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ELT M4 — The Largest Adaptive Mirror Ever Built

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The Extremely Large Telescope (ELT) is at the core of ESO's vision to deliver the largest optical and infrared telescope in the world. Continuing our series of Messenger articles describing the optical elements of the ELT, we focus here on the quaternary mirror (M4), a true technological wonder; it is the largest deformable mirror ever made. In combination with M5, M4 is vital to delivering the sharp (diffraction-limited) images needed for science by correcting for atmospheric turbulence and the vibrations of the telescope itself. Here we describe the main characteristics of M4, the challenges and complexity involved in the production of this unique adaptive mirror, and its manufacturing status.

Background: how the ELT works

Let's briefly recall 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 the purposes of imaging and spectroscopy. The light is collected by the giant primary mirror 39 metres in diameter, relayed via the M2 and M3 mirrors (each of which has a diameter of ~ 4 metres) to the M4 and M5 mirrors that form the core of the adaptive optics of the telescope; the light then reaches the instruments on one or other of the two Nasmyth platforms. This design provides an unvignetted field of view (FoV) of 10 arcminutes in diameter on the sky, ~ 80 square arcminutes (approximately a ninth of the full moon). Thanks to the combined use of M4 and M5, the optical system is capable of correcting for atmospheric turbulence and the vibration of the telescope structure itself induced by motion and wind.

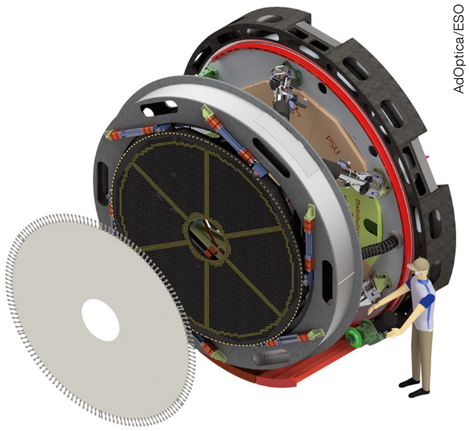
This adaptive capability is crucial to allowing the ELT to reach its diffraction limit, which is ~ 8 milliarcseconds (mas) in the *J*-band (at λ ~ 1.2 μm) and ~ 14 mas in the *K*-band. In so doing the ELT will be able to yield images 15 times sharper than the Hubble Space Telescope and with much greater sensitivity. Translated into astrophysical terms this means opening up new discovery spaces, from exoplanets closer to their stars, to black holes, to the building blocks of galaxies both in the local Universe and billions of light years away. For example, the ELT will be able to detect and characterise extrasolar planets in the habitable zone around our closest star Proxima Centauri, or to resolve giant molecular clouds (the building blocks of star formation) down to ~ 50 parsecs in distant galaxies at z ~ 2 (and even smaller structures for sources that are gravitationally lensed by foreground clusters) with an unprecedented sensitivity.

The quaternary mirror (M4)

M4 is the main adaptive mirror of the telescope. The term "adaptive mirror" means that its surface can be deformed to correct for atmospheric turbulence, as well as for the fast vibration of the telescope structure induced by its motion and the wind. In the case of M4, more than 5000 actuators are used to change the shape of the mirror up to 1000 times per second.

In combination with the M5 mirror, M4 forms the core of the adaptive optics of the ELT. With a diameter of 2.4 metres, M4 will be the largest adaptive mirror ever built. By comparison, current adaptive mirrors are just over 1 metre in diameter, for example the 1.1-m M2 adaptive secondary on the VLT UT4 telescope (Yepun).

Adaptive mirror technology was translated into an industrial product for astronomy more than two decades ago by the Italian companies Microgate s.r.l and ADS, internationally known under the



AdOptica/ESO

Figure 1. Rendering of the M4 adaptive mirror unit for the ELT.

consortium name of AdOptica. Many 8-metre telescopes now have a metre-scale adaptive mirror. The same technology is now being adapted to serve the ELT, in order to produce a mirror with an area five times larger. The M4 mirror uses the same principle as a loudspeaker; the mirror is made of a very thin shell levitating 100 microns away from its reference surface (this corresponds to the thickness of a standard A4 sheet of paper) and it acts like a membrane which deforms under the effect of about 5000 voice coil actuators. A voice coil actuator is a type of direct drive linear motor and the name "voice coil" comes from one of its first historical applications, vibrating the paper cone of a loudspeaker. It consists of a permanent magnetic field assembly and a coil assembly. The current flowing through the coil assembly interacts with the permanent magnetic field and generates a force that can be reversed by changing the polarity of the current.

Depending on the current injected into the coil the mirror can be pushed or pulled up to a distance of 90 microns from its mean position. With the help of a very fast and precise set of capacitive sensors and amplifiers that are co-located with the voice coil actuators, the mirror's position is measured 70 000 times per second to an accuracy of a few tens of nanometres (the size of the smallest virus) with the actuators being driven up to 1000 times per second.

M4 is made of several state-of-the-art components, the mirror and its reference

Figure 2. (Left) One of the shell mirrors of the M4 in Zerodur©.

Figure 3. (Right) The reference body in silicon-carbide being inspected after brazing the six parts.

structure being two of the most critical ones. The mirror is an assembly of six optically polished thin shells, or petals, made of the low-expansion glass-ceramic Zerodur© (manufactured by Schott GmbH). The six petals are obtained from a 35 mm-thick blank, which is polished and thinned down to a thickness of less than 2 mm — necessary to achieve the desired flexibility for shaping the mirror — and then finally cut into a precise shape by Safran Reosc (France; see Figure 2).

In order to adjust the shapes of the thin shells, a rigid and sufficiently accurate flat reference structure is also needed to hold the petals. This structure must be stiff enough to provide a good reference surface, whatever the orientation of the telescope. It also needs to hold all the actuators, which will deform and change the shape of the six petals.

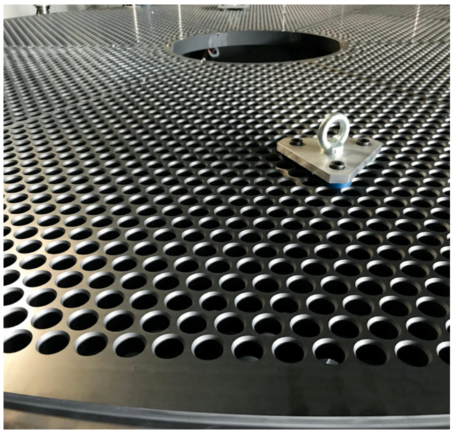
The 2.7-metre diameter lightweight structure is made of Boostec® silicon carbide, one of the stiffest materials available (stiffer than steel, carbon fibre or beryllium). Its surface has more than 5000 holes which will hold the actuators (see Figure 4), while the back surface is composed of several ribs to reinforce the structure. Owing to its large dimensions, the silicon carbide structure is made of six parts brazed together, similar to the Herschel primary mirror which was manufactured more than a decade ago. The manufacture of the structure is significantly challenging, not only because of the depth, length, and thickness of the ribs, but also given the requirements on its straightness, as well as the number and accuracy of the actuator holes.

The back of the reference structure is supported by a 12-point whiffletree and laterally at six points on the mirror edge. The overall M4 sub-system is mounted on six position actuators (a hexapod system), which provide the fine alignment of the mirror. It is further mounted on a rotating mechanism (called a switcher) which is used to select the Nasmyth focus to which the light will be directed.

Manufacturing the M4

Safran Reosc (France) started to manufacture the thin segment mirrors in 2017 and four thin shells are now ready for integration in Italy. The remaining eight shells still need to be delivered in order to have two sets of six shells each (during ELT operation one set is integrated on M4, while the other is being recoated). The reference body manufacturing also began in 2017 and six segments have been brazed in the last few months. The reference surface will need to be lapped to 5 microns flatness before being delivered to Italy.

To have a mirror fully tested in Chile by early 2024, AdOptica has to ensure the procurement and manufacture of all the other components, including all the voice coil actuators and more than 60% of the permanent magnets, which are already in house and are waiting to be integrated. In addition, more than half of the electronics boards are either ready or under calibration, and most of the mechanical parts are ready, including the reference structure cell support and its whiffletree.



Mersen Boostec

Figure 4. Detail of the M4 reference body.

The final integration will start at AdOptica once the reference structure has been delivered. Given the number of components that need to be assembled to a high degree of precision, the integration will be a lengthy task requiring procedures to ensure that the assembly and calibration meet requirements. It should take 1.5 years to fully integrate the M4 mirror and start the final calibration of each mirror segment and their associated capacitive sensors. A test tower is being specially developed to verify and test the M4. It will be used in Europe to calibrate the M4 unit before being transferred to Chile where it will be used before the mirror is installed on the telescope and kept on-site for any future major maintenance activities that may be required.