# Constructing the E-ELT

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**At its meeting on 3 and 4 December 2014, the ESO Council gave the green light for the construction of the E-ELT in two phases and authorised spending of up to 1012.5 million euros on Phase 1, which will provide a fully working 39-metre telescope with a suite of powerful instruments. It will allow the initial characterisation of earth-mass exoplanets, studies of the resolved stellar populations in nearby galaxies as well as ultrasensitive observations of the deep Universe. This article provides the context for this momentous decision and describes the two-phase approach.**

## Background

With its 39-metre primary mirror, the European Extremely Large Telescope (E-ELT) will be the largest optical and infrared telescope in the world. By opening up observational parameter space in several decisive ways, the E-ELT is set to revolutionise many areas of astrophysics and technology. Its timely construction is therefore of the highest priority for ground-based astronomy worldwide.

To set the scene for the recent Council decision, it is useful to cast our minds back to 2012. Following the detailed design phase and successful technical and financial reviews, ESO Council approved the E-ELT construction as a Supplementary Programme in December 2012. This approval was based on a financial model in which the construction cost of the E-ELT is funded by: (i) ESO's current income; (ii) a 2% year-on-year increase of the Member States' annual contributions, on top of normal indexation, for a period of ten years; (iii) a one-time extra contribution by the Member States which can be paid in up to ten annual instalments; and (iv) extra income resulting from Brazil's accession to ESO.

However, since not all Member States were in a position to commit in December 2012, and since Brazil had not yet completed its accession at that time, the approval was subject to the condition that contracts worth more than 2 million euros could not be awarded until 90% of the E-ELT's cost-to-completion of 1083 million euros (in 2012 prices) had been committed. The only exception to this rule was the work required for the preparation of the site. By June 2014, all 14 Member States had joined the E-ELT resulting in 71% of the E-ELT's cost-to-completion being in hand. Poland's accession as an additional Member State to ESO will raise this fraction to 78% in the course of 2015.

Concurrently with the project's approval in December 2012, ESO Council and the Executive began to explore potential options open to ESO in case the ratification of the Brazilian Accession Agreement would not be completed in the foreseen timescale. Fortunately, the ratification process has since progressed well, but at present is not yet completed. The ESO file has passed three commissions within the Brazilian Chamber of Deputies, but still needs to pass a fourth commission and a Plenary Session. The file will then go to the Senate, where the procedure is expected to take around six weeks, followed by the Brazilian President's signature.

Considering the progress of the competing giant telescope projects, the needs of the E-ELT instrument consortia, the dwindling overlap with the foreseen operational period of the James Webb Space Telescope (JWST) to be launched in 2018, and the need to maintain the interest of ESO's industrial partners, it became clear by mid-2014 that the ongoing day-by-day delay was posing an increasing risk to the project and to the scientific aspirations of the ESO community. Finding a way to allow the project to move forward, even in the temporary absence of Brazilian funding, while still respecting Council's "90% rule", thus became a matter of some urgency.

## Moving forward

After considering several options to resolve this situation, it became clear from consultation with ESO's governing bodies in the first half of 2014, that the eventual solution would have to: (i) preserve the superb scientific capabilities of the E-ELT as much as possible; (ii) preserve the current baseline first-light date of 2024 as much as possible; and (iii) avoid the need for any long-term loans. As a result Council, in June 2014, asked for the development of a two-phase construction plan for the E-ELT, such that the funding needed for Phase 1 does not require the completion of Brazil's ratification of its Accession Agreement or any additional funds from the current Member States. This is achieved by transferring some 106.5 million euros to Phase 2 and by extending the duration of construction by up to two years, unless additional funds can be identified.

This plan was developed in consultation with ESO's governing bodies through a series of meetings that took place from July 2014 onwards. It was formally recommended by the Scientific and Technical Committee in October 2014 and by the Finance Committee in November 2014. Based on these recommendations, the ESO Council approved the two-phase approach and, most importantly, authorised spending up to 1012.5 million euros on Phase 1 during its meeting on 3–4 December 2014. The decision needed ten positive votes. Three of the 14 votes are so-called *ad referendum* votes, which means that they are to be considered as provisionally positive and subject to confirmation by the authorities in these three Member States before the next Council meeting.

Council remains committed to building the entire E-ELT as originally designed and scheduled. In particular, the two-phase approach only involves the potential deferral of some items but no design changes (with the exception of the telescope's pre-focal stations, see below). Furthermore, future approval of Phase 2 is only contingent on the availability of funding. Individual Phase 2 items will be reinstated (and/or first light brought back to 2024) as soon as the required additional funding becomes available. In particular, as soon as Brazil completes its ratification process, Phase 2 will be reinstated in its entirety. Finally, it is extremely important to note that the procurement schedules of the baseline construction

plan and of the two-phase plan only start to diverge in 2017. This is the earliest time at which any Phase 2 item would have to be deferred. If Brazil completes its ratification process before this time then the two-phase plan is identical to the original baseline. In the unlikely event of Brazil joining later, some delays and extra cost will be accrued, but the full E-ELT will still be built. Effectively, the two-phase plan therefore simply allows ESO to move ahead with the construction, while awaiting the completion of the Brazilian ratification process.

## The two-phase approach to E-ELT construction

There are few technical options to reduce the overall cost of the 39-metre E-ELT, as the current design is the result of the delta phase B study, that had, as its main goal, the identification and implementation of such options for the original 42-metre phase B design. A detailed analysis of the baseline plan has been carried out to identify which components are indispensable and lead to first light with a working and competitive telescope (Phase 1), and which components can be moved to Phase 2 to await the availability of additional funds. For this exercise to result in a financially viable Phase 1, a target of ~ 110 million euros had been set for the total scope of the components to be moved to Phase 2. The main items that were identified for transfer to Phase 2, and thus for potential deferral into the future, include infrastructure and telescope components, as well as an adaptive optics module. These are briefly described here.

The baseline plan includes power conditioning to stabilise its quality so that power cuts or surges affect operations as little as possible. Deferring this procurement could somewhat increase the technical downtime, but would not affect the ability to do science or the date of first light. The Chilean government has assisted in enabling the construction of a grid connection to the Paranal–Armazones area. Work started in mid-2014 and will be completed in 2018. It is possible that the quality of the resulting grid power will be sufficient for smooth operations, so that this procurement could be reduced in cost, or might not be necessary at all.

The E-ELT's primary mirror (M1) is composed of six identical sectors of 133 segments each. The 133 segments are different to each other both in shape and optical prescription. The baseline plan foresees the procurement of a seventh sector strictly needed to guarantee the replacement of the segments in a turnaround plan to maintain a constant reflectivity and micro-roughness level. This is achieved by replacing two segments every day (the worst ones in terms of both reflectivity and scattering/micro-roughness) with two mirrors from the (freshly coated) seventh sector. In this way the entire M1 mirror is totally refreshed in approximately 18 months.

It is, however, possible to postpone the procurement of the seventh sector and, for the first few years of operation, either wash the segments *in situ* or periodically leave several segments unfilled for short periods. Paranal experience shows that a proper washing of aluminium-coated mirrors recovers almost 100 % of the condition of a freshly coated mirror. Alternatively, and still without procuring the seventh sector, the segments could be recoated rather than washed, accepting a few missing segments in M1 at any time. The result would have a minor scientific impact, but a higher maintenance workload, provided the most demanding extreme adaptive optics observations are scheduled for times when the mirror is fully populated. Transfer of the seventh sector to Phase 2 also enables the M1 coating plant to be descoped (one plant instead of two).

The procurement of some of the inner rings of segments of M1 has emerged as one of the most important transfers. Analysis has demonstrated that the maximum number of rings that can be moved to Phase 2 is five, representing 210 M1 segments. This will obviously have an impact on collecting area (reduced by 26 %), but the 39-metre annular aperture will preserve the original spatial resolution (loss of ~ 25 % at low–mid spatial frequencies while leaving the higher spatial frequencies almost untouched). The loss in sensitivity can, in most cases, be recovered by increasing the integration time. Removing the sixth inner ring was considered but the risk that this would negatively impact the wavefront control of the telescope was deemed too high.

Since the procurement of M1 is currently on the critical path of the E-ELT, reducing the number of segments in Phase 1 will generate some schedule margin for the project. Fewer rings will also reduce the overall workload for M1 segment procurement and installation, thereby accelerating the Assembly, Integration and Verification (AIV) sequence for the telescope. However, the interfaces of the main support structure will still be installed and aligned, as would be required for the proper installation of the segments, because the mirror cell loading affects the interfaces. Moreover, this will minimise the downtime required for the future installation of the deferred segments. The telescope balance will be maintained by installing dummy masses at the missing M1 interface points.

The instrument optics will be designed for the full M1 aperture. The pupil stop which masks the unfilled area (and which is present in all infrared instruments) will match the partially populated primary and will need to be exchanged for the smaller central obstruction when the full primary is installed.

The E-ELT instrumentation roadmap foresees a total of seven first-generation instruments. Originally, the two first-light instruments, the Multi-AO Imaging Camera for Deep Observations (MICADO) and the single field visible and near-infrared integral field spectrograph HARMONI, including their associated adaptive optics (AO) systems (the multi-conjugate AO [MCAO] module MAORY and a laser tomography AO [LTAO] module, respectively, together with six laser guide stars), as well as two additional instruments, were to be supported from the construction budget. However, the non-indexation of ESO's budget in 2013 led to the removal of one of the latter two instruments from the E-ELT construction budget to the instrumentation development line in the E-ELT operations budget. The current baseline construction plan thus includes three instruments and their associated AO systems, where the Mid-infrared E-ELT Imager and Spectrometer (METIS) has been identified as the third instrument due to its more advanced

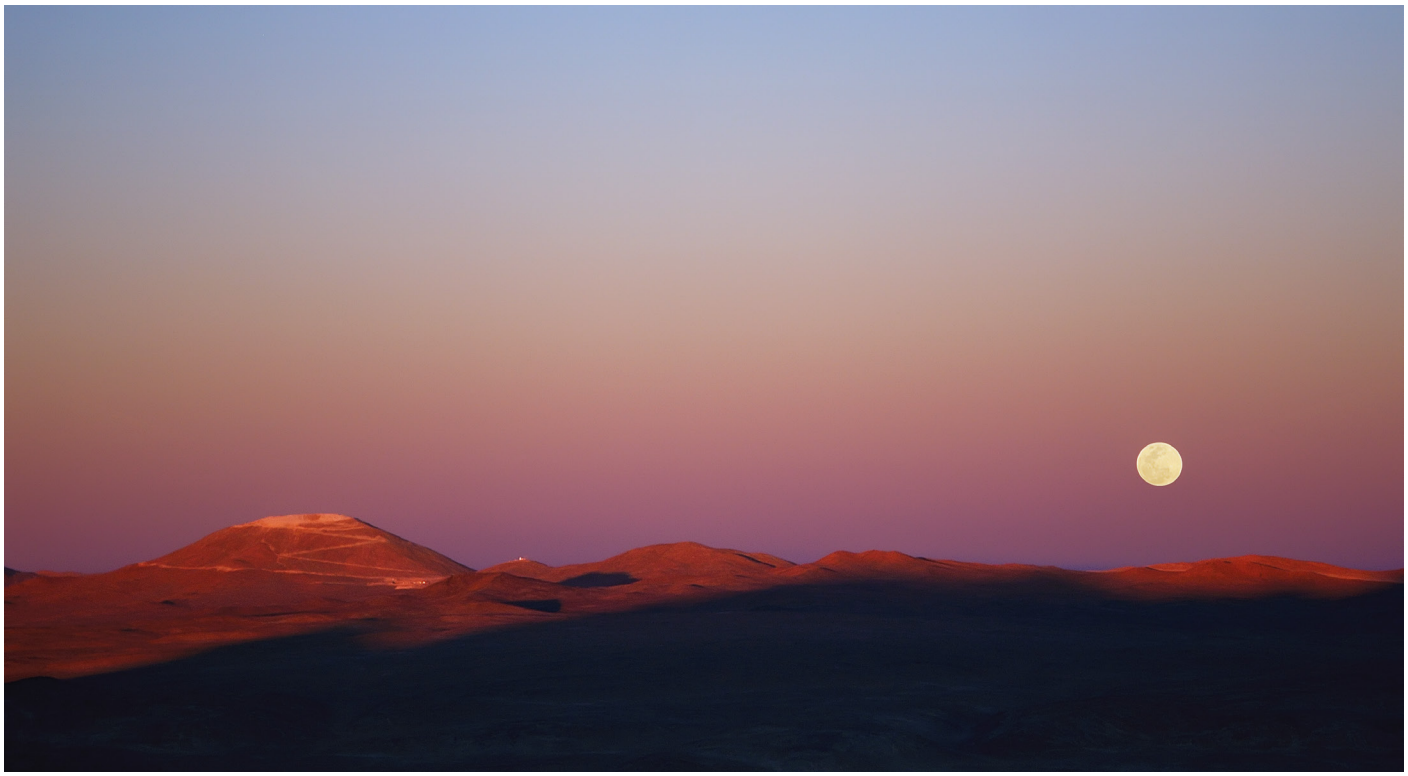

Figure 1. A recent image of the site of the E-ELT on Cerro Armazones, taken from the VLT platform on Cerro Paranal.

technical readiness compared to the other two potential candidates (a multi-object spectrograph [MOS] and a high-resolution spectrograph [HIRES]), each of which requires a competitive Phase A study to be carried out first). Deferring any of these three instruments or some of the AO capabilities would obviously result in a loss of science.

Nevertheless, in order to reach the goal for the total scope of the items to be moved to Phase 2, some transfer in the area of instrumentation was necessary, and so a very difficult decision had to be made. After considering several options it was decided to move two of the six powerful lasers and the LTAO module to Phase 2. The deferral of the LTAO module would severely affect the sky coverage of both HARMONI and METIS, leaving both instruments with single conjugate AO (SCAO) only, but keeping all three instruments as well as MAORY in Phase 1 was deemed important because it maximises the support of the instrument building community and secures the investment already put in place by many of the Member States. In addition, it is estimated that the LTAO system needs only seven years to implement, whereas METIS needs nine. There is therefore more time to secure the Phase 2 funding needed for LTAO and still be ready at first light. LTAO is the highest priority item in Phase 2 and will be implemented as soon as the required funding has been identified. Importantly though, Phase 1 does include funding for the preliminary design of the LTAO system, as well as for MOS and HIRES.

Each of the E-ELT's two Nasmyth platforms is to be equipped with a pre-focal station (PFS). Since all three Phase 1 instruments can be attached to a single PFS, the second PFS can be moved to Phase 2. Its deferral would have no impact on science while only three instruments are in use. In addition, the first PFS can be descoped by utilising a simplified adapter and the existing planned wavefront sensing systems of the instrumentation and the AO systems. This approach requires an evolution of the interface between the telescope and the instruments, requiring a closer collaboration between the activities of the telescope and instrument design teams. The simplified adapter will not provide ground layer AO (GLAO) capability but will be compatible with SCAO, LTAO and MCAO. The design of the descoped PFS will take into consideration a possible future retrofit which would restore the original PFS capability. This is the only design change required by the two-phase approach.

## First light of Phase 1

The items described above amount to a total transfer of 106.5 million euros to Phase 2. The funds so far committed to the E-ELT (including the funds expected from Poland's accession to ESO in 2015) therefore represent 86 % of the cost-to-completion of Phase 1 of 997.5 million euros (in 2014 prices). This still leaves a gap of 4 % to meet ESO Council's 90 % rule. Several options are available to close this gap. However, at this time the

Figure 2. The members of the ESO Council and senior ESO staff photographed in the Council Room at ESO Headquarters during the meeting at which the decision to approve the two-phase construction of the E-ELT was made on 3 December 2014.

only safe planning option is to consider a delay of the date of first light for Phase 1 by about two years. The postponement of the start of operations by approximately two years would allow adding much of the E-ELT operations funding, foreseen in the baseline plan for this period, to the Phase 1 construction funding, and would help to create a smoother cash-flow profile. On the other hand, it would also slightly increase the cost of Phase 1. If indeed required, the extension of the construction period would be accomplished by re-scheduling some procurement actions. The contracts themselves would not be stretched and all currently existing contracts will continue as planned. This avoids the need to re-design any subsystem and makes it possible to revert to the original timeline, or close to it, as soon as Brazil completes its ratification process or another new Member State joins.

The main impact of a two-year delay in first light and the start of regular operations would be on scientific competitiveness, especially considering that the first-light date in the baseline plan has already been tracking the delays in the start of construction for some time. The delay would increase the risk of one of the competing projects arriving on sky significantly earlier than the E-ELT and would reduce the chances of any overlap between the operations of the E-ELT and JWST. This would be exacerbated by the potential slower pacing of instrument arrivals.

## Conclusions

ESO's Member States are fully committed to building the E-ELT while keeping the La Silla Paranal Observatory as well as the Atacama Large Millimeter/submillimeter Array (ALMA) at the forefront of astronomy. With its decision to adopt the two-phase approach to the construction of the E-ELT, and to authorise spending on Phase 1 for a cost-to-completion of 1012.5 million euros, Council has given the green light to move full-steam ahead with the construction of the world-leading E-ELT on a competitive timescale. This momentous decision marks the end of a period of uncertainty after the programme was formally approved in late 2012 but not all the required funding had been committed.

The Phase 1 E-ELT as described above will be a very powerful science machine, integrated into the Paranal system. It will enable the initial characterisation of earth-mass rocky exoplanets, allow the study of resolved stellar populations in nearby galaxies out to the Virgo Cluster and provide unprecedented sensitivity for studies of the deep Universe. Phase 2 is, however, absolutely required to meet the longer-term scientific aspirations of the community.

It is important to realise that Council's decision does not mean that only the Phase 1 E-ELT will be built. The construction will proceed according to the baseline schedule, aiming for first light in 2024, until at least early 2017. If Brazil has completed the ratification of its Accession Agreement by that time, then the two-phase approach (and this article) will have become entirely irrelevant, except for having prevented further delays.

The signal sent by this decision to the worldwide scientific community, to the E-ELT instrument teams and to industry in the ESO Member States is thus entirely positive: the E-ELT is now becoming a reality.

### Acknowledgments

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