E-ELT Assembly, Integration, and Technical Commissioning Plans

P. Gray*, Ciattaglia, E., Dupuy, C. Gago, F., Guisard, S., Marrero, J., Ridings, R., Wright, A.
European Southern Observatory (ESO), Karl-Schwarzschild-Str. 2, Garching, Germany

ABSTRACT

EELT AIV is the activity of assembly, integration and verification of EELT (European Extremely Large Telescope) subsystems to deliver a telescope capable of fulfilling its top-level requirements and ready to start science commissioning, leading to operations. The AIV (Assembly Integration Verification) phase covers all technical activities on Armazones and nearby Paranal Observatory from the moment the sub-systems and components are delivered or accepted on-site (from the responsible sub-system project manager).

AIV includes final system tests of the completed telescope (known as "Technical Commissioning") and the installation, alignment and telescope integration of the science instruments. The AIV phase ends with the handover of the completed telescope with installed instruments, to the start of Science Commissioning. Responsibility then passes to the Commissioning team, however the technical resources for debugging and tuning the telescope and instrument will come from a combination of the AIV team working together with the Paranal operations staff.

AIV is one of the major technical challenge of E-ELT. The sheer scale and complexity of the telescope involves challenging logistics and scheduling i.e. 798 mirror segments with a staged delivery over four years, including 9,048 edge sensor and 2,394 position actuators. More than ten major sub-systems e.g. M2-3-4-5, PreFocal Station (PFS) and instruments will be integrated and tested in parallel.

Finally, the technical commissioning phase will be a significant challenge. E-ELT is a highly complex active telescope system with a fully-integrated adaptive optics (AO) system. During early testing nothing will be straightforward and there will be many system-level problems to overcome. It will take a dedicated team of the "best of the best" people to troubleshoot, debug, tune, and hand over as an operational facility.

Keywords: E-ELT, EELT, telescope, assembly, integration, commissioning, AIV, Armazones, ESO

*pgray@eso.org; phone +49 89 3200 6313; www.eso.org

Figure 1. EELT Telescope and Dome Conceptual Design

1. INTRODUCTION

AIV is one of the major technical challenges of EELT[1] and is the last major hurdle to be overcome in order to deliver the world's largest telescope ready for science in 2025. The construction of the E-ELT telescope has already considerable technical challenges: the complexity of phasing 798 M1 segments; the mass production of thousands of M1 components[4]; the polishing and testing a 4 m class convex M2 mirror[4]; the manufacture and control of the large M4 adaptive mirror; and finally the sheer scale and moving mass of the E-ELT dome and telescope.

The E-ELT project defines the AIV phase as the complete activity of assembly, integration and technical commissioning to deliver both a science-ready operational telescope and the first light instrument suite which are technically capable to meet the top-level requirements and ready to start science commissioning leading to operations.

The scale and complexity of the E-ELT means that AIV involves considerable logistical and scheduling challenges i.e. 798 mirror segments with a staged delivery over four years and more than 4,524 edge sensor pairs, 2,394 position actuators. There are ten major sub-systems; the M2-3-4-5 mirror units each of which is a major system in itself; the large Prefocal Station (PFS)[3] with the acquisition, guiding and wavefront sensing systems; and finally the four major instruments and post-focal AO systems will be integrated and tested in parallel.

AIV is responsible for technical activities that occur on-site in Armazones from the moment the sub-systems and components are delivered or accepted on-site (by the sub-system E-ELT project manager). This is followed by the final system tests of the completed telescope (known as "Technical Commissioning") and the installation, alignment and telescope integration of the science instruments. The AIV phase ends with the handover of the completed telescope with installed instruments to the start of Science Commissioning. Responsibility then passes to the Commissioning team, however the technical resources for debugging and tuning the telescope and instrument will come from a combination of the AIV team working together with the Paranal Observatory operations staff.

This paper outlines: the overall strategy which is being followed for E-ELT AIV; the planned resources (staff, facilities, equipment) which will be employed; the detailed scheduling of tasks and milestones; and specific details of some of the more critical AIV activities.

2. E-ELT AIV STRATEGY

The planning, coordination and execution of all on-site AIV activities is under the responsibility of the E-ELT AIV Manager, assisted by the sub-system project managers and their teams. The staff required to support the on-site AIV activities are provided from a pool of dedicated AIV staff resources supplemented by staff from the sub-system teams working on-site. The AIV Manager is responsible for supervising, coordinating, and prioritizing their work.

For project deliverables which involve additional on-site work by contractors, the relevant project manager retains authority for their direct management. However, the AIV Manager will monitor and coordinate their activities to ensure it fits-in with the overall E-ELT schedule and priority, especially when the contractor's activities overlap and/or require the use of shared resources, equipment, and/or facilities.

3. E-ELT AIV OVERVIEW

The AIV phase starts with the arrival of the first M1 mirror assemblies several years prior to their telescope installation. The large number of M1 segments that go into the E-ELT M1 necessitates that the production be spread out over several years. Mirror segments will be shipped to Chile as soon as they are completed. On arrival segments will be immediately coated, integrated and functionally tested, then put in storage at Paranal ready for immediate telescope installation.

Similarly, the large number of M1 components (edge sensors, position actuators[6], mounting frames) will be delivered to Chile as early as possible. On arrival they will be unpacked, inspected, tested and put in storage using an assembly-line process, made ready for direct telescope installation.

Meanwhile, on the Armazones summit, the Dome and Main Structure (D&MS) contractor[2] will be constructing and integrating the telescope structure and its enclosure. This work continues for several years and is managed as an independent activity, eventually delivering to ESO a working dome and telescope structure. On-site acceptance testing of these deliverables is part of the D&MS contract. Only after successful demonstration of the agreed performance requirements will the telescope structure and dome be handed over to AIV responsibility, ready for installation of the telescope opto-mechanics.

The mechanics of each of the major E-ELT mirror sub-systems (M2-3-4-5) is being procured as a complete functioning unit and will undergo extensive acceptance testing with a dummy mirror in Europe prior to being shipped to Chile. The mirror cells and positioners will be partially dismantled before shipping. AIV re-assembles the sub-units and performs various functional and safety tests using dummy mirror blanks. The mirror optics, which in some cases are procured as separate contracts, are shipped to Chile, where AIV will unload, prepare and coat each mirror, before placing in short-term storage to await final integration. Other major sub-assemblies such as the PFS unit and its opto-mechanics are also accepted and tested in Europe, then re-integrated and aligned by AIV at Armazones.

The installation and alignment of the M1 mirror segments[5] is a long duration activity undertaken by teams of AIV technicians working over an extended 12m+ period. The M1 segments are installed in the telescope in rings, from the

center out. Midway through this activity, the M2-3-4-5 sub-units are installed on the telescope using dummy mirrors and functionally tested and controlled under telescope conditions. These sub-units are then removed from the telescope and the real coated mirror optics installed. When a sufficient number of rings of M1 segments have been installed, the telescope is capable of forming an image (1stStar) and night time technical commissioning can now begin. A purpose-built Test Camera will be used for troubleshooting and tuning the telescope optics and independently verifying its performance.

Towards the end of the telescope technical commissioning phase, the four large E-ELT first light instruments[8,9,10] and AO systems[7] are made ready for telescope installation. Their size necessitates that they be assembled off-telescope as modules, before being lifted, installed and integrated on the Nasmyth platforms directly. Responsibility for troubleshooting, testing and commissioning the science instruments is handed over to the Science Commissioning team.

4. FACILITIES, WORK AREAS & SUPPORT EQUIPMENT FOR E-ELT AIV

One of the biggest challenges of the E-ELT AIV phase is to efficiently execute a large number of parallel telescope integration tasks with limited resources. The size and space of the E-ELT buildings and facilities which are available at Armazones are designed primarily for steady-state operations. The E-ELT Auxiliary Building which surrounds the dome does contain a number of technical work areas, including the large Instrument Assembly Area (IAA).

The IAA will have a large floor area, high ceiling and two high-capacity 12T cranes. It will be equipped with utilities and infrastructure (network, cooling supply, LN_2, compressed He) to enable the off-telescope testing of sub-systems.

Even so, to progress the critical activities during the final stages of telescope integration requires the use of multiple integration facilities and work areas. By carefully planning the sequence of off-telescope pre-assembly and integration it is possible to choreograph a sequence of tasks which makes optimum use of the limited Armazones facilities.

ESO plans to base its operational support for E-ELT using the existing infrastructure of the Paranal Observatory. This was one of the drivers for the selection of Cerro Armazones as a site for E-ELT. The Armazones summit platform is connected to Paranal Observatory over a 30km sealed road (estimated journey time 30-45mins). Adopting this approach, a number of the E-ELT AIV activities are planned to be undertaken at Paranal, with the telescope components and sub-systems being transported installation-ready to Armazones.

A new E-ELT Mirror Facility (EMF) will be constructed at Paranal in synergy with the existing infrastructure which will include a dedicated facility for the coating and integration of M1 mirror segment assemblies, as well as a large 5 m mirror handling facility with equipment for lifting and coating the large mirrors. Adjacent to the EMF building, the E-ELT Technical Building (ETB) will be constructed, which will provide a general work area for handling and integrating the numerous M1 components. Finally, a new E-ELT warehouse will be constructed to store and organize the large number of incoming E-ELT components and spare parts.

One unique facility needed at Paranal is the Segment Storage Yard (SSY). This is a large fenced off enclosure where the coated mirror segments will be safely stored inside their individual transport containers while they awaiting telescope installation. This is a one-off facility needed during AIV when the complete set of E-ELT mirror segments are initially needing to be installed.

5. VERIFICATION – THE ‘V’ IN AIV

The verification and validation of the E-ELT (where ‘E-ELT’ means everything, the telescope, dome, facilities, instruments, as well as operational tools, processes and procedures) is an important last step of the E-ELT Programme. The ultimate purpose is to demonstrate systematically through checks, tests and measurement that the E-ELT meets the expectations of the end-users (astronomers and operations) in terms of performance, efficiency and operability.

It is important to make E-ELT available for science as quickly as possible. To achieve this, the verification and validation process needs to be efficient and effective, and to target the systems and performance requirements which matter the most. It may take a period of fine tuning and optimising for some aspects of E-ELT performance to reach their full potential. Nevertheless it is the goal of the E-ELT programme to deliver ready for science use, a telescope which both meets its top-level requirements and which can be maintained and operated efficiently.

The overall strategy will be to rely as much as possible on selected off-telescope functional testing of sub-systems, followed by more thorough system-level testing as part of the general tuning and debugging process. Only where strictly necessary will a separate formal verification test be done.

E-ELT has a comprehensive system engineering-led process[11] for ensuring that technical requirements are verified in a number of ways (by design, analysis, inspection, test) during the design phases, via critical reviews. The contractual process involves several stages of acceptance testing where key requirements of components and sub-systems are checked against a compliance matrix. Therefore, at the time of shipment and delivery to Paranal/Armazones, many of the E-ELT components will have undergone several stages of verification via reviews, quality control checks, factory testing and formal contractual acceptance.

Where necessary, additional on-site functional checks will be made of some individual components in order to reduce the risk of wasted time and effort if faulty components were to be installed on the telescope (e.g. M1 edge sensors, position actuators, electronics and cabling), where the huge number of components makes it more difficult to troubleshoot and identify individual faulty components. Essentially, these inspections and tests of large numbers of components and sub-assemblies are "verifications" performed by quality control and checking.

Large sub-systems such as the M2-3-4-5 Units and the PFS, which are to be mounted on the telescope and whose dismounting for corrective work is complicated, will be verified and tested off-telescope where they can be accessed more easily. The amount of time allocated to these "off-telescope" testing and verifications will depend on the complexity and usefulness compared to "on-telescope" testing of the sub-systems.

For the complete telescope and instrument system, the emphasis during technical commissioning will be more on validation and less on formal verification. That is, does the EELT fulfill the needs and expectations of astronomers and operations support staff? During commissioning, the telescope and its instruments will be used as a system, operating nightly under realistic observing conditions. As well as directly measuring key performance parameters, it will be possible for the 'end-users' to experience the E-ELT first-hand, and properly validate the E-ELT. Note: 'end-users' in this case, are the science commissioning astronomers and scientists, as well as the telescope operations, technical and maintenance staff.

Formally, it is intended that the E-ELT will be verified against the requirements listed in the Level 1 Specification and eventually the Top Level Requirements (TLR) documents. However, the on-going checks, tuning and performance measurements during commissioning are the final validation that the E-ELT Programme has achieved its goals.

6. AIV STAFFING & RESOURCES

The assembly and integration of E-ELT will require a significant number of people. As with the limitations imposed for available technical work areas, it is not possible to schedule an optimum technically-paced AIV schedule because of the finite number of available staff. The E-ELT AIV phase can only progress as fast as the people performing the work. Therefore staffing the AIV phase is a key requirement.

The AIV work falls into several skill sets and expertise areas. There are a number of repetitive installation procedures such as the installation and alignment of the M1 mirror segment interface frames which require teams of skilled opto-mechanical technicians. This work is suited to be done using teams of technical staff which can be contracted and trained to perform a dedicated procedure. Likewise, the incoming handling, inspection and testing of the numerous M1 components can be handled by contracted staff, specifically trained for a mass-production approach. Neither of these tasks are expected to be needed during later E-ELT operations, therefore are suited to outsourcing.

E-ELT has a significant number of complex opto-mechanical systems. Each of these will require experienced senior engineering staff to commission, troubleshoot and tune. Staffing for these tasks will be provided from a combination of engineering talent drawn from the Garching-based project staff, experienced Paranal-based engineering operations staff, and group of new additional engineering staff hired specifically for E-ELT AIV and operations support.

ESO plans to fully integrate the E-ELT into existing Paranal Observatory operations. There is considerable expertise in the existing Paranal engineering staff. ESO intends utilizing this experience by hiring new staff for Paranal engineering operations, freeing up the existing engineers to help with E-ELT AIV.

Finally, one of the biggest technical challenges of E-ELT will be to make it work on-sky as a telescope which meets its ambitious performance requirements. This will require a group of talented technical commissioning staff who will work at night through the final stages of telescope integration to test, tune, and debug the various optical sub-units and control

systems, making them work together as a telescope. Fortunately, ESO has on its staff a number of experienced engineers and scientists who have extensive experience of wavefront sensing and control. Although E-ELT presents some unique new challenges, this group of people will be key to delivering a working E-ELT at the end of technical commissioning.

7. DETAILED PLANNING & SCHEDULING OF AIV ACTIVITIES

The E-ELT had in the past developed a project schedule for the AIV phase which included the overall sequence and estimates for the duration. This schedule was, to a large extent developed top-down based on previous experience with telescope integration and estimates of times required for the various key tasks. However, because of the complexity and number of tasks involved in E-ELT AIV, and because of the importance of balancing key limited resources of telescope access, technical work areas and people, a more detailed technical schedule was required.

A very detailed bottom-up schedule has been developed for the E-ELT AIV phase which breaks down tasks into steps (typically in fractional hours) and links up activities with interdependencies. This allows a more realistic estimate to be made of many one-off tasks such as M2-3-5 mirror coating and installation. Even more importantly, for several key activities involved with the installation and alignment of M1, the bottom-up estimate of task duration allows a much more accurate estimate to be derived for highly repetitive tasks involved with M1 where everything is multiplied by the number of segments (798). For example, the installation and alignment of the all-important 798 interface frames for the M1 segment assemblies is a critical path AIV activity which is estimated to take almost a year. A slight change in the time for an individual step such as the fine alignment process can have a dramatic effect on the total activity duration and hence the overall schedule.

8. DOME & MAIN STRUCTURE (D&MS)

The D&MS contractor[2] is responsible for the complete erection, installation and commissioning of the E-ELT telescope structure, as well as the dome and auxiliary building as a finished facility. They will be handed over to ESO under AIV responsibility after it has been demonstrated, through acceptance testing, to have met its functional and performance requirements.

These acceptance tests will verify that the as-built structure meets the dimensional requirements to the agreed accuracy and provides stable, predictable and repeatable interface mounting points for the telescope optics. This is a key requirement to be demonstrated before ESO's AIV tasks can commence. Of particular importance is the dimensional accuracy and repeatability of the critical interface points for the M1 mirror segments. The contractor will perform a number of surveys and dimensional measurements as part of the formal contractual acceptance testing. AIV staff will witness these tests and attend the acceptance review meetings, however after acceptance, it is planned that ESO undertake a number of additional surveys and measurements to reconfirm the dimensional accuracy of the structure, prior to commencing the installation and alignment of the E-ELT opto-mechanics.

The telescope structure will be fitted with dummy mass units which mimic the loading of the finished telescope so as to ensure the acceptance testing verifies the final telescope configuration. A distributed set of dummy masses (200 tonne in all) mimics the loading for M1, and mass dummies for M2-3-4-5, are installed to provide balance about the elevation axis.

The telescope will be delivered by the contractor fully equipped with encoders and axis motors to permit it to move, slew and track about both EL and AZ axes. The pointing performance will be tested using a small optical pointing telescope (OPT) attached to the structure which will be used at night to perform preliminary pointing tests to verify the accuracy and repeatability of the telescope structure and drive system. Note that this does not fully verify the overall pointing performance.

During acceptance testing, the D&MS contractor will be utilising their own local control system. After handover of the dome and telescope structure, the ESO AIV group will install and connect the final E-ELT Control System, and begin an extensive program of testing, debugging, and troubleshooting of the dome and telescope structure control system. This may involve repeating and re-verifying some of the on-sky tests with the OPT. An important component of the E-ELT control system to be tested will be the Interlock and Safety System (ILS) which must be fully tested and verified before AIV activities can commence, in order to ensure the safe use of the telescope and dome during the particularly complex AIV activities.

9. SUB-SYSTEMS AIV - M2-3-4-5 & PRE-FOCAL STATION (PFS)

Each of the opto-mechanical sub-units M2-3-5 is a major undertakings in its own right. It is planned to contract out the mechanical mirror support cells, together with their positioning systems as separate contracts. Each of these sub-systems will undergo rigorous acceptance testing before leaving Europe, using a dummy mirror which mimics the mass, dimensions, stiffness, inertia and interface characteristics of the real mirrors.

On arrival in Chile, the M2-3-5 sub-units will be unloaded and partially re-assembled by the AIV group. Then using a dummy mirror, AIV will carry out a further series of tests, checks and measurements. This work will be performed in the Paranal E-ELT Mirror Facility (EMF). After these verifications have been completed, the sub-units are stored temporarily ready for telescope installation in Armazones.

Separately, each of the M2-3-5 mirrors will be delivered to Paranal in custom-built shipping containers. On arrival these will be unpacked and inspected by AIV, then prepared and coated in the EMF 5 m. coating unit with the E-ELT over-coated silver coating. The deliver and coating of these mirrors is planned as late as possible (just-in-time) to maximise the available time for production and to minimise the time for coating degradation and aging. Replacing the dummy mirrors used for testing with the real M2-3-5 mirrors in the mirror cells, occurs just before 1st Light and after telescope testing of the sub-units with dummy mirrors.

The Pre-Focal Station is a large sub-unit which performs the critical functions of acquisition and guiding as well as wave front sensing for active optics control. It also allows the telescope beam to be fed to one of the three Nasmyth instruments via a flat M6 mirror. The PFS also houses an M1 phasing camera and the Test Camera to be used during Technical Commissioning.

Due to its size, the PFS will be integrated, aligned and tested by the AIV team directly on the Nasmyth Platforms, although some off-telescope testing and pre-verification of some sub-assemblies will be undertaken in the lab. The contractual procurement of individual PFS sub-systems and components may be split, hence the full sub-system testing may only be performed after final telescope installation.

The adaptive M4 sub-unit is a special case. Due to its complexity and need for final troubleshooting and tuning after integration, the M4 sub-unit will be re-integrated and tested by the contractor in the laboratory at Armazones. After final acceptance by ESO, the M4 unit will undergo some additional off-telescope testing by the AIV group, before finally being installed on the telescope along with the other finished sub-units.

10. M1 MIRROR SEGMENTS, SENSORS & ACTUATOR COMPONENTS

The procurement and shipment of the large number of components that make up E-ELT's M1 primary mirror is a major production and logistics challenge. The task of manufacturing, inspection, packing, shipping, testing and installation of a project with this scale and complexity has not been previously undertaken in optical astronomy. This coupled with the fact that E-ELT is being built on a remote site in northern Chile further complicates the problem. It requires a well-planned, systematic, industrial-approach in order to be successful. Fortunately, much can be learned from manufacturing industry where complex, large-scale assembly and just-in-time logistics is a proven, well-developed process.

The optical fabrication and assembly of the 798 M1 mirror segments expects an average production rate of approximately 16 per month with a delivering spread over four years. To match the overall AIV schedule, requires that the first M1 segments are delivered starting in mid-2020. The M1 segment AIV activity starts with the arrival of the uncoated M1 segments in their individual transport containers packed in standard shipping containers. As each shipment arrives, the segments are unloaded, inspected, cleaned and coated with the E-ELT protected silver coating. The edge sensors are installed and checked, together with cable harness and electronics. Each segment assembly is then tested and verified as installation-ready. It is then enclosed in a hermetically sealed plastic bag filled with inert gas and re-installed in its transport container before being moved to a secure protected storage yard in Paranal, and staged ready for transport to Armazones for telescope installation. The storage yard has space for 798 stored M1 segment, stacked in rows two high covering an area of 60 x 120 m.

Prior to the arrival of the M1 mirror segments, the first shipments of edge sensors (ES) are delivered to Paranal. The large quantity of edge sensors (9,048) are delivered progressively in batches over a period of almost three years. One of the new E-ELT technical buildings (ETB) at Paranal will be set up as a processing facility to handle the incoming inspection, test and storage of edge sensors. The large quantity of edge sensor production is expected to involve batch testing of samples,

however due to their importance for the segmented M1 mirror, the AIV process will include an additional test and verification on every edge sensor of some critical ES characteristics prior installation. The edge sensors and associated electronics and cable harnesses will be installed on the segment assemblies immediately after AIV coating, prior to storage and before telescope installation.

Another important AIV task is the delivery, inspection and testing of the position actuators (PACTs). The 2,394 PACT actuators[6] will be shipped somewhat later, since they are only fitted after the M1 segment mounting frames have been installed. As with the edge sensors, it is planned to follow a quality control program during the PACT manufacture process which tests only batches of production samples. After delivery of the PACTs to Paranal, every unit will be inspected and undergo a basic set of tests, and made ready for telescope installation. As for the edge sensors, it is important during AIV to ensure that all PACTs are functionally verified before telescope installation.

Finally, in addition to the M1 opto-mechanical components, there is a large quantity of M1 control electronics and cabling which is delivered in shipments, unpacked and inspected prior to telescope installation. The job of installing the electronics hardware and cabling is an extended activity which is expected to take over 12 months with teams of technicians working concurrently with the teams installing the opto-mechanics.

11. M1 MIRROR ASSEMBLIES – TELESCOPE INSTALLATION & ALIGNMENT

One of the major tasks for AIV is the job of installing and aligning the M1 mirror segment assemblies in the telescope structure. The nominal accuracy to which the steelwork of the M1 structure can be fabricated is not sufficient accuracy to permit the adjustment needed to align properly the M1 mirror. Interface structures (known as Fixed Frames) are installed first on the structure and accurately aligned in six degrees of freedom, verified using laser tracking technology and positioned with a combination of adjustment fixtures and shimming.

The entire task of installing and aligning 798 fixed frames is estimated to take a team of technicians at least 10-12 months. The procedures and equipment used in this process will be optimised to ensure maximum efficiency. Small time consuming delays in any steps of the process result in a substantial increase in the total task duration. Since this process is on the critical path of the overall E-ELT AIV schedule, process delays have a direct impact on the 1st Light milestone. Considerable effort is being made therefore to automate and streamline the process to avoid significant schedule delays.

After installation and alignment of the fixed frames, the coated M1 mirror segments can be installed in the telescope. Mirror segments have been stored pre-coated and installation-ready at Paranal. They are transported in batches to the Armazones telescope site, then unpacked and moved inside the dome and up to the M1 cell level using a lifting system. From there they are lifted and moved across to the installation location in the M1 cell, before being lowered into place on their fixed frame interfaces. This part of the process is hoped to be relatively straightforward since it will be a normal daily procedure for recoating segments during normal operations.

The work of fixed frame installation and alignment, followed by M1 segment installation extend for a period of over one year, with a continuous daily cycle of M1 segment installation. Meanwhile, a number of other telescope AIV activities are proceeding in parallel, both at the Paranal areas and on-site at Armazones.

12. TELESCOPE OPTICAL ASSEMBLY & ALIGNMENT

Each of the M2-3-4-5 sub-units will have been assembled, tested and verified off-telescope using dummies in place of the mirrors. These units will have been transported to the telescope, lifted and handled, then mounted on the telescope in the exact same manner as will be used for the final installation. The purpose of these tests is to confirm and verify the process prior to installing the real glass mirrors. When installed on the telescope, the sub-units will be connected to the EELT's telescope control system and functionally tested. During this test period, the overall alignment and dimensional accuracy of the EELT telescope is confirmed using reference targets mounted on the structures and dummy mirrors

Once the tests with these dummy mirrors have been satisfactorily completed, the units are dismounted from the telescope to have the dummy mirrors removed and the coated real mirrors installed. The installation and integration of the coated M2 and M3 mirrors is done at the EELT mirror facility in Paranal. Purpose-built transport containers are used to move the units with the mirrors already installed, by road over the 30 km distance Armazones-Paranal using a truck-towed trailer transport. The M5 and M4 sub-units will be integrated and tested nearby the telescope in the Armazones Instrument Assembly Area.

The M2-4-5-3 units are all re-installed in sequence on the telescope. The PFS has been assembled and integrated on the Nasmyth platform, together with its opto-mechanics sensor arms and wave front sensing detector system. Installed together with the PFS is the M1 Phasing System and Test camera. Meanwhile the installation of rings of M1 segments has been proceeding in parallel. At this point the EELT is capable of collecting and focusing light as a telescope (1st Star milestone) and on-sky testing can start with a partially populated M1 (four rings #5-8 i.e. 156 segments/20% of M1). The EELT Technical Commissioning phase can now begin.

13. ON-SKY TESTING & TECHNICAL COMMISSIONING

During this phase the AIV activities become a continuous 24 hour day-night operation. During the daytime, the installation of M1 mirror segments continues with batches of fresh mirror segments being installed, and then gradually connected to the M1 control system and brought into approximate optical alignment.

Each night a specialist AIV team of telescope commissioning engineers and scientists, supported by telescope operators and software/IT staff will carry out a planned series of on-sky tests, adjustments, tuning and troubleshooting, gradually improving the performance and developing a deeper understanding of the optimum control strategies and procedures which work best for E-ELT on-sky operations. A regular activity will be the final alignment and phasing of the newly-installed M1 mirror segments, bringing them into operation as the E-ELT gradually grows ring by ring to the complete 39 m aperture of 798 segments.

The testing program will be structured to make best use of the available night time hours. Each test will be pre-planned, and executed, and the results recorded and archived for later analysis. Through this progressive series of testing, troubleshooting and tuning, the verification of the E-ELT performance will be gradually verified and validated. Each night, the technical commissioning team and telescope operators will log and report any technical problems which require followup during the day. This Problem Reporting System is an important communications tool in ensuring prompt and thorough followup to technical issues, ensuring that night time hours during technical commissioning can be optimally spent testing performance and tuning the telescope, and not wasted chasing technical problems which could have been rectified in daytime.

14. INSTRUMENT AIV & INSTALLATION

During the later stages of telescope integration, the first of the four large E-ELT science instruments and post-focal AO systems will arrive at Armazones to begin integration and installation. Having to integrate, install, and commission the complete E-ELT 1st Light instrument suite, while at the same time integrating and commissioning the telescope is another major challenge of the E-ELT project. An important goal of E-ELT is to be on-sky and begin science observation as quickly as possible, and for this it is as equally important to have ready the science instruments capability, as it is the E-ELT telescope.

ESO has many years of experience integrating and commissioning new instruments for the VLT telescopes. E-ELT instruments present some new challenges not only because of their size and weight, but also because of the increased complexity of interfacing the instruments, which have their own in-built adaptive optics and wave front sensing systems, with a telescope which includes multiple active and adaptive control loops as well as laser guide stars.

Many, although not all of the 8 m class VLT instruments could be assembled and tested off-telescope in the Paranal integration facilities. For E-ELT, the Armazones Instrument Assembly Area (IAA) does have a generous floor space and crane capacity for off-telescope instrument integration. However, for the majority of the E-ELT 1st Light instruments it will be necessary to partially re-assemble modules of the instrument in the IAA lab area. The final complete installation, alignment and testing will be done directly on the Nasmyth platforms. Although the Nasmyth platforms provide a large working area with good crane access, the working conditions for instrument integration are not ideal and can conflict with telescope operation and other daytime telescope activities.

The first major instrument to arrive is MAORY[7] which is the large post-focal AO system which will feed the MICADO imager/spectrograph[8]. The large size and overall mass of MAORY requires it to be installed piece by piece as modules, the first stage being the installation and alignment of the instrument supporting structure which must hold MAORY at the optical axis height 6 m above the Nasmyth platform.

As MAORY nears completion of its telescope installation, the MICADO instrument team arrives with their instrument. They proceed to unpack and re-assemble the instrument, first off-telescope in the IAA lab, then moving and lifting the instrument up onto the Nasmyth platforms to be mated with MAORY.

Following immediately after MICADO AIV activity, the large HARMONI instrument[9] arrives with its instrument integration team, and again, re-assembles, integrates and tests their instrument as modules off-telescope, before moving and lifting to the Nasmyth platform. Last in the sequence of instrument integrations is the mid-IR instrument METIS[10].

15. DELIVERING E-ELT READY FOR SCIENCE COMMISSIONING

After the final activities of M1 installation and telescope technical commissioning, the AIV phase starts to wind down. The official end to AIV is the 1st Light milestone (currently planned for November, 2024) at the end of the technical commissioning phase and when all 798 segments have been installed and aligned. Responsibility for the remainder of the E-ELT project activities then passes to the Science Commissioning team, which delivers the fully operational telescope to Paranal Science Operations. Figure 2 below shows the transition from AIV/Technical Commissioning into the Science Commissioning, then eventual Science Operations with the relative responsibilities for each phase.

The activities of the AIV team will continue for a time beyond the 1st Light milestone. The AIV technical staff will provide the on-going technical support to the instrument teams during the instrument commissioning and for continued troubleshooting and tuning of the E-ELT telescope. During the final stages of this process, more and more of the Paranal operations staff will be directly involved with providing followup technical support for night time commissioning work as well as daytime routine maintenance of E-ELT telescope systems, with the goal of eventual handover of full technical responsibility to the Paranal Observatory technical operations team.

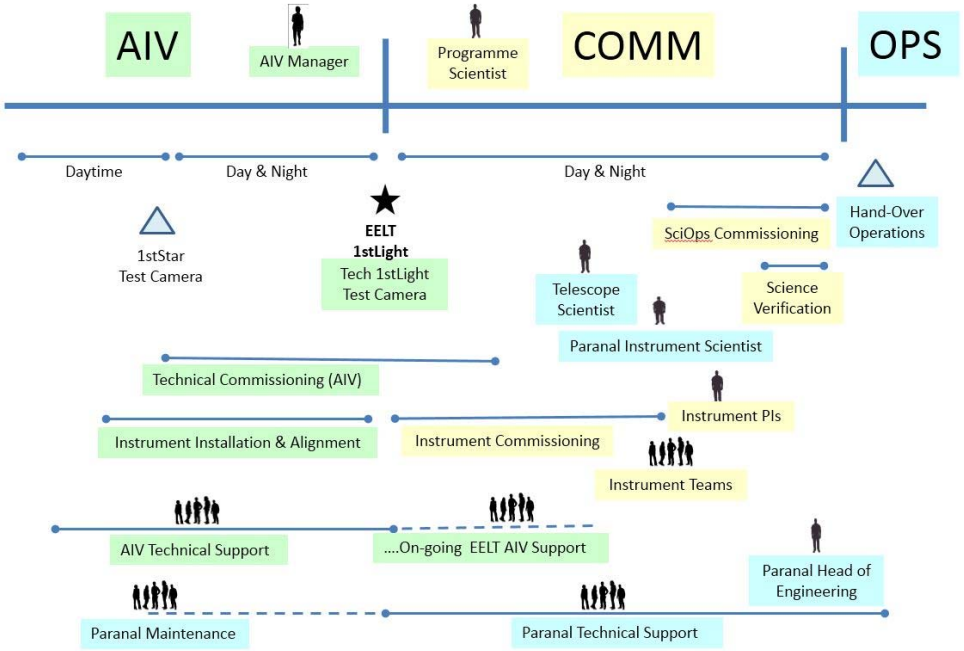

Figure 2. Diagram showing phased delivery of EELT from AIV to science commissioning and operations

16. CHALLENGES AHEAD & CONCLUSIONS

The E-ELT Programme is putting considerable effort into the early planning and preparation for the E-ELT AIV phase. This strategy is based on previous experience with the VLT and on-going Paranal observatory experience, and an acknowledgement that the size, scale, and complexity of E-ELT presents a new level of challenge for the critical AIV phase. The large numbers of M1 components, the technical challenges of a large segmented telescope and the fully integrated active-AO-LGS E-ELT telescope, all present new and significant hurdles to overcome. This paper has outlined

the strategy which we believe, through detailed planning and thorough preparation, will result in the successful on-time delivery of an E-ELT and instrument suite which is both scientifically productive and meets its ambitious performance goals.

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