

## Major Mechanical Requirements and Design

The position of the secondary mirror must be controlled in five degrees of freedom. The mirror accuracy and stability requirements are linked to the optical design of the telescope and to the optical error budget. A stiff M2 Unit mechanical design and very limited cross talk between the kinematic functions are required. During tilt and chopping it must also be ensured that no reaction force is transmitted to the telescope spiders which, being optimised for low beam obstruction and wind cross-section, act as a flexible support. To avoid any excitation of the spiders, the tilt and chopping mechanism is equipped with a reaction force compensation device.

Of particular importance is also the reproducibility of the zero position of the mirror when the tilt and chopping mechanism is not in operation to ensure accurate blind pointing of the telescope.

The final design developed by Dornier is shown in Figure 1. The complete mechanical and electronic units are located inside a welded plate steel structure interfacing the spiders and creating a rigid, closed environment for the mechanisms and the electronics. In kinematic terms, the design includes a separate-stage architecture with focusing, centring and chopping stages in cascade.

### *Focusing Stage*

Focusing is performed by moving M2 in steps along the telescope tube axis when a pre-defined focus error budget is exceeded, as detected by the image analyser. An accuracy of 1 µm is demanded. The focus drive of the M2 Unit acts on a focus trolley sliding on linear guides and moves together with

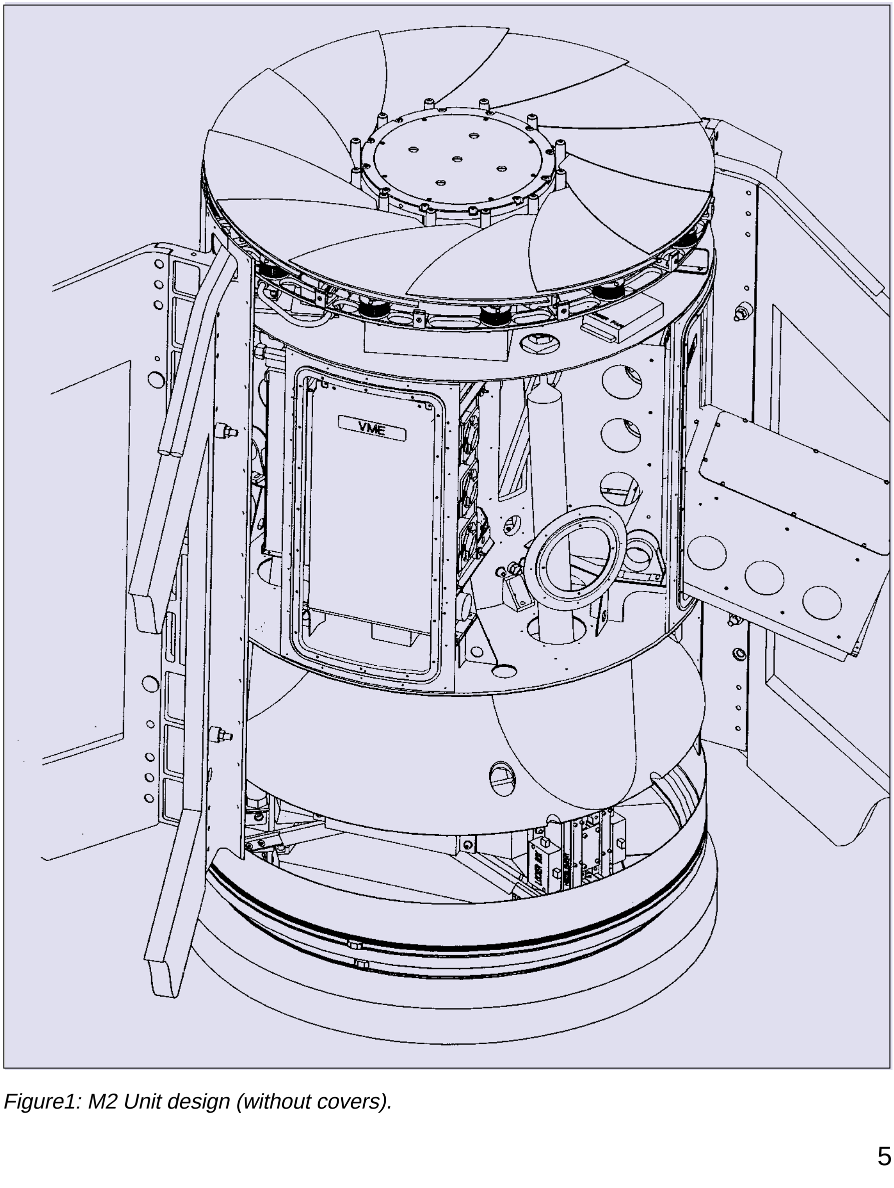


*Figure1: M2 Unit design (without covers).*

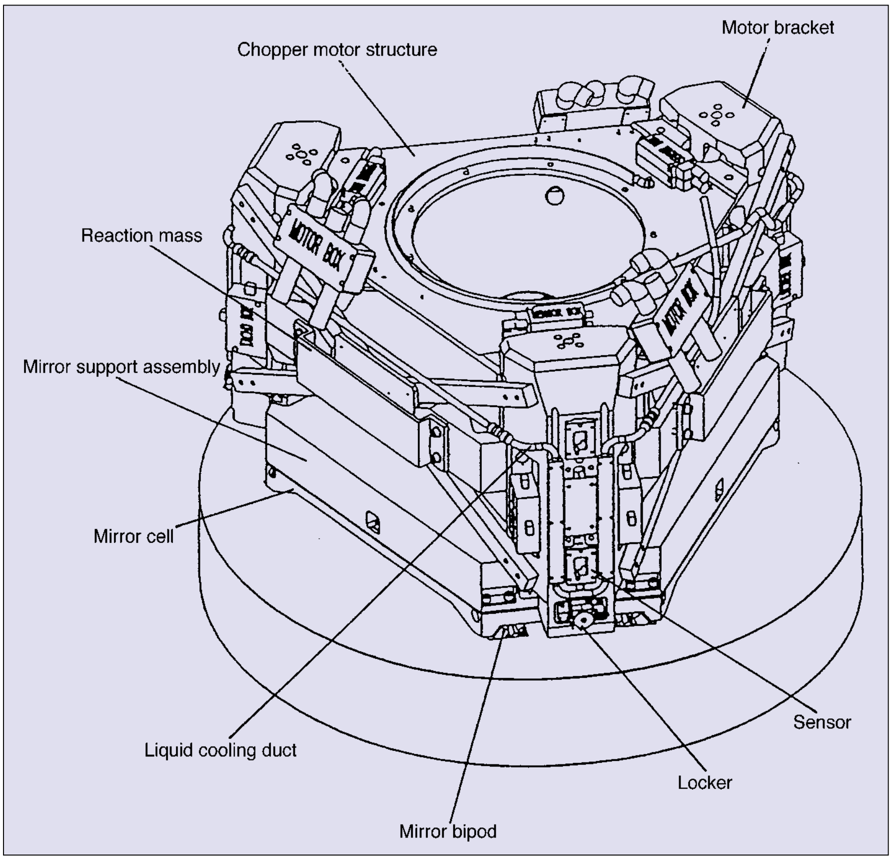


*Figure 2: Chopper assembly.*

the centring stage, the tilt and chopping stage, and the mirror. The linear bearings, optimised for stiffness, low friction and hysteresis, are carefully prestressed by means of cylindrical wedges. Strain gauges are permanently installed on the bearing races to monitor the prestress and to allow checks and maintenance during the operational life of the M2 Unit. The focusing drive can be removed on line and replaced as a single unit.

### *Centring Stage*

Centring is performed by moving the M2 around its centre of curvature which is located 4.5 m behind the mirror vertex. Similarly to defocus, the decentring coma, which is an aberration caused by the misalignment of two optical systems, is generated by mechanical flexures. Centring errors will be corrected by moving M2 in steps (accuracy 0.3 arcsec) according to the error measured by the image analyser.

The mechanical design is based on two oppositely mounted eccentrics, one fixed to the focusing stage and the other fixed to the chopping assembly. The movement along the centre of curvature of the mirror is imposed by a pantograph realised with three centring bars equipped with flexures and oriented towards the centre of curvature of the mirror. To obtain the desired stroke, the two eccentrics are moved in opposite directions, while to obtain the desired direction of the centring motion, the two eccentrics are rotated in the same sense. Thus the entire chopper structure moves on the surface of an ideal sphere centred on the centre of curvature of the mirror.

### *Field stabilisation and Chopping*

The tilt of the mirror is used for “field stabilisation”, which is the correction of the residual tracking error of the telescope in continuous mode by means of the M2. It is driven by the signal obtained from the autoguider or from the instrument. The system, required to operate up to 10 Hz, will allow correction of atmospheric image motion and of wind buffeting.

Chopping is kinematically identical to field stabilisation. A maximum chopping frequency of 5 Hz with a throw of 0.5 arcmin, and a duty cycle $\geq$ 80 % are specified. The chopping axis of the M2 rotates to take into account the field rotation due to the Alt-Az mount of the VLT.

The tilt and chopping stage is shown in Figure 2. It consists of a fixed structure, the mirror support assembly and the reaction mass. The mirror support assembly is equipped with three linear motors, which are able to develop 450 N peak force, mounted directly above the three supports of the secondary mirror. A similar arrangement is used for the reaction mass. The moving assemblies tilt around a mechanical pivot. During operation the reaction forces from the mirror assembly and from the reaction mass, driven in opposition of phase, are equal

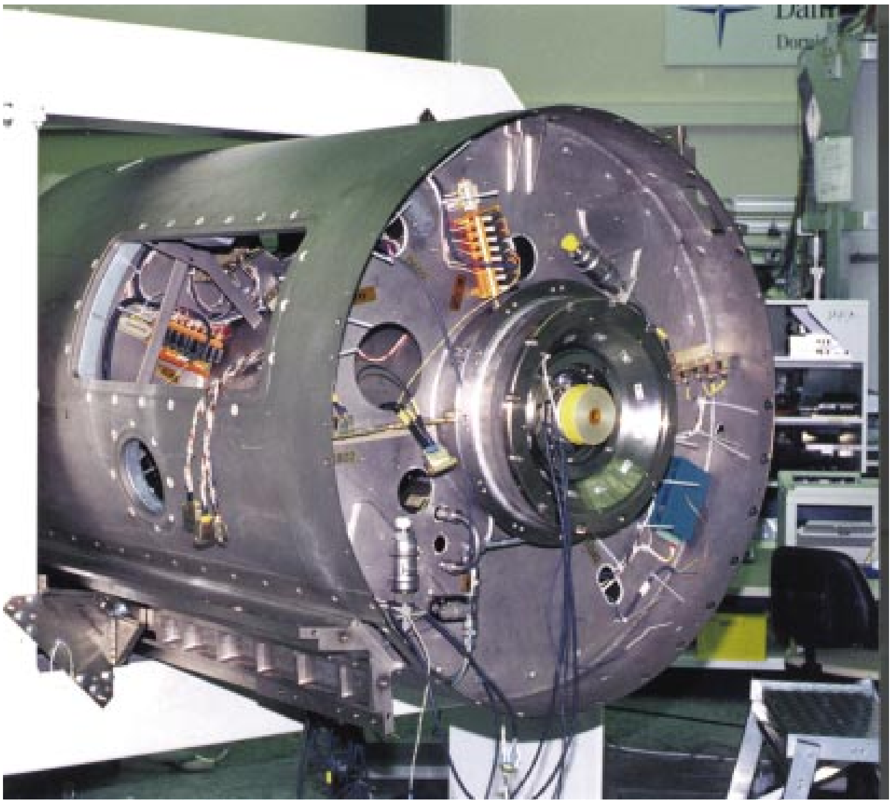


*Figure 3: The M2 Unit in the integration stand.*

in magnitude and opposite in direction so as to achieve a net zero force and moment on the structure. This requires the coincidence of the pivot with the centre of mass of the moving assembly, obtained by design first, and by adjustment later. The system uses optical incremental encoders with 8 nm resolution, mounted together with the tachometers in a small sensor assembly, optimised to eliminate resonant frequencies below 2000 Hz. A low value of the inertia of the moving masses was achieved through the use of Beryllium for the mirror, and Titanium for the mirror support assembly.

## Control Electronics

The M2 Unit contains its own Local Control Unit (LCU) This demands careful use of the space inside the unit, but minimises the cables and the connectors to be routed along the telescope spiders. The LCU electronic cabinets can be accessed through openings in the mechanical housing.

The control system of the tilt and chopping stage uses two independent servo-loops, controlling two of the motors (masters), while the third one (slave) is commanded in such a way that the reaction force which is applied on the pivot is kept equal to zero. Each of the two servos consists of a speed loop within a position loop. The reaction mass is controlled in a similar way to eliminate dynamic reactions to the telescope spiders.

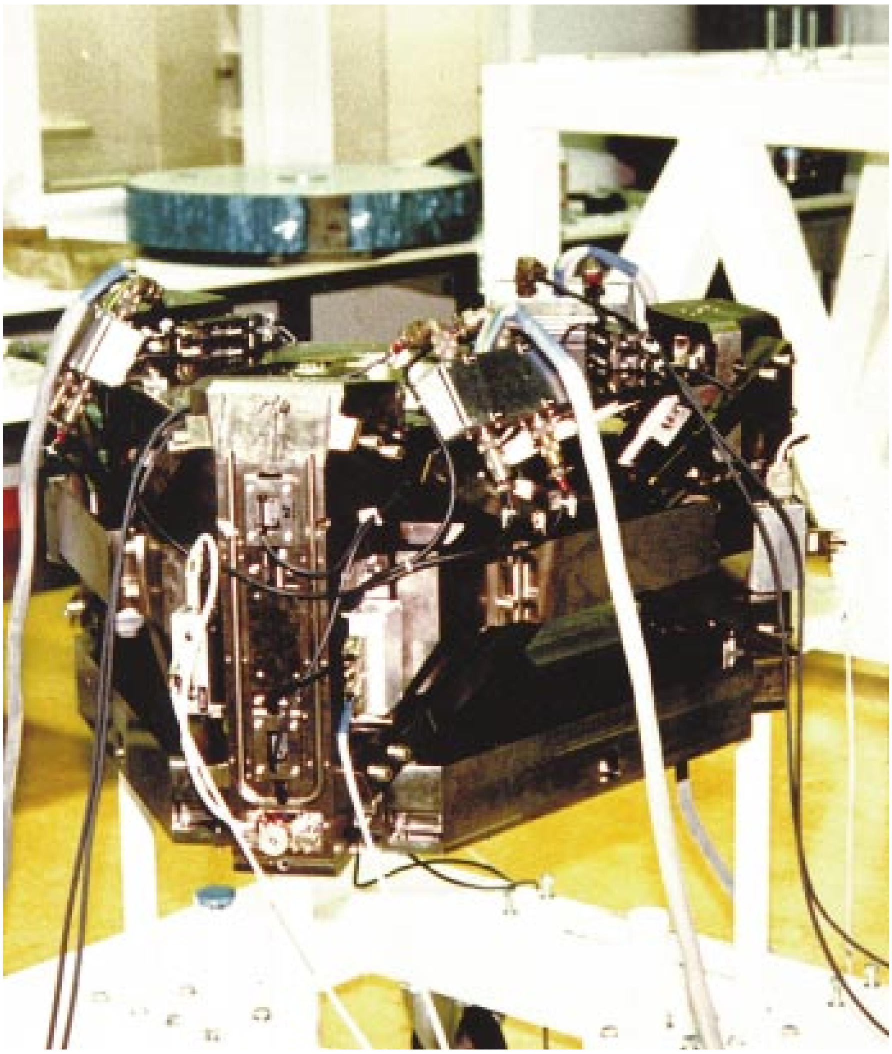


*Figure 4: Tilt and Chopping stage during integration (dummy M2 in the background).*

## Thermal Control

The thermal control of the M2 Unit combines active and passive control methods:

- Active temperature control of the M2 Unit surface (housing and sky baffle) by means of electrical heaters and passive radiation/convection to the ambient air. The inner surface of the thermal skin is equipped with thermistor controlled heater mats and is coated externally with a low-emissivity foil.
- De-coupling of the interior temperature of the M2 Unit from the ambient air is achieved by means of insulation.
- Active temperature control of the electronic boxes is achieved by liquid coolant and, when necessary, by auxiliary heaters and fans. The fan arrangement is mounted on a vibration absorber and has been tested for vibrations.
- Liquid cooling of the chopping motors. The power dissipated is less than 12 W/motor.
- Minimised heat exchange between chopper and mirror by means of active temperature control of the parts opposite to the mirror back side. The mirror temperature and the mentioned parts will be maintained within ±3°K from the ambient temperature.

## Secondary Mirror Characteristics and Manufacturing Process

The secondary mirror is a convex hyperbolic mirror of 1116 mm useful optical diameter, whose centre of curvature is located 4.5 m behind the vertex. The deviation between the best fitting sphere and the mirror surface is approximately 70 µm. The micro-roughness of the optical surface is $\leq$ 2 nm RMS.

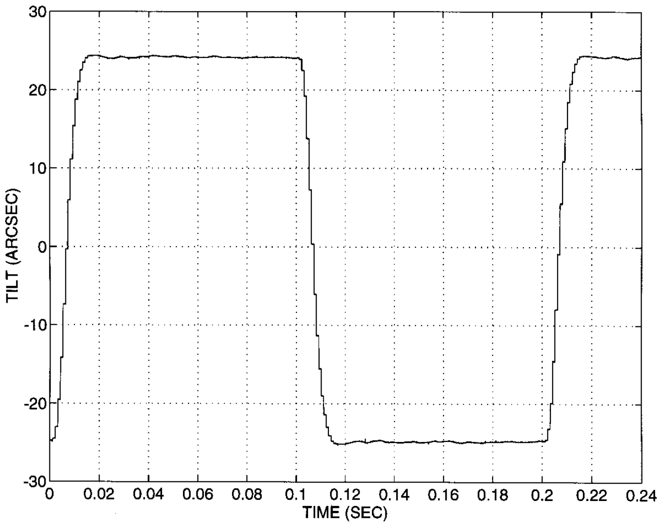
The specification of the optical quality is based on the concept of Central Intensity Ratio which compares the performance of the telescope to an ideal diffraction-limited telescope in well-defined atmospheric conditions. The required optical quality makes use of the active correction capability of the VLT and calls for a CIR of 0.98 at $\lambda = 500$ nm.

The mechanical characteristics of the mirror are of no less importance than the optical ones. The mirror must be stiff and light to limit the actuators forces and power dissipation, to achieve a high closed-loop bandwidth and to minimise the stresses. In its final design the first eigenfrequency of the mirror assembly is around 400 Hz, while the final mass of the mirror is 42 kg.

To achieve these performances, the blank, exhibiting an open back flat structure, is made of light-weighted, Nickel-plated Beryllium. The optical figuring is done on the nickel layer. The support system uses three flexural bipods located at approximately two thirds of the radius and screwed onto the blank in reinforced areas. The mirror cell is made of Titanium.

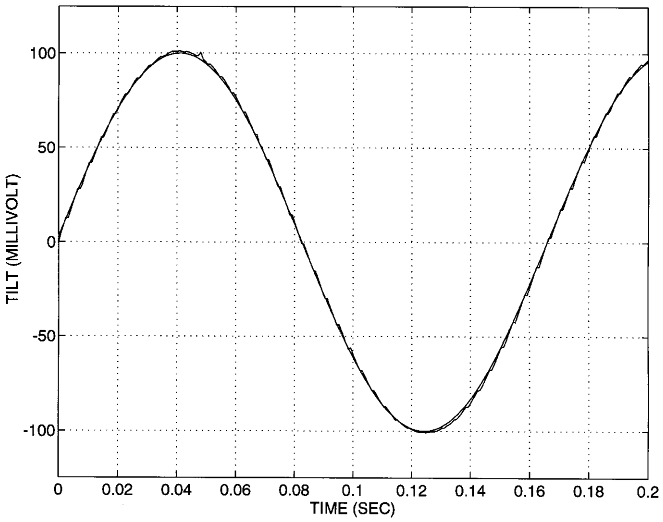
The manufacturing technology can be considered to represent the state of the art for large Beryllium optics. The requirements set on the secondary mirror, especially in mechanical terms, led to select a structural grade Beryllium (I-220H), rather than an optical one. Starting from Beryllium powder obtained by impact grinding in order to overcome the anisotropy of Beryllium, a billet of 1.2 m diameter is produced by Hot Isostatic Pressing (HIP). The billet exhibits a density $\geq$ 99.7% of the nominal density. After radiographic inspection, the blank is light-weighted and the interfaces for the supports are generated by machining.

The procedure of grinding to the aspherical shape includes also a certain number of thermal annealing cycles for the removal of internal stresses and to



Chopping ± 25 arcsec @ 5 Hz
Jitter = 0.08″ RMS, Settling time < 20 msec

*Figure 5: Chopping preliminary performance.*



Field stabilisation @ 6 Hz (Tilt command superimposed on actual tilt)
Relative tracking error < 1.31 % (electronic noise of test set-up)

*Figure 6: Field stabilisation preliminary performance.*

stabilise the mirror. The blank is then electroless nickel plated. Due to the large surface of the structural pockets and ribs at the back of the blank, a thinner layer of nickel is put on the back face than on the front face to avoid unnecessary weight increase. The minimum thickness of Nickel on the front surface is dictated by the polishing process. The blank is slightly oversized to avoid edge effects during polishing. After polishing, the edge of the mirror is cut by electromachining. This generates also a sharp edge, necessary for reducing infrared emissivity.

In all manufacturing processes, great care has been used to avoid any figure change induced by the release of internal stresses or by the removal of material, thus guaranteeing the long-term stability of the blank. To this purpose, a large number of thermal cycles were foreseen at each manufacturing stage and also during polishing.

## Status of Manufacturing and Integration

The Final Design Review (FDR) of the M2 unit was performed at Dornier premises in November 1995. At that time, in less than sixteen months from the start of the activity, a breadboard of the tilt and chopping stage had been designed, manufactured and assembled, and preliminary tests had been started. The tests, performed with a dummy secondary mirror, showed that the specified performance can be achieved. The compensation system of the chopping stage showed its ability to reduce the forces leaked to the spiders to below 5 N. A further reduction is expected by means of the final tuning with the real mirror. Since then the chopper has been refurbished and the system is approaching its final testing. Figures 5 and 6, elaborated at ESO by E. Manil, show the performance of the chopper already achieved during the preliminary tests.

The rest of the electromechanical unit is well advanced in the integration and testing phase. The mechanical structure is mounted in a dedicated stand which serves for integration and testing. The thermal skin, the heaters, the insulation and the liquid cooling loop are mounted. The focusing system was tested at unitary level and is assembled. The linear guides have been adjusted and their precision checked. The centring stage with the two eccentric drives has been singularly tested and is undergoing integration in the unit. The chopper is completing the unitary tests and it will be mounted soon on the M2 unit. The electronics is largely manufactured and the cabling has been assembled with the help of a full-scale model.

The acceptance of the first Beryllium blank by REOSC, although slightly delayed, is a remarkable milestone considering the difficulty and the criticality of most of the processes involved in the manufacturing of a blank of such size. The blank exhibits a very low internal stress, excellent micro-yield strength, is coated on both sides with low-stress Nickel closely matching the thermal expansion coefficient of the Beryllium. All these characteristics, extremely important for the polishability and for the long-term stability of the blank, were obtained through a carefully-controlled manufacturing process.

The shape of the blank differs from the final asphere by about 7 μm peak to valley. Although critical tasks still lie ahead before the figuring is completed, the present results are both exciting and technically promising. It is worth noting here that this is one of the largest Beryllium blanks ever produced.

After its completion and optical verification, the mirror will be shipped from REOSC to Dornier where it will be integrated in the M2 Unit for final testing, before being shipped to Chile.

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