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The ELT in 2017: The Year of the Primary Mirror

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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. With its unrivalled sensitivity and angular resolution the ELT will transform our view of the Universe: from exoplanets to resolved stellar populations, from galaxy evolution to cosmology and fundamental physics. This article focuses on one of the most challenging aspects of the entire programme, the 39-metre primary mirror (M1). 2017 was a particularly intense year for M1, the main highlight being the approval by ESO's Council to proceed with construction of the entire mirror. In addition, several contracts have been placed to ensure that the giant primary mirror will be operational at first light.

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 to carry out imaging and spectroscopy. As shown in Figure 1, the light is collected by the giant primary mirror (39.3 metres in diameter), relayed via the secondary and tertiary mirrors, M2 and M3 (both of which have ~ 4-metre diameters), 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 about 80 square arcminutes (i.e., ~ 1/9 of the area of the full moon). Thanks to the combined activation of M4 and M5, it 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 ELT to reach its diffraction limit, which is ~ 8 milli-arcseconds (mas) in the *J*-band (at $\lambda \sim 1.2$ μm) and ~ 14 mas in the *K*-band, thereby providing images 15 times sharper than Hubble 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 giant primary mirror

One of the many technological marvels of ESO's ELT is the primary mirror, M1, along with all the necessary infrastructure and control schemes that are needed to make it work. At 39.3 metres in diameter it will be the largest optical/infrared telescope ever built. Of course, this comes with attendant challenges. The mirror is segmented, being made of 798 quasi-hexagonal mirrors, each of which is about 1.45 metres in size (corner-to-corner), is only 50 mm thick and weighs 250 kg. The full M1 has a six-fold symmetry; there are

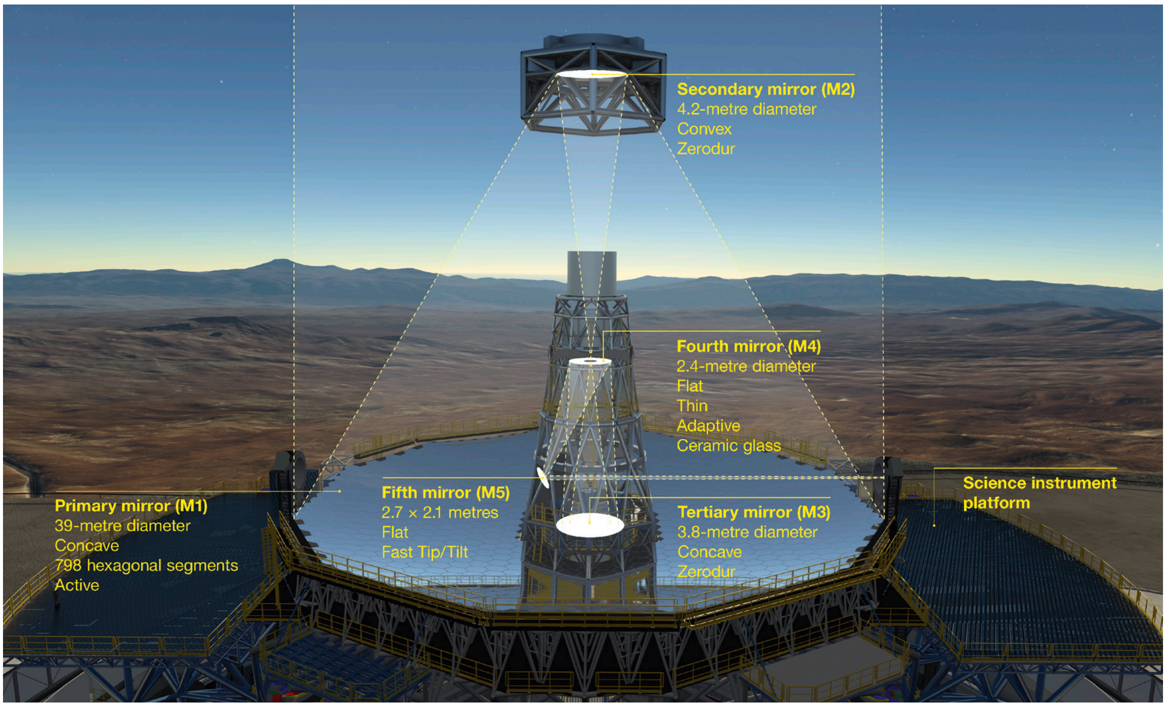
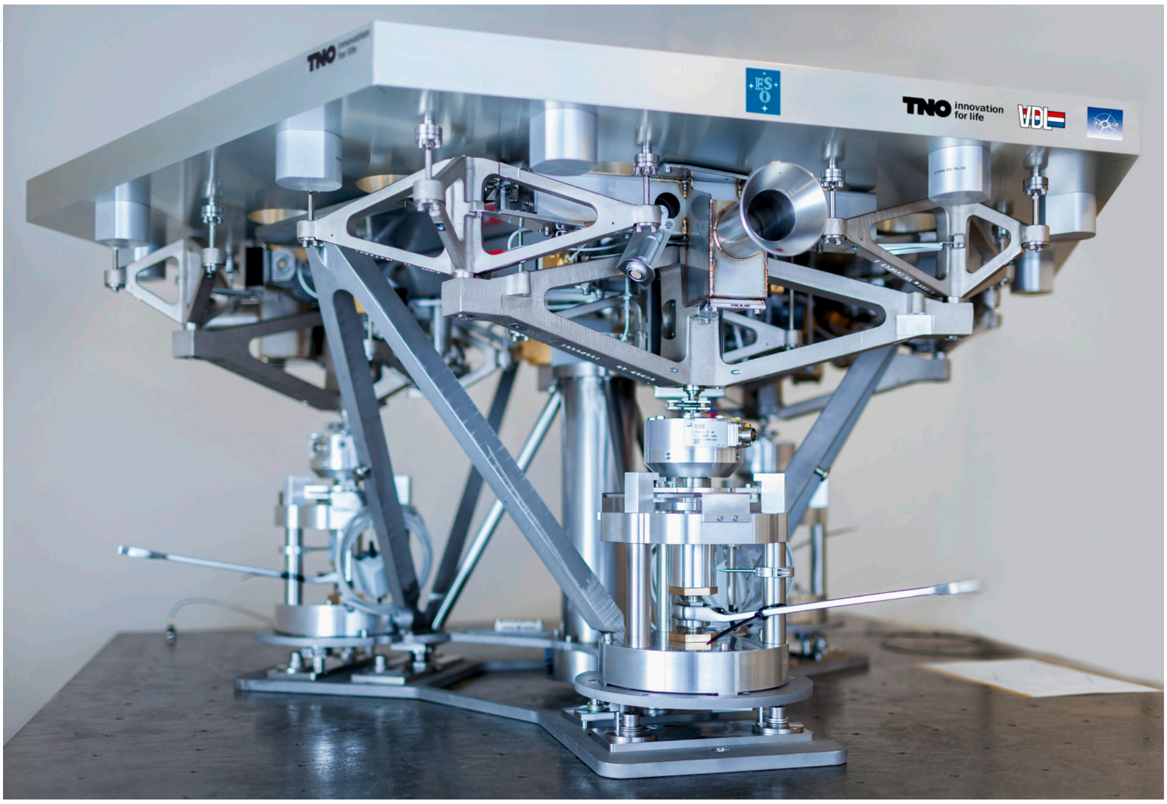


Figure 1. This diagram shows the novel five-mirror optical system of ESO's ELT. Before it can reach the ELT's scientific instruments, light is first reflected from the telescope's giant concave 39-metre segmented primary mirror (M1), after which it bounces off two further four-metre-class mirrors, one 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.



Henri Werij/TNO

Figure 2. One segment support structure of the giant primary mirror of the ELT undergoing testing.

six identical sectors of 133 segments each. In each sector all 133 segments are different from each other in shape and optical prescription; in other words there are 133 different segment types. In order to facilitate recoating there will be a seventh sector with 133 segments, i.e., one for each segment type. This adds up to a grand total of 931 segments.

M1 is evidently a very complex system. Therefore, to achieve the required scientific performance, it needs to be maintained in position and be phased to an accuracy of tens of nanometres — 10 000 times thinner than a human hair — across its entire 39-metre diameter! This is extremely challenging, as the full structure will be moving constantly during an observation, and will be affected by wind and thermal changes.

There are various ways in which M1 can be actively controlled. Each segment, made of the low-expansion ceramic material Zerodur© (from SCHOTT), is supported on a 27-point whiffletree, which is a mechanism to evenly distribute the support across the back of the segment using 27 points of contact across its surface. The load on the whiffletree can be adjusted via warping harnesses so as to slightly change the shape of the mirror to compensate for optical aberrations induced by gravity and thermal effects (see Figure 2). Moreover, each segment assembly can be moved in height and tip/tilt relative to the structure by using three positioning actuators (PACTs). These three actuators can move independently with an accuracy of 2 nm with a maximum excursion (or stroke) of 10 mm to adjust its position and maintain the perfect co-alignment of all the segments and effectively create a giant monolithic mirror. To achieve this, each side of each hexagonal segment has two “edge sensors” that constantly measure piston, gap and shear with respect to the adjacent segment to nanometre accuracy and provide the necessary information to the control system to activate the PACTs, allowing the segments to work together to form a perfect imaging system.

All in all, the M1 is a colossal system, featuring a staggering 798 segments, almost 2500 PACTs and about 9000 edge sensors (4500 pairs), not including the seventh sector and the spares.

ESO Council approval of the full M1

When the construction of the ELT was approved by Council in December 2014, it was split into two phases. Phase 1 was for the 39-metre ELT with the Multi-AO Imaging CAmera for Deep Observations (MICADO), the High Angular Resolution Monolithic Optical and Near-infrared Integral field spectrograph (HARMONI) and the Mid-infrared ELT Imager and Spectrograph (METIS) instruments and the Multi-conjugate Adaptive Optics RelaY (MAORY) adaptive optics module. The Phase 1 ELT was still capable of achieving breakthrough discoveries, although it excluded a number of critical components, notably the five inner rings (Figure 3), the seventh sector of segments for M1, and one of the facilities needed to maintain the quality of the M1 coating. The intention was to include these items in a second phase of construction at a later date.

ESO’s management and governing bodies always recognised the critical importance of these Phase 2 items. Hence, at its December 2017 meeting, following positive recommendations from

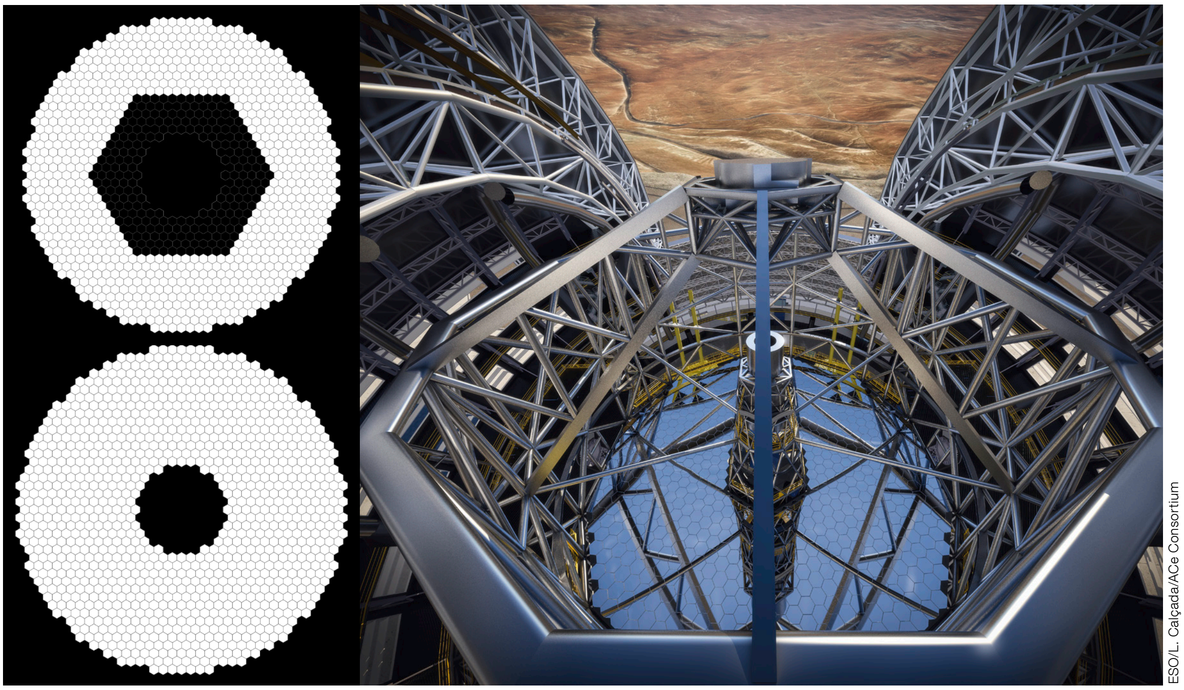


Figure 3. Left: Schematic graph comparing the Phase 1 M1 (top) without the 5 inner rings, i.e., only 588 mirrors and a large central obscuration, and the full M1 as now approved by ESO Council (bottom) with 798 segments, including the Phase 2 segments. Right: A view of M1, once it is mounted on the main structure.

the external ELT Management Advisory Committee (EMAC) and from ESO's statutory advisory bodies, the Scientific and Technical Committee (STC) and Finance Committee (FC), the ESO Council gave its authorisation to exercise contractual options to procure the previous unfunded Phase 2 items related to M1 (i.e., the five inner rings, the seventh sector and the second M1 maintenance unit). This decision enables the highest possible science return for users and for instrumentation, lowers the risk to the programme and lowers the final cost of the full ELT. Indeed, if M1 segment production were to be stopped after Phase 1 between 2019 and 2020, the costs involved in restarting the production of the blanks, segment polishing and the mirror supports at a later date would almost certainly be prohibitive, especially if the same stringent tolerances had to be maintained after (potentially) reopening and refurbishing the production facilities.

The full M1, including the inner five rings, has clear advantages regarding scientific return. It expands the collecting area of the primary mirror by 36 % compared to the Phase I configuration, which increases its sensitivity (i.e., its capability to efficiently collect light from fainter and/or more distant sources). It reduces the linear size of the central hole by nearly a factor of two (see Figure 3), which improves the ability to control the shape of the mirror surface. Filling the gap and reducing the linear obscuration is also very important for the ELT's ultimate performance as it is easier to concentrate light on science detectors with a smaller central obscuration; the peak of the point spread function (PSF) is a factor of two higher. This means that the energy is more focused, further increasing sensitivity and improving the adaptive optics performance and sky coverage. A smaller central obscuration is particularly important for the study of exoplanets using the technique of high-contrast imaging: the better the PSF the easier it is to suppress the light from the much brighter central star and to detect planets that are close to the star, thereby making the goal of directly observing Earth analogues attainable.

Making the M1 mirror

Now that the ESO Council has approved the construction of the full M1, procurement and production of the various components of M1 are going ahead. Indeed, 2017 is known as "the year of M1" within the ELT project, reflecting the many steps that were taken towards the fabrication of the various M1 components, including segment blanks, segment polishing, segment supports, PACTs, edge sensors, and the M1 Control System.

All major contracts related to these components of M1 have been approved, signed and initiated, except for the series production of M1 segment supports, the contract for which is expected to be awarded in early 2018. The timely initiation of all of these contracts is particularly important for two reasons: first, M1 fabrication lies on the so-called critical path for the ELT, meaning that any delay would have a direct impact on the date of first light; second, these contracts are interdependent. For example, the blank is required to start the polishing, and the segment support is required at the end of the polishing process for final testing and ion-beam figuring.

As 2017 was such a successful year for procurement, we can provide some details about the major contracts involved. In a ceremony held in January 2017, a contract was signed for the production of the edge sensors with FAMES, a consortium composed of Fogale (France) and Micro-Epsilon (Germany), together with three other ELT procurements (the M2 and M3 Cells with SENER and the blanks for M2 and M3 with SCHOTT). The contract with FAMES covers the design and fabrication of a total of approximately 9000 edge

SCHOTT/ESO

Figure 4. This image shows the first cast from which six blanks will be obtained by SCHOTT (Germany) at their facility in Mainz. This first cast is a thick cylinder that will be cut into six slices, each of which will become a segment blank.

sensors (~ 4500 pairs) for the 798 hexagonal segments of M1. These sensors are the most accurate to ever be used in a telescope and can measure the relative positions of the segments to an accuracy of a few nanometres. The challenge in this case is two-fold — the sensors must reliably provide the required precision, and production must proceed at an appropriate pace to deliver thousands of sensors by the specified deadline.

At a joint signature ceremony at the end of May 2017, two important contracts were signed to produce the 798 segments for the M1. The first one was signed with SCHOTT (Germany) for the production of the blanks. The second one was signed with Safran Reosc (France) for the polishing of the blanks and their integration with the segment supports. These are two of the most prominent companies involved in European astronomy, and the ceremony was a great occasion for their teams and the ESO management involved in the project to meet and shake hands, effectively forming a partnership and becoming part of a larger "family" working together to build ESO's ELT.

Production has already started, and in January 2018, the first six segment blanks were successfully cast by the German company SCHOTT at their facility in Mainz (Figure 4). After casting, the mirror segment blanks will go through a process of slow cooling and heat treatment. The blanks will then be delivered by SCHOTT to Reosc to figure and polish the segments, cut them into hexagonal shapes, integrate them into their support systems, and perform optical tests before delivery to Chile. During the polishing process, each segment will be polished until it has no surface irregularity greater than about 8 nm. To meet the challenge of delivering such a large number of polished segments within seven years, Safran Reosc will build up to a peak production rate of one mirror a day. To meet this demand, Safran Reosc has already begun the necessary refurbishment of a facility at their Poitiers plant. The contract for the segment polishing is the second-largest contract for the construction of the ELT, after the one for the dome and telescope structure, which was awarded to the Ace Consortium in May 2016. It is also the third-largest contract ESO has ever signed.

In June 2017, ESO also signed a contract with the company Physik Instrumente GmbH & Co. KG (Germany) to manufacture the PACTs, which will continuously adjust the positions of the 798 hexagonal segments of M1 on the telescope structure. Apart from the external contracts, M1 also requires a significant amount of work internally at ESO; in October 2017, the final design review of the M1 Local Control System (LCS) was completed and there is now a focus on building a critical test bench to develop and validate the telescope wavefront control algorithms.

This is only a fraction of the impressive amount of work going on, both at ESO and at the various industrial partners, towards the efficient, accurate and timely manufacturing of all the various components that will make up the ELT.

The life of the M1 mirror

It should be noted that the manufacturing, assembly and installation of M1 only represent its first steps, as M1 will lead a life that requires constant reconfiguration. Indeed, to maintain the best reflectivity and sensitivity of the telescope, each mirror will need to be recoated every 18 months, like the mirrors of the VLT. Given the number of segments, this means removing, recoating and reinstalling two segments on the telescope every day for the entire lifetime of the telescope. This represents a significant logistical effort, in order to keep up an efficient stripping, washing and coating process, as well as a well-defined maintenance plan for the thousands of ELT components. For this reason, the seventh sector of segments and the second maintenance unit (including the washing, stripping and coating plants) are particularly crucial for managing the efficient recoating of segments without regularly creating temporary holes in M1. This ensures optimal mirror control and image quality at the lowest operational costs, especially for the most demanding extreme adaptive optics applications.

The M1 mirror is certainly one of the most challenging sub-systems of the entire ELT Programme. It comprises thousands of highly sophisticated components that require extreme accuracy, not only during their manufacture, but also during installation and observations. This is certainly a challenge and the ELT Team is closely following the development of all the M1 components to ensure the ELT's first light in 2024.