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ELT M5 — The Lightweight Field Stabilisation 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. Following on from our previous Messenger articles we continue with the description of the optical elements of the ELT. In this article we focus on the quintenary mirror (M5), the field stabilisation unit. In combination with the M4 mirror, M5 is vital to delivering the sharp diffraction limited images needed for science by correcting for the vibrations of the telescope, wind shaking and the atmosphere. We describe the main characteristics of the M5, as well as the challenges and complexity of this unique field stabilisation unit and its design and manufacturing status.

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 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 is around 4 metres in diameter) to the M4 and M5 mirrors that are the core of the telescope's adaptive optics; the light then reaches the instruments on one of the two Nasmyth platforms. This design provides an unvignetted field of view (FoV) of 10 arcminutes in diameter on the sky — an area of 80 square arcminutes (1/9 of the full Moon's area) — and thanks to the combination of M4 and M5 it is capable of correcting for both atmospheric turbulence and the vibration of the telescope structure itself induced by motion and wind. This adaptive capability is crucial in allowing the ELT to reach its diffraction limit, which is ~ 8 milliarcseconds in the *J* band (at $\lambda \sim 1.2$ μm) and ~ 14 milliarcseconds in the *K* band, thereby providing images 15 times sharper than those from the NASA/ESA 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, it will be possible to detect and characterise, with unprecedented sensitivity, extrasolar planets in the habitable zone around our closest star, Proxima b, or to resolve giant molecular clouds (the building blocks of star formation) down to ~ 50 parsecs in distant galaxies at $z \sim 2$ (and even smaller structures for sources that are gravitationally lensed by foreground clusters).

The quintenary mirror (M5)

M5 is the field stabilisation unit of the telescope. The term "field stabilisation" means that the mirror is moving in a rigid way (tip-tilting) to steer the image and correct for vibrations of the telescope structure induced by its motion and by the wind, as well as some of the atmospheric turbulence. This is achieved by the M5 cell which is composed of three piezo actuators. It supports and moves the M5 mirror up to 10 times per second. M5 is a flat, elliptical mirror with a diameter of 2.2 metres on the minor axis and 2.7 metres on the major axis (see Figure 1). The role of the M5 unit (mirror + cell) is to reduce the image movement down to a level where the M4 mirror can take over. The M5 mirror assembly needs to be very stiff and at the same time very light (less than 500 kilogrammes in total) to allow its cell to move it fast enough whilst remaining flat when moving.

Initial studies have demonstrated that to achieve this highly demanding level of performance only specialist materials can be used for the mirror, either silicon carbide (SiC) or ultra-low-expansion

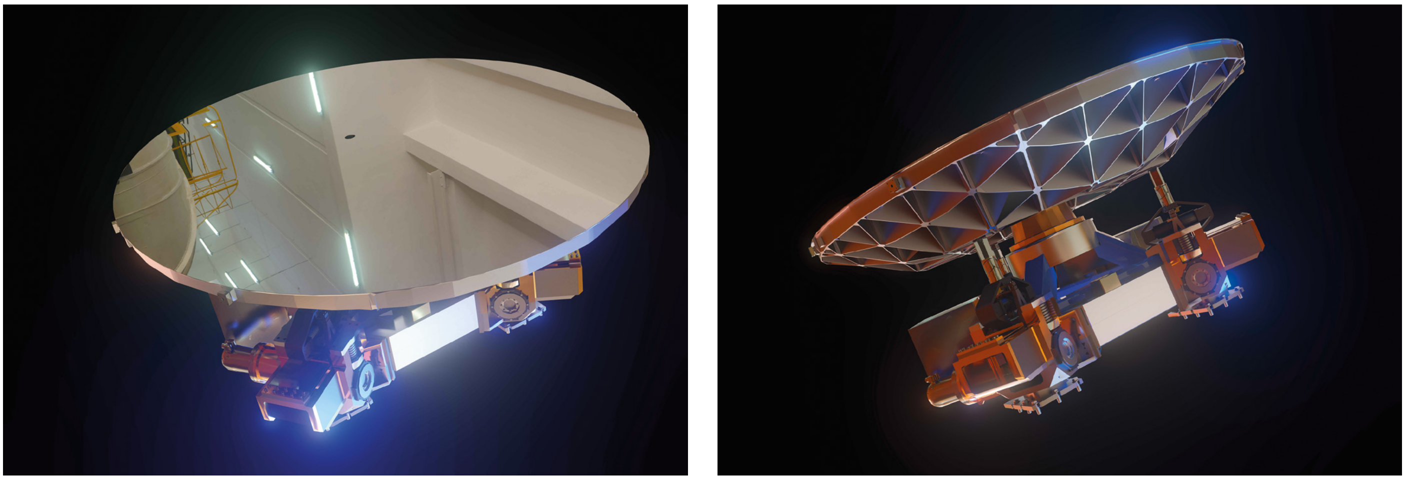


Figure 1. The ELT M5 mirror is a 2.7 × 2.2-metre ellipsoidal mirror made of silicon carbide, supported by the M5 cell (ESO renderings of SENER Aeroespacial and Safran Reosc design).

glass machined in a special way to make it extremely lightweight.

The French company Safran Reosc has been selected to manufacture the M5 mirror assembly while the Spanish company SENER Aeroespacial is responsible for the M5 cell.

Safran Reosc developed a design for the M5 mirror using Boostec® SiC. This material is well known for its high stiffness (stiffer than steel, carbon fibre or beryllium) and low density, properties that make the mirror very lightweight. SiC has been used for many space telescopes and the Herschel Space Observatory primary mirror is a good example of its technological feasibility, as well as acting as the reference body for the ELT's M4 mirror.

As in the case of the Herschel primary mirror, it is not possible to manufacture such a large mirror in a single piece, so M5 is made of six segments which must be brazed together. SiC is a very porous material and has micron-sized holes on the surface which would remain after the mirror is coated, so the segments first need to go through another very complex process called chemical vapour deposition (CVD), in which a layer of pure silicon about 900 nanometres thick is spread over each of the SiC segments.

The M5 unit is a lightweight structure including three different types of ribs following triangular patterns. The mirror is supported by three axial supports and one central lateral support (Vernet et al., 2020).

The design of the support is optimised to allow the tip-tilt movement and also provide the required stiffness laterally and in clocking. The three axial and the central lateral supports are mounted on a fast-motion tip-tilt stage with a stroke of ±0.5 milliradians inducing a displacement of more than ±0.5 millimetre. This is achieved using three piezo actuators (see Figure 2). The operation of the actuators is based on a design developed by CEDRAT TECHNOLOGIES for the M5 demonstrator more than ten years ago. Each actuator includes a system to preload the piezo stacks, an amplification frame based on patented amplified piezo actuators (APA®) and protection of the active material from the environment. The stainless steel amplification frame connects the M5 mirror and the alignment stage and magnifies the piezo stack deformation to provide the required stroke and stiffness. It also acts as one of the interfaces with the M5 mirror assembly. The cell also includes an active alignment system which allows the M5 mirror to piston by ±5 millimetres and tip-tilt by ±5 milliradians at a low rate. The alignment stage resolution is 0.025 millimetres for piston and 0.025 milliradians for tip-tilt and its repeatability is ±0.1 millimetres for piston and ±0.05 milliradians for tip-tilt.

CEDRAT TECHNOLOGIES

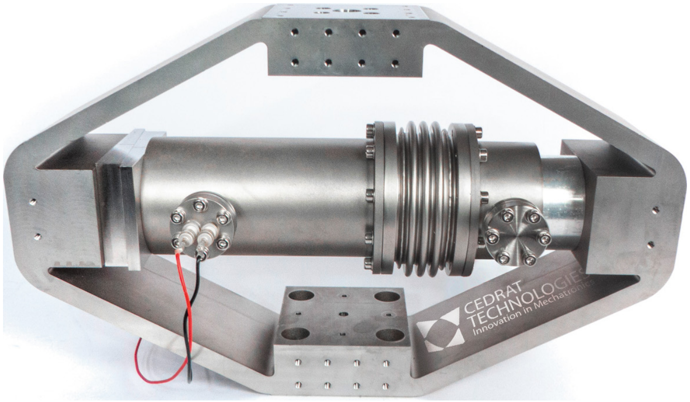


Figure 2. Amplified piezo actuator.

Manufacturing the M5 mirror

Whilst the cell is at the preliminary design stage, the mirror assembly had its Final Design Review in May 2021 and the actual mirror blank has already been in manufacturing for more than a year. This is mostly because the manufacturing procedures for such a unique SiC mirror are complex and extremely challenging. The full production chain is shown in Figure 3 and consists of the following key steps:

1. The silicon powder is mixed with some additives and inserted into a mould which is pressed to become what is called a "green blank".
2. The green blank is machined into the required segment shape.
3. The segment is sintered, a special process by which the particles of the material are fused together by heat or pressure to become a solid mass, but without reaching the melting point.
4. The segment is ground and prepared for the CVD cladding.
5. Using a very challenging technique a thin layer of silicon is deposited using CVD.
6. At this point each segment is ground and prepared for the final assembly and brazing.
7. Once the six segments are ready, the final mirror blank is assembled and brazed.
8. A final grinding of the surface removes any small misalignment.

These are the eight key steps in the manufacturing of the mirror blank. After that, the blank will be transferred to Safran Reosc and the lateral and axial supports will be integrated before proceeding with the final grinding and polishing phases.

As described above, six segments are needed for the mirror blank but to reduce the risk of delay it was agreed that six spare segments ready for cladding would also be prepared. So far five segments have been successfully manufactured with CVD cladding, six additional segments are ready for CVD cladding and the last one has been sintered. Figure 4 shows three of the segments after CVD cladding at Boostec.

One of the critical aspects that the SiC manufacturer Mersen Boostec needs to verify before starting any grinding of the optical face is that the thin CVD layer reached the right thickness and adhered adequately to the segment. This has been achieved for five segments. Once the six segment blanks are ready, it will take approximately nine months to complete the grinding and preparation for brazing.

The final step in the mirror blank manufacturing is the brazing of the six petals.

Mersen Boostec

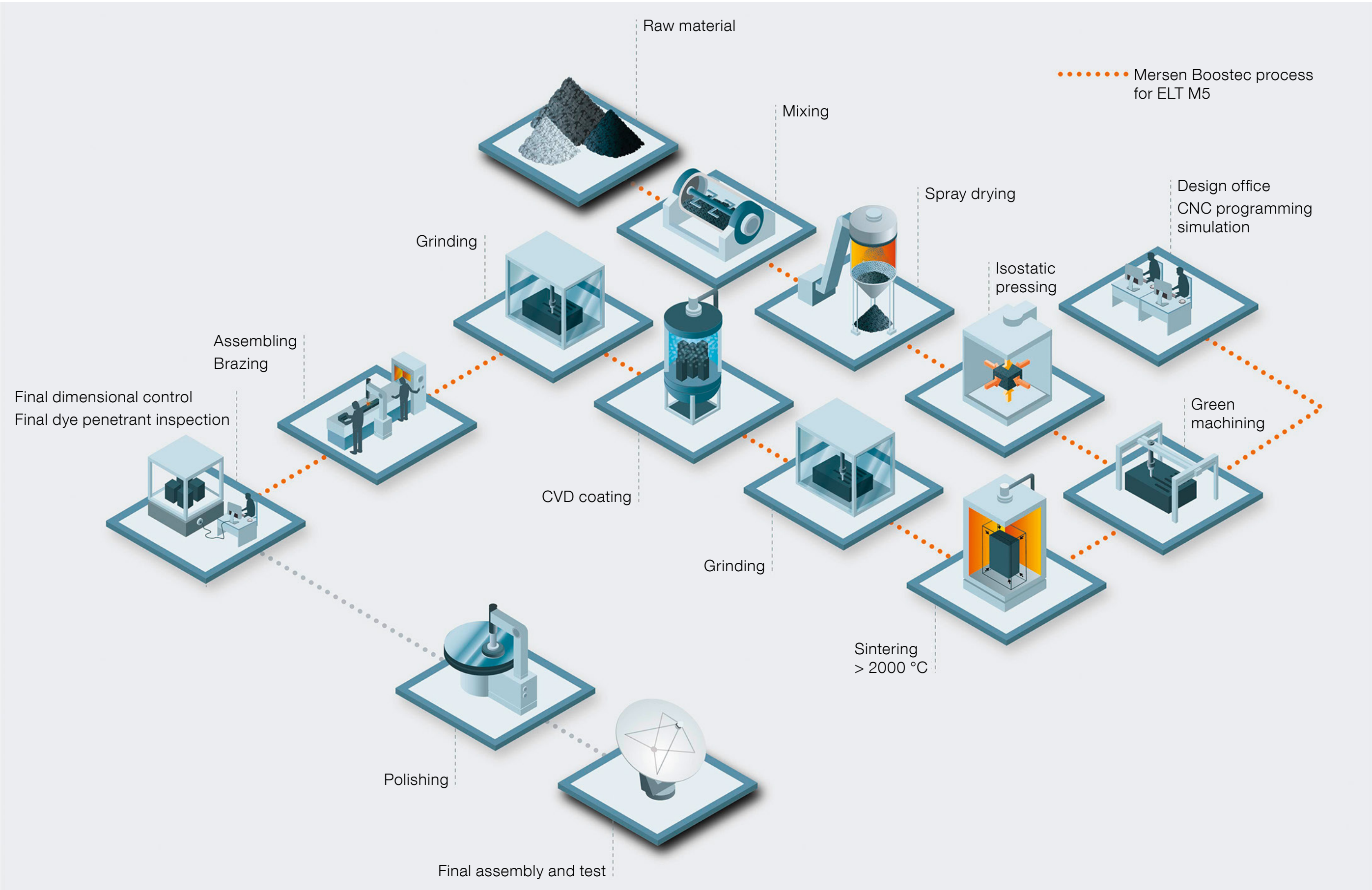
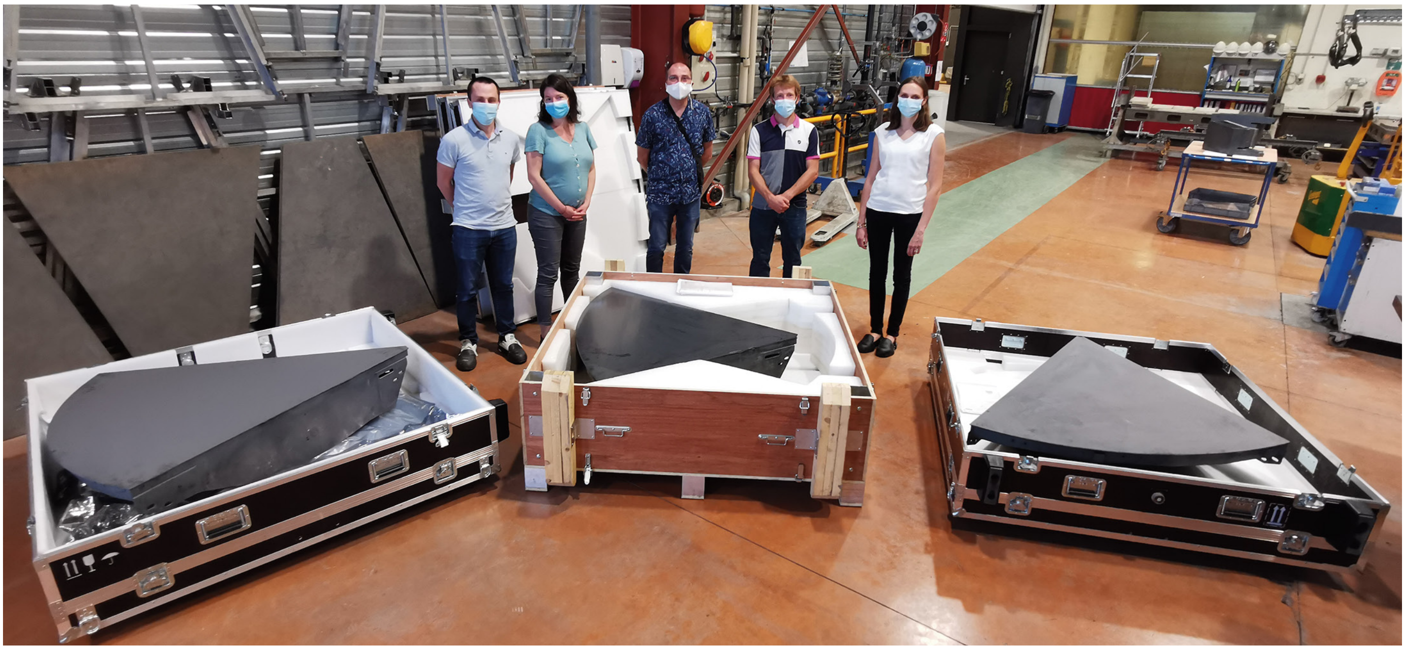


Figure 3. (Above) Full manufacturing process of the M5 mirror.

Figure 4. (Below) Early July 2021: three mirror segments with CVD cladding at Boostec.

Mersen Boostec



Before brazing them together, the segments must be aligned in such way that the positions of the axial support interfaces are within the required tolerance and that the brazing joints meet the specified thickness. Once the six petals are well aligned, the unit is brazed. The CVD layer requirements reduce the tolerance one can accept in the segment positioning as any misalignment of the optical surface will reduce the final CVD layer available for polishing. After brazing, Mersen Boostec will perform a final grinding of the flat optical surface to make the blank ready for delivery to Safran Reosc.

The mirror blank will be delivered to Safran Reosc in the autumn of 2022 and once the axial and lateral supports are mounted, polishing will last for two and a half years. The mirror will be ready to be shipped to the observatory by the end of 2025.

M5 cell description

The M5 cell design is driven by the technological challenge of performing a fast-steering motion capable of rejecting perturbations at the scale of a few tens of milliarcseconds on the sky.

SENER Aeroespacial is the company developing the M5 cell re-using experience acquired with the development of a functional M5 field stabilisation unit demonstrator (Barriga et al., 2014), in collaboration with CEDRAT TECHNOLOGIES for the piezo actuators.

The design of the M5 cell has been driven by stricter requirements than those that applied to the demonstrator and this has forced the SENER Aeroespacial team to apply state-of-the art methods and procedures whilst analysing different alternatives and iterating them to obtain a robust result. Moreover, the addition of a new functionality — providing active alignment at low rate in piston and tip-tilt — has necessitated the division of the M5 cell into two stages, which has added a new twist to the design (see Figure 5).

The high relative accuracy and resolution requirements have driven the design of the tracking chain and have justified the selection of high-precision sensors and state-of-the-art acquisition electronics. The decision to reposition the M5 Cabinet and the front-end electronics to the M5 cell has also improved the design of the M5 cell.

Another demanding requirement has been the new and higher minimum eigenfrequencies of the M5 cell, and this has had direct implications for the stiffness of the final model.

The technological challenge of both improving the stiffness and the stroke of the M5 tip-tilt actuators and developing a new compact actuator for the M5 alignment stage has been met with good results.

SENER Aeroespacial, together with CEDRAT TECHNOLOGIES (for the APA), is presently finishing the qualification campaign of the different mechanisms. The Final Design Review is expected to take place in the autumn of 2021, well in line with the schedule.

References

Barriga, P. et al. 2014, Proc. SPIE, 9145, 91451O
Vernet, E. et al. 2020, Proc. SPIE, 11445, 114453O

Figure 5. M5 cell alignment and tip-tilt stage.