E-ELT Phase B Final Design Review
September 21-24 2010
Report of the Review Board

Introduction

A comprehensive design review of the E-ELT project was held at ESO headquarters in Garching on September 21-24, 2010. The Review Board consisted of 11 members: Chuck Claver (NOAO/LSST), Matt Johns (GMT), Doug MacMynowski (Caltech/TMT), Buddy Martin (Steward Observatory Mirror Lab), Harald Nicklas (Univ. Gottingen), Roberto Ragazzoni (INAF), Francois Rigaut (Gemini), Steve Shectman (Carnegie/GMT, chair), Luc Simard (HIA/TMT), Doug Simons (Gemini) and Larry Stepp (TMT). Members of the Review Board have been involved in many recent or ongoing telescope projects: GMT, TMT, LBT, LSST, Gemini and Magellan, and have experience with project management, optical fabrication, telescope engineering, control systems, instrument development, adaptive optics and observatory operations.

In early August the members of the Review Board were provided with the Telescope Construction Proposal, which provides a detailed technical summary of the telescope design, together with additional documents summarizing the E-ELT Science Case, Instrumentation Plan, Operations Plan, and System Engineering. At the same time, the Review Board was provided with more than 300 reference documents which provide detailed information on all aspects of the E-ELT development effort. A few weeks prior to the review, Board members were presented with additional reports on the E-ELT Management Plan and Construction Schedule, and during the review were given access to confidential documents concerning the project budget.

Prior to the review, Board members submitted more than 300 RIXes with questions, comments and suggestions. The project prepared responses to all RIXES to the satisfaction of the Review Board, most in advance of the review, some during the review, and in a few cases shortly afterwards.

The Review Board heard ~20 hours of presentations by 18 representatives of the project, who prepared ~1000 viewgraphs specifically for the review. Additional members of the project team attended the presentations, and extensive discussions on points of particular interest occurred between members of the Board and the project staff, both during the presentations and off-line during breaks in the presentations.

Technical Readiness

Terms of reference were provided to the Review Board in a short document prepared by ESO management. The top-level question posed to the Review Board was whether the technical maturity of the design of the E-ELT is sufficient to warrant the program entering the construction phase. It is the unanimous conclusion of the Review Board that the answer to this question is “Yes.”

Of course the E-ELT project, and the Review Board, are aware of many areas where the design can be improved during the final design process. This is entirely to be expected in a project of this size and complexity. Many of these areas are discussed in the detailed discussion which follows the introductory remarks in this report. It is especially noteworthy that most of the issues have been openly identified and discussed by the E-ELT project, and work to resolve them is ongoing. Although the issues to be resolved vary from minor to very important, and some of them are critical to the performance of the telescope, they do not affect the overall conclusion that the project is ready to enter the construction phase, and that there are no fundamental barriers to the ultimate success of the E-ELT project.

The performance requirements for the E-ELT are challenging and in a few areas the design has difficulty in fully satisfying the top-level requirements under the full range of observing conditions. Once again it must be stressed that the project is fully aware of these issues, has been open and forthcoming about discussing them, and is working to resolve them.

The perception at ESO at the beginning of the E-ELT design process was that the European effort was significantly behind the other two ELT projects (TMT and GMT). Thanks to an outstanding effort by the E-ELT project, the level of design and construction readiness of the E-ELT is now at least comparable to that of the other two projects. This is especially impressive considering that E-ELT is the most ambitious of the three.

The terms of reference also request that the Review Board identify critical components and performance issues which pose a significant risk to the success of the project. These are discussed at length in the detailed remarks which follow. Most noteworthy is that the project cannot succeed without a fully adaptive M4, and that some difficulties remain in the performance of the M2 mirror which is exposed to significant wind disturbances.

Cost

More than half of the estimated cost of the E-ELT is the result of Front-End Engineering Designs leading to firm, fixed-price offers. The Review Board agrees that the FEED methodology has been highly effective in generating reliable cost estimates.

The cost per unit of collecting area or per kg of fabricated material are in general consistent with (and in some cases lower than) the costs which have been generated by other projects. Overall the E-ELT budget is highly cost-effective.

Independent industrial design studies have been conducted for the major subsystems of the E-ELT as part of the FEED process. One consequence is that in some cases heterogeneous solutions to similar problems have been generated for different telescope subsystems. This will lead to a certain amount of increased effort in the long-term maintenance and operation of the facility. It is also evident in some cases that one design is better than another according to a variety of metrics such as performance, reliability, simplicity and cost. During the detailed design process, the E-ELT project should work with its vendors to resolve these issues, where it is possible to do so without seriously compromising the results of the industrial procurement process.

Schedule

The E-ELT construction time of 6-7 years is comparable to the construction time for an 8m-class telescope. No 8m-class telescope was constructed in significantly less time. However the construction process for the E-ELT is far more complex than for an 8m-class telescope. The amount of material involved is an order of magnitude greater, there is extensive machining of very large components which can only be performed on-site, and there is much less opportunity to find and correct problems during factory pre-assembly, which will be limited.

The on-site assembly effort has been intensively scheduled with a high level of interleaved activity by different contractors on different components of the facility. This intensive level of simultaneous activity makes the project vulnerable to delays which can then carry over from one part of construction to the others.

The situation regarding the schedule for AIV and commissioning is even more difficult than it is for construction, both in respect to the comparison to 8m-class telescopes, as well as to the much greater complexity of the facility and of the activities which must take place. The Review Board does not consider the time allocated to AIV and commissioning of the E-ELT to be credible.

The consequence of these considerations is that ESO must be prepared for the likelihood that the actual time to complete the telescope will be considerably longer (by perhaps 2-3 years) than is called for in the schedule.

In some respects it may be advantageous for the E-ELT project to promulgate such an aggressive schedule in order to keep the project moving as rapidly as possible. However it is especially important that the project should avoid making important programmatic decisions, that might compromise the technical performance of the completed facility, because of unrealistic considerations regarding the schedule.

Contingency

The current contingency for the E-ELT construction budget is 180M Eur. The Review Board understands that 45M Eur of this contingency is in fact the best estimate for the effect of the variance between the cost escalation of the ESO funding stream and the cost escalation of the construction budget during the course of the project. While it is reasonable to hold these funds in the contingency account, the Review Board does not consider them to be part of the true contingency allocation. While the contingency held by the FEED contractors is a necessary component of the FEED contracts, the Review Board does not consider contingency held by the FEED contractors to be available contingency funds at the project level.

The remaining contingency (135M Eur) represents 12% of the estimated cost of the project. There are of course a variety of sources which can result in calls on the contingency funds: schedule delays, estimating errors both for manpower as well as component and subassembly costs, problems with technical performance and so on. While there are several methodologies which can be used to estimate the appropriate level of contingency, to some extent the different methodologies are making estimates for different effects. For this reason the various contingency estimates may be partly additive rather than strictly comparable to one another.

The result of these considerations is that contingency estimates must be interpreted with a certain level of judgment and in view of the tolerance of ESO for different levels of uncertainty in the final cost of the project. It is the opinion of the Review Board that the contingency allocation for the E-ELT project should be higher than 12%. However the appropriate level of contingency is a matter of judgment which must be arrived at by the various levels of management of ESO and of the E-ELT project.

Detailed Discussion

The following sections present a detailed discussion of the E-ELT project. The remarks were prepared by members of the Review Board with detailed knowledge and experience pertaining to each area, but the entire Review Board has reviewed and subscribes to the content of the report. The sections are organized along similar lines to the materials and presentations prepared by the project.

Project Management

The Management Plan describes the overall ESO structure under which the E-ELT Project will be conducted, including reporting channels, team members and responsibilities, work breakdown structure, safety and risk management, as well as various elements of project control including configuration management, change control, interface management, quality assurance, etc.

The project is organized around a management structure with well-defined roles and lines of reporting for key individuals and committees starting from the Council level and extending down to WBS level 3 managers. Staffing is complete to level 3.

The WBS is organized around the deliverables of the project. It is well developed at this stage. Budgeting and scheduling take place within the framework of the WBS. Progress will be tracked by expenditure versus work completed using earned value analysis.

Safety procedures for E-ELT follow standard ESO practice. A risk management plan has been developed specifically for E-ELT and is described in reference documents.

In general, the Review Board considers the management structure and controls for E-ELT as described in the review material and presentations to be appropriate for a project of this type and scale.

System Engineering

System engineering controls for E-ELT are described in the Management Plan. In general the procedures comply with ESO standard practice but are extended in some cases for this project. Project documents are maintained in a database with well-defined procedures for configuration management and change control. A Configuration Control Board is in operation.

Specifications for the E-ELT project are captured in a database maintained by System Engineering. A staff member has been tasked with maintaining the database. The top-level requirements (TLR) have been established for the project and are set forth in a document which is under change control. The development of Telescope-Site-Infrastructure level 1 specifications has been a bottom-up exercise that will need to be reconciled with the TLR. The project has indicated that this reconciliation is a planned activity. In some cases where the design of the telescope does not meet the full performance specified in the TLR, the project may have to reconcile these realistic estimates with its stakeholders.

A large fraction of the level 1 requirements are complete but there are items in the document that are not yet specified, particularly in the areas of thermal controls, interfaces and other-miscellaneous. Various work packages that will be contracted starting in the near future will draw on these requirements for their specifications, so it is important for the project to continue the development of these areas.

The project maintains an N-squared register of all interfaces between subsystems down to level 3 of the WBS under the control of System Engineering. The register entries are electronically linked to associated interface documents. 88 major interfaces have been identified of which 31 remained to be specified. Most of the latter are associated with subassemblies still in conceptual design. A more comprehensive presentation by the project covering the interface control process was skipped due to a shortage of time. The Review Board expects that the project will complete the relevant interface documents prior to the release of work packages for the associated subsystems.

The requirement for a maximum 10% thermal emissivity of the telescope optical system as specified in the TLR and level 1 requirements is inconsistent with the current design. The discrepancy will have to be resolved when the level 1 requirements are reconciled with the TLR and telescope design.

The telescope image error budgets for single-conjugate adaptive optics (SCAO) and ground-layer adaptive optics (GLAO) are specified in a document which is under configuration control. The specifications have been derived from the TLR. The project has employed a bottom-up approach to calculating the contributions from various error sources to the error budgets through finite element and optical analysis.

The SCAO error budget is expressed in terms of wavefront error (WFE) under the operating conditions specified in the TLR. The requirement that the wavefront error be less than 210nm rms is very challenging given that the atmospheric contribution over which the project has no control is 170nm, leaving only 123nm for the rest of the telescope. The computed WFE from all sources in the current design is 336nm. By far the largest contribution to the error budget, 222nm, is tip-tilt of the secondary mirror assembly due to wind-caused vibrations with the telescope pointed directly into a high wind.

The project plans to address the performance of the secondary mirror mount during detailed design. The performance estimate for M2 under the influence of wind may be conservative due to the choice of assumed spectrum, and because the current performance estimate corresponds to ~90th percentile conditions. Moreover several design options have been identified for mitigating this source of error, and at some point it will be reasonable to adopt one or more of them. Operational mitigation, for example by observing at an angle to a high wind, can also be used to ameliorate this effect.

GLAO performance is calculated in terms of point source sensitivity (PSSn), a measure of the concentration of light in the image relative to a reference configuration. The metric is not easily converted to more common measures of image quality such as wavefront error or full-width at half-maximum amplitude. In order to achieve the top-level requirement that the FWHM of the image point spread function be reduced by a factor of 2 over the seeing-limited case at 2 microns under median seeing conditions, a PSSn of about 4 is required. The calculated value in the error table is 1.75.

The project has developed a detailed error budget and evaluated many sources of performance degradation, including wind buffeting (on the structure, on M2, on M1 segments), dome seeing, residual errors from gravity and thermal deformation of the main structure, the effect of the M2 spider on segment misfigure and phasing, vibrations, control system errors (sensor and actuator noise, sensor drift, calibration, phasing), the effects of not having all sensors present and phased all the time, polishing errors, mirror support print-through, thermal deformation of M1 segments, wavefront sensing errors, etc. Performance estimates have been derived in an efficient manner by building appropriate models to answer specific questions, rather than by investing unnecessary effort in building a single comprehensive simulation.

There is time during the construction phase for further maturation of the performance estimates to have a significant impact on subsystem designs. The Review Board encourages the project to continue refining performance estimates in order to identify concerns before contracts are let, and to improve the eventual performance of the telescope. This should be accomplished without delaying the construction schedule, in particular with regard to the dome and main structure contracts which are on the critical path and must be contracted early.