DOI: 10.18727/0722-6691/5348

ESO's Extremely Large Telescope Optics Update

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The Extremely Large Telescope is at the core of ESO's vision to deliver the largest optical and infrared telescope in the world. We present an updated status report on the five mirrors of the telescope, focusing on the challenges and the progress made in the last few years.

Background: how the ELT works

The optical design of ESO's Extremely Large Telescope (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 to carry out imaging and spectroscopy. The light is collected by the giant primary mirror (M1, 39.3 metres in diameter), relayed via the secondary and tertiary mirrors, M2 and M3 (each of which has an approximately 4-metre diameter), to M4 and M5 (the core of the telescope adaptive optics). The light then reaches the instruments on one of the two Nasmyth platforms.

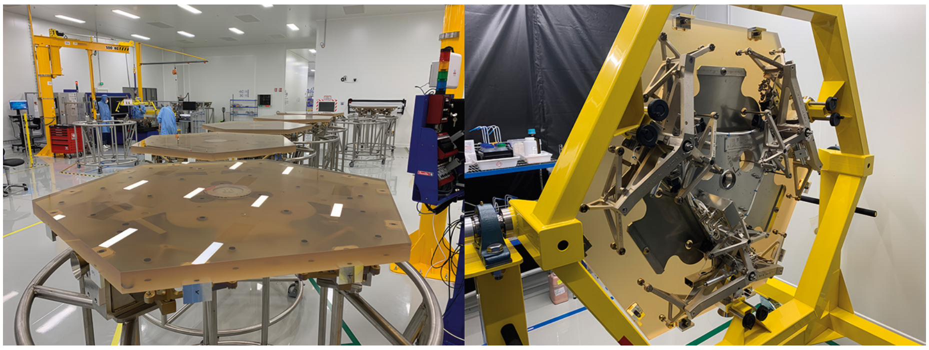
This design provides an unvignetted field of view (FoV) with a diameter of 10 arcminutes on the sky, or an area of about 80 square arcminutes (i.e., about one ninth of the area of the full Moon). Thanks to the combined action of M4 and M5, the ELT will have the capability to correct for atmospheric turbulence as well as the vibration of the telescope structure induced by its movement and the wind. This is crucial to allow the telescope to reach its diffraction limit, which is about 8 milliarcseconds (mas) in the *J* band (at $\lambda \sim 1.2$ μm) and about 14 mas in the *K* band (at $\lambda \sim 2.2$ μm), thereby providing images 15 times sharper than the Hubble Space Telescope, and six times sharper than the James Webb Space Telescope.

Translated into astrophysical terms this means opening up new discovery spaces — from exoplanets close to their stars, to black holes, to the building blocks of galaxies — both in the local Universe and billions of light-years away. Specific examples include the ability to detect and characterise extra-solar 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 pc in distant galaxies at redshift $z \sim 2$, and even smaller structures for sources that are gravitationally lensed by foreground clusters, all with unprecedented sensitivity.

The 39-metre primary mirror

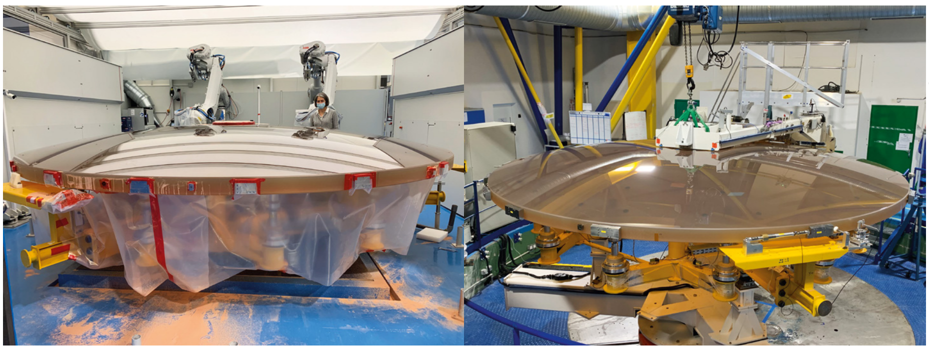
The production of the full M1 mirror was approved by ESO's Council in 2017 (Cirasuolo et al., 2018). M1 is made of 798 Segment Assemblies, each one made up of a polished mirror Segment, integrated to a mechanical Segment Support, and equipped with twelve Edge Sensors. Each Segment Assembly is installed on a subcell, made of a Fixed Frame Assembly and three position actuators (PACTS). In operation, Segment Assemblies need to be exchanged daily for maintenance and re-coating. For that purpose, an additional set of Segment Assemblies have been ordered (the seventh sector), so in all 931 optics are procured. In total, more than 10 000 components have been ordered to build M1.

Schott (Germany) was contracted to manufacture the Zerodur© blanks by the end of 2017 (the 'glass'). The first 18 blanks were delivered to Safran Reosc (France) in May 2019. Production by Schott has been steady since then. By the end of 2023 more than 800 blanks had been finished and accepted. This represents more than 85% of the full production. Schott will complete the manufacturing of the blanks by June 2024.



Safran Reosc

Figure 1. M1 segment polishing at Safran. Left: the segments are waiting for final inspection. Right: Segment support control after its integration with the mirror.



Safran Reosc

Figure 2. The M2 mirror after its last polishing run: left, on the polishing stand and right, during interferometric measurement.

The contract to produce the Segment Supports and Fixed Frame Assemblies was signed in April 2018 with VDL (the Netherlands). Production started with 18 validation models to qualify the production and verification means, to fine-tune the manufacturing procedures, and to make the integration at Safran Reosc straightforward and reliable. Production was then ramped up, and the first deliveries to Safran Reosc took place in September 2019. Today 85% of the production is finished and accepted. VDL expect to complete the production by mid-2024.

The Segment Blanks and Segment Supports are being delivered to Safran Reosc to produce the 931 Segment Assemblies. The main production steps are as follows:
– First, the segment mounting interface pads are bonded to the circular Zerodur© blank.
– The blank is then fine-ground aspherical and polished to sub-micron accuracy.
– Thereafter the segment is cut to a near-hexagonal contour and Edge Sensor pockets are machined.
– The Edge Sensor interface pads are bonded in their pockets, and the segment is integrated onto its Segment Support.
– The Segment Assembly is then finish-figured to final tolerances by ion beam figuring.

Optical testing is performed with the optical surface horizontal and looking upwards, by short cavity Fizeau interferometry against a reference test plate combined with computer generated holographic correctors (CGH). The optical quality requirements apply to the fully integrated Segment Assembly, over the whole Segment surface (there is no segment clear aperture).

The Segment Assembly production contract with Safran Reosc was kicked off in September 2017. Safran has set up for the purpose an existing 4000-square-metre building at their facilities in Poitiers (France). In parallel they designed, procured, and installed the production and test means. These are highly automated to maximise the production rate. All processes went through extensive testing and fine-tuning until the whole production line was qualified, and the first 18 validation Segment Assemblies were produced, allowing manufacturing ramp-up.

The first Segment Assembly was finished in May 2022 and by the end of 2023 more than 180 segments had entered production and more than 110 have been finished and packed, waiting for acceptance and shipment (Figure 1). The first 45 segments were accepted in December 2023 and the 18 validation segments were delivered to Paranal on 12 January 2024. Safran Reosc is continuing to ramp up production and has achieved a

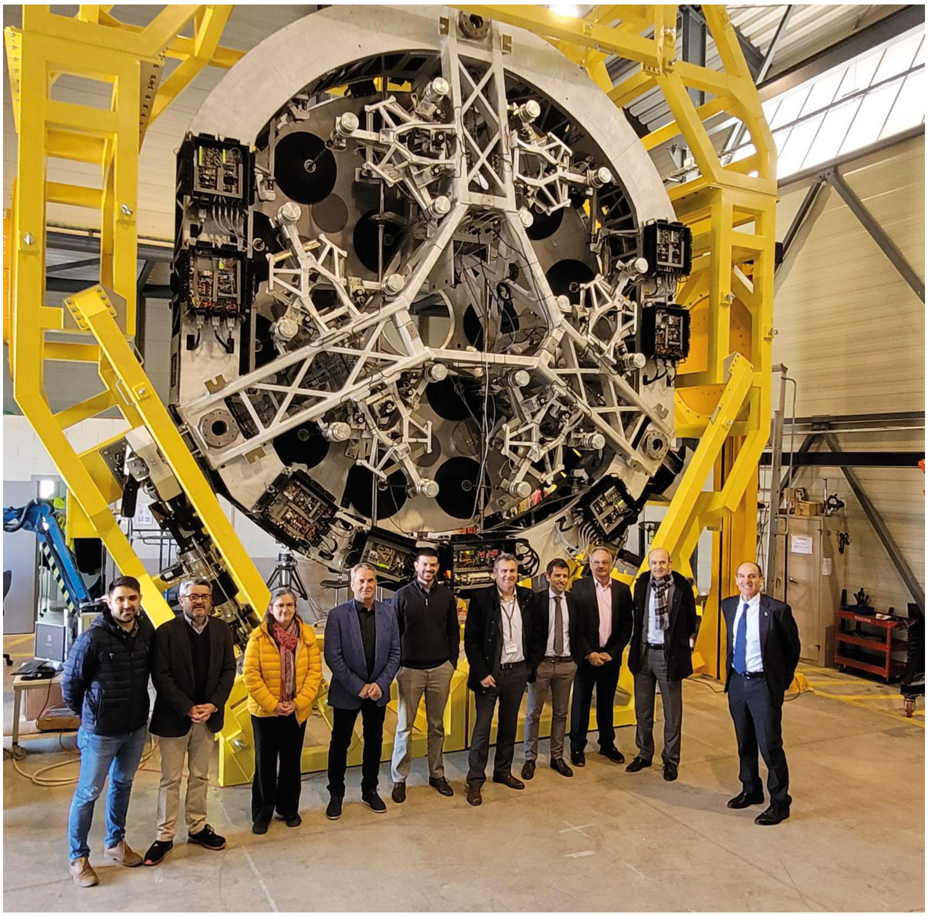

Sener Aerospacial

Figure 3. The M2 Cell in final testing.

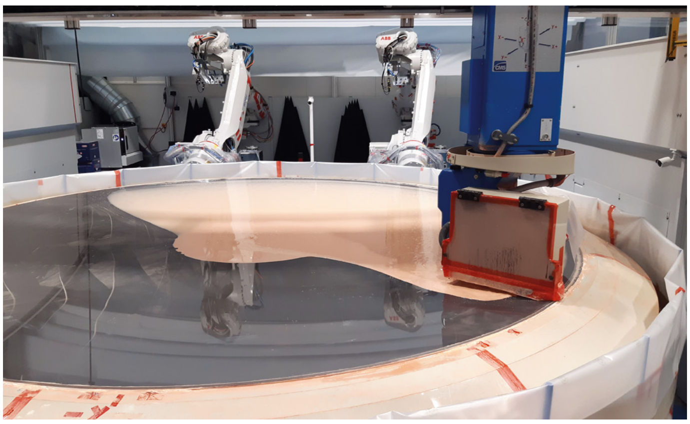

Safran Reosc

Figure 4. The M3 mirror during the second grinding run.

Sener Aerospacial

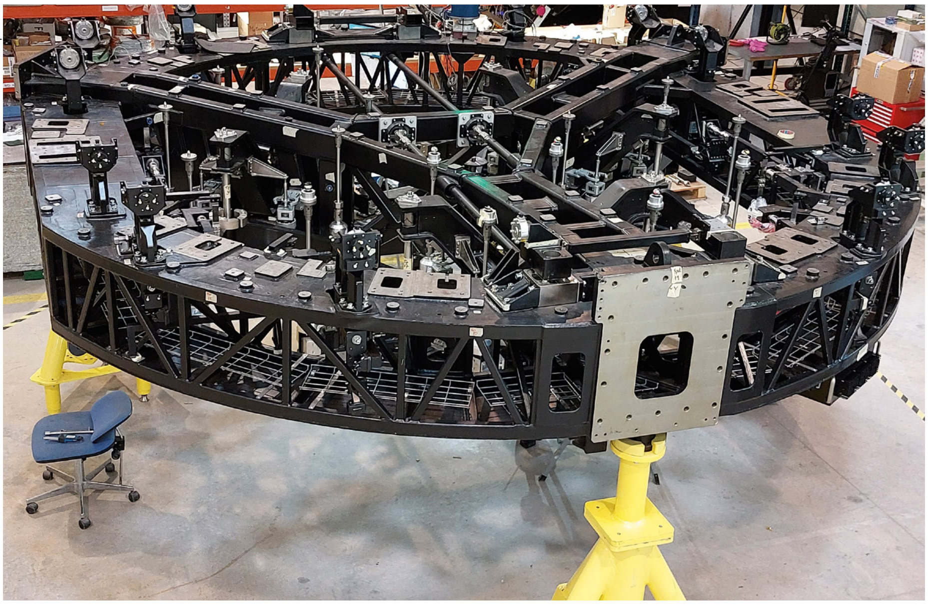


Figure 5. The M3 Cell in integration.

throughput of about four Segment Assemblies a week, the objective being to reach five a week in the first quarter of 2024. At this rate the production of the 931 Segment Assemblies should be completed by mid-2027.

The Fames consortium, composed of Fogale (France) and Micro-Epsilon (Germany), started production of the Edge Sensors three years after the signature of the contract and the first set of Edge Sensors was delivered in January 2021. Production has been continuing steadily and so far more than 2900 Edge Sensors, equivalent to 65% of the total, have been delivered to Chile. Production will be finished before summer 2024.

The contract for the procurement of 2500 PACTs was signed in June 2017 with Physik Instrumente GmbH & Co. KG (Germany). The final design was completed by mid-2021 and the first units were ready for verification a few months later. Following intensive testing and some final adjustments, Physik Instrumente were able to start mass production. The pre-series PACTs were accepted in the first quarter of 2023, and by the end of 2023 nearly 1000 PACTs had been accepted, about 40% of the total required. Production continues at full speed and its completion is foreseen before summer 2024.

The secondary and tertiary mirrors

The secondary and tertiary mirrors are two four-metre-class mirrors. The secondary is highly convex and aspheric while the tertiary mirror is concave and slightly aspheric (Cayrel et al., 2019).

Safran Reosc started to grind the M2 Blank in March 2019. The blank went through several grinding runs followed by four polishing runs (Figure 2). At the time of writing the mirror surface quality is about 60 nm RMS, almost within specification as regards the low-order frequencies. Safran Reosc has started the final figuring steps, including correction and smoothing the high-frequency residuals. It is expected that polishing of the M2 Mirror will be finished by autumn 2024.

In parallel Sener Aerospacial (Spain) passed the final design review of the M2 and M3 Cells — that will hold the mirrors in place — by the end of 2019, and the manufacturing readiness review in March 2020. They started the integration of the M2 Cell in early 2022. Today the M2 Cell is in final acceptance testing and it is expected to be delivered by summer 2024 (Figure 3). Sener Aerospacial is verifying the compliance of the cells using aluminium dummy mirrors. The M2 Cell will then be shipped to Safran Reosc, the M2 mirror will be integrated on the cell and the full assembly will be optically tested. This final verification, called system test, will take place between the end of 2024 and early 2025.

The M3 mirror is at a less advanced stage as priority is being given to the M2 mirror and both mirrors share a common production method. M3 has already been through two grinding runs (Figure 4), and it is now waiting for the acceptance of the M2 mirror to get back in production. The M3 Cell is more advanced than its mirror. It is currently in final integration (Figure 5) and it is expected to be finished by the end of 2024.

The quaternary mirror

The M4 mirror provides the main adaptive optics of the telescope. M4 will use more than 5000 actuators that can change the shape of the mirror up to 1000 times per second. In combination with M5, M4 is therefore the core of the adaptive optics

Adoptica

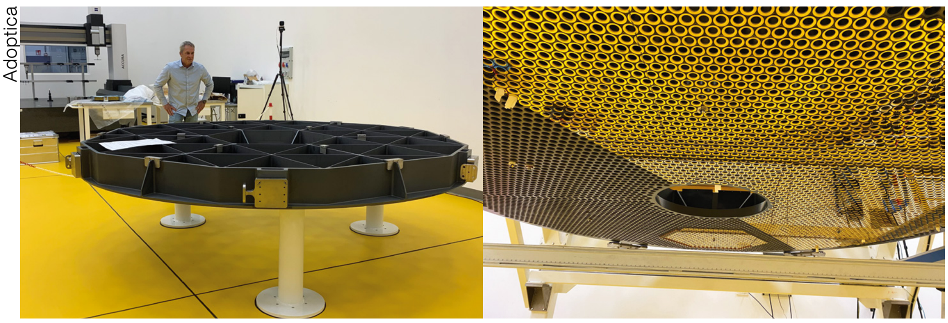


Figure 6. The M4 reference structure during integration of the mounting interfaces (left picture) and of the borosilicate tiles (right picture) on the M4 reference structure.

Safran Reosc

Figure 7. Shell inspection before final cutting.

Sener Aerospacial

Figure 8. The M5 Cell with the dummy mirror.

Mersen Boostec

Figure 9. The M5 Blank under inspection after grinding of the front face by Mersen Boostec.

of the ELT and, with a diameter of 2.4 metres, it will be the largest adaptive mirror ever built. It was one of the first contracts started under the ELT project. The Final Design Review was passed in 2018 and the Adoptica consortium (Microgate and ADS International, Italy) began procuring the various components. In 2019 the M4 SiC reference structure was brazed at Mersen Boostec (France) and Adoptica began procuring all the other parts of the unit (Vernet et al., 2019). The reference structure front surface was lapped by AMOS (Belgium) and delivered to Adoptica by the end of June 2022. Adoptica completed the bonding of the mounting interfaces and is bonding borosilicate tiles onto the reference structure, which will form capacitive cavities with the M4 thin shells for position feedback (Figure 6). This task is very delicate, requiring tight positioning accuracy, and it will take quite a long time given that several thousand tiles have to be bonded. Adoptica is planning to complete it in spring 2024. In parallel, Safran Reosc completed the production of the twelve M4 thin shells (two sets of six shells). The last ones were delivered in July 2023 (Figure 7).

All the other sub-systems are ready to be assembled with the reference structure. The unit integration activities will be finished before summer 2024 and Adoptica will then start the calibration phase of the full system followed by the performance verification. Technical acceptance in Europe is foreseen in early 2026 and acceptance in Chile one year later.

The fifth mirror

M5 is a flat elliptical mirror of diameter 2.2 metres on the minor axis and 2.7 metres on the major axis (Vernet et al., 2021). M5 is the field stabilisation mirror of the telescope; it will tip-tilt to correct for vibrations of the telescope structure induced by its motion and by the wind. This is achieved by three actuators which move the M5 mirror two to three times a second.

The M5 Cell is being designed and manufactured by Sener Aerospacial. The Final Design Review was passed in February 2022. All the procurements and the M5 Cell integration were completed during the last months of 2022. The M5 aluminium dummy mirror was mounted on the M5 Cell in February 2023, allowing Sener Aerospacial to fine-tune the system and reach the required performance. Today the cell is in final testing (Figure 8). Acceptance of the cell is foreseen in March 2024.

The M5 Blank is being made by Mersen Boostec as a subcontractor of Safran Reosc. It is quite challenging and is a world first, consisting of making six lightweight SiC petals, coating them with a thick CVD SiC layer, and brazing them together with a very high accuracy. The blank manufacturing started in 2021 and the six petals were brazed together in March 2023. After extensive verification of the brazed blank, the front surface has been ground, in two steps between July and November 2023 (Figure 9). Mersen Boostec is currently grinding the support interfaces, the last step before acceptance of the blank and transfer to Safran Reosc. This is planned in March 2024. Once at Safran Reosc, the blank will be equipped with its axial and lateral support before the polishing and final figuring process are started. The mirror assembly is expected to be delivered to Chile the first quarter of 2028.

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