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ELT – Where the Secondary Mirror Becomes a Giant

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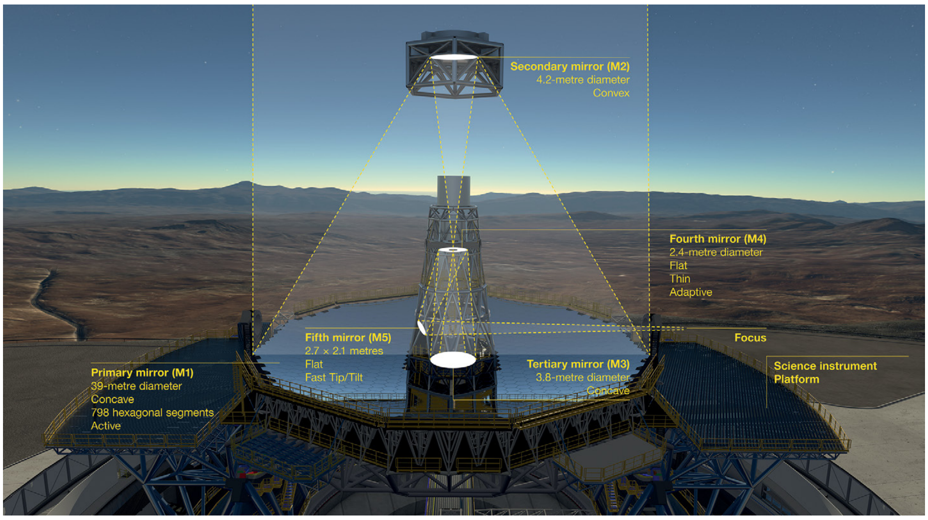

Figure 1. This diagram shows the novel five-mirror optical system of ESO's ELT. Before reaching the science instruments the light first reflects off the telescope's giant concave 39-metre segmented M1 mirror; it then bounces off two 4-metre-class mirrors, one convex (M2) and one concave (M3). The final two mirrors (M4 and M5) form a built-in adaptive optics system to allow extremely sharp images to be formed at the final focal plane.

The Extremely Large Telescope (ELT) is at the core of ESO's vision to deliver the largest optical and infrared telescope in the world. Following on from our previous Messenger article describing the primary mirror (M1), here we focus on the secondary (M2) and the tertiary (M3) mirrors of the ELT, outlining the complexity and challenges involved, and the current manufacturing status.

Background: how the ELT works

The optical design of the ELT is based on a novel five-mirror scheme capable of collecting and focusing the light from astronomical sources and feeding state-of-the art instruments for imaging and spectroscopy. As shown in Figure 1, the light is collected by the giant 39-metre-diameter M1 mirror and relayed via M2 and M3 (both of which have ~ 4-metre diameters) to M4 and M5, which are the core of the adaptive optics of the telescope. After M5 the light reaches the instruments on one of the two Nasmyth platforms.

This design provides an unvignetted field of view with a diameter of 10 arcminutes on the sky, an area of ~ 80 square arcminutes (1/9 the size of the full moon on the sky). Thanks to the combined activation of M4 and M5, the ELT will be able to correct for both atmospheric turbulence and the vibration of the telescope structure itself induced by motion and wind. This is crucial to enabling the ELT to reach its diffraction limit, which is ~ 8 milliarcseconds (mas) in the *J*-band (at λ ~ 1.2 μm) and ~ 14 mas in the *K*-band, thereby providing images 15 times sharper than the Hubble Space Telescope.

Translated into astrophysical terms, this means opening up new discovery spaces, from exoplanets close to their host stars, to black holes, to the building blocks of galaxies – both in the local Universe and billions of light-years away. Specifically, the ELT will be able to detect and characterise extrasolar planets in the habitable zone around our closest star, Proxima Centauri, and resolve giant molecular clouds (the building blocks of star formation) down to ~ 50 pc in distant galaxies at redshifts z ~ 2, as well as even smaller structures in sources that are gravitationally lensed by foreground clusters — all with an unprecedented sensitivity.

The secondary (M2) and the tertiary (M3) mirrors

The ELT's M2 mirror, with its 4.25-metre diameter, will, like many aspects of the ELT, set another record in the astronomical landscape. M2 will be the largest secondary mirror ever used on a telescope, and the largest convex mirror ever produced. For comparison, the secondary mirrors on the 8-metre VLT Unit Telescopes are just over 1 metre in diameter. Even more impressively, M2 is larger than the primary mirror of the VISTA telescope and indeed the primary mirrors of many other telescopes that are operating today. There is also the added challenge that M2 will hang upside-down over the 39-metre M1 mirror, about 60 m above the ground, held in mid-air by its support structure (called the M2 cell) and anchored to the telescope main structure. The M3 mirror is similarly large and complex, with its 4-metre diameter. The mirrors alone weigh more than 3 tonnes each; with the cell and structure the overall weight of each assembly is about 12 tonnes.

Both M2 and M3 are produced by the German company SCHOTT and are made of a special low-expansion glass-ceramic material called ZERODUR®. This special material is ideal because it is not sensitive to thermal fluctuations thanks to its very low thermal expansion coefficient. This means that the form and the shape of the mirrors will not change significantly with temperature during observations. This material is also extremely resistant; it can be polished to the required finishing level and has been used in telescope mirrors for decades.

Figure 2. This image shows some of the people behind the scenes at the technical acceptance of the massive 3-tonne blank for the ELT's M2.

The manufacture of the M2 and M3 mirrors is a great example of the strong collaboration between ESO and European industries. The production of the blanks is being carried out by the German company SCHOTT, the final polishing of the surface by the French company Safran Reosc, and the cells to hold the mirrors will be made by the Spanish company SENER.

Challenges with M2 and M3

The M2 mirror is a convex 4.25-metre F/1.1 thin meniscus, about 100 mm thick, with an 800-mm central hole. Its optical surface shape is very aspheric, with a departure from a sphere that is close to 2 mm. The size, convexity, aperture ratio and asphericity make this mirror extremely difficult to polish and test.

The M3 mirror is a concave 4.0-metre F/2.6 thin meniscus, about 100 mm thick, with a 30-mm central hole. Its optical surface shape is mildly aspheric, with a departure from a sphere of only about 30 μm. Besides its 4-metre size, the M3 mirror is easier to manufacture and test compared to the M2, and the required M3 mirror production and metrology processes are more common.

The M2 and M3 mirror blanks (i.e., the "glass" made by SCHOTT) weigh about 3 tonnes each, and require sophisticated production methods and processes. After an initial raw material casting in a cylindrical mould, each blank is carefully cooled down and annealed for about three months, so as to maximise the material's homogeneity, and minimise the internal stresses and the number of bubbles and inclusions. The resulting glassy boule then undergoes a six-month heat treatment to transform the material into glass-ceramic and adjust the near-zero coefficient of thermal expansion to a few parts per billion accuracy. Each blank is then machined to its final geometry, and acid etched to remove residual subsurface damage and maximise the mirror strength.

The blanks are then transported to Safran Reosc for figuring and polishing, in the same facilities where the 8-metre VLT primary mirrors were polished in the 1990s. These facilities have been refurbished to accommodate the specific requirements of figuring and testing M2 and M3. Each blank follows the same finishing process: adhesive bonding of the invar interface pads, and then a series of steps to achieve the final surface quality; grinding and fine grinding to an accuracy of a few μm, followed by polishing and figuring to an accuracy of a few nm — about 20 000 times thinner than a human hair. Both the grinding and polishing processes rely on a combination of small tool figure correction and mid-size tool smoothing on a dedicated 4-metre figuring machine. At the grinding stage the mirror figure is monitored using a 4-metre 3D coordinate measurement machine (3D CMM).

Interferometry testing through null correctors has been developed for polishing, using a giant Fizeau Test Matrix for M2 and computer-generated holograms (CGH) for M3. Both mirrors are supported on dedicated active metrology mounts during figuring to accurately match the force distribution in the mirror cells' support. Each mirror requires about two years for figuring and polishing, not including the time needed to upgrade the facilities, the production of testing equipment and commissioning.

Both M2 and M3 mirrors are hosted on the telescope in dedicated cells, which provide shape adjustment capability to compensate static errors to some extent and position control for locating the mirrors within the telescope. The overall weight of each assembly (mirror and cell) is about 12 tonnes and the requirements to position such a massive structure are really challenging — despite the weight, the requisite accuracy of the positioning stage is on the order of just 0.1 mm.

The cells for M2 and M3 have similar design concepts. Each mirror is axially supported on its back surface with an 18-point whiffletree, and laterally at 14 points on the mirror's outer edge. As the M3 mirror is away from any pupil, the active correction of this mirror is mandatory. On the other hand, low-order deformations of the M2 mirror have very limited error propagation in the field, so the active shaping of M2 is implemented as a provision only.

In order to align the M2 mirror with respect to the rest of the optics (M1, M4, M5), the whole assembly will be moved relative to the telescope structure using six position actuators (hexapod). Three actuators are oriented along the mirror optical axis, the three others are located within the plane of the centre of gravity, as shown in Figure 3. It is worth noting that the relative accuracy of this hexapod, which will move every few minutes, is in the sub-µm range, which presents a real challenge.

M2 and M3 in the making

After sixteen months of manufacturing, the M2 mirror blank was completed by the SCHOTT company and accepted in December 2018 (see Figure 2). It was then stowed in its transport container and shipped to France for the final polishing by Safran Reosc in its refurbished facilities. The VLT M1 facilities have been modified by Safran Reosc to host the M2 and M3 mirrors. All aspects related to their production have been designed, procured, and installed and are being commissioned at the time of writing. The metrology facilities are complete and ready for the grinding phases. The interferometric metrology facilities are in the final stages of manufacturing. Grinding of the M2 mirror started in March 2019.

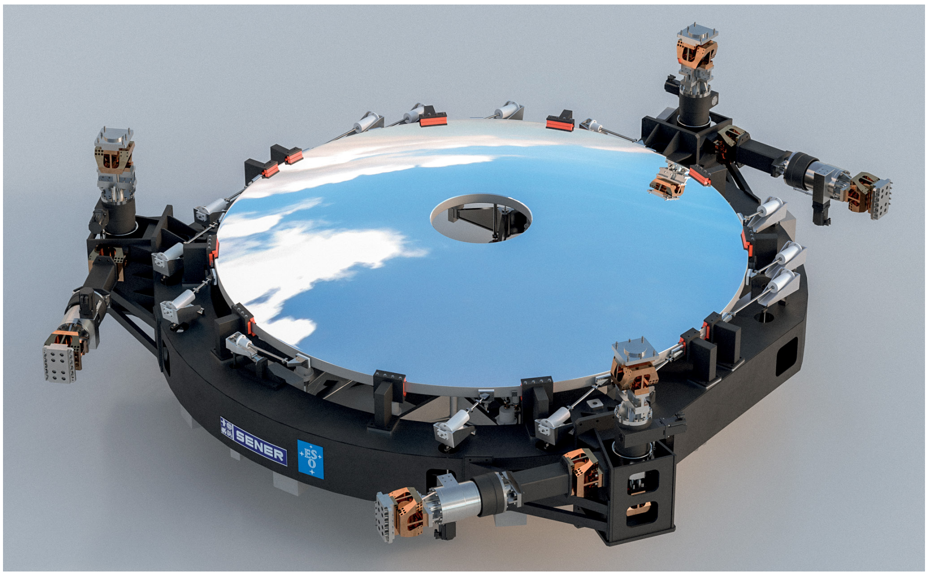

Figure 3. Rendering of the M2 mirror in its mirror cell.

The M3 mirror blank has also been cast and is now in its final stages of manufacturing; it is expected to be completed in line with contractual deadlines. The design of the cells is also progressing well at SENER and has successfully passed Preliminary Design Review (Figure 3).

SCHOTT

The M2 blank of the ELT being transported to France for final grinding and polishing by Safran Reosc.