ESO ELT System Requirements Verification

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ABSTRACT

This paper presents the plan for the system-level requirements verification of the ESO ELT. It describes the process to undertake this already ongoing activity and the tools supporting such process.

Verification methods (design, analysis, inspection and/or test), verification level (whether the concerned requirement is verified at system or subsystem level), milestones (at which stage in the programme the requirement is verified) and constraints, when applicable, are discussed. Particular emphasis is put on addressing how the key system requirements, i.e., the ones with a larger impact on the science return, are planned to be verified. Also, special attention is given to describe the model approach in place to help in the system-level verification activity.

Finally, some conclusions and lessons learned extracted so far from the system requirements verification activity are summarized.

Keywords: requirements, specifications, verification, compliance, models

1. INTRODUCTION

The ESO ELT construction is progressing well according to the schedule[1]: several major subsystems have already undertaken the Preliminary Design Review (PDR) and some others are approaching. In order to ensure that the system (i.e., the overall ELT) under construction meets the system requirements and eventually the user needs, a verification strategy has been set up since the beginning of the ELT construction programme. This strategy follows the classical V-diagram approach where the verification attributes for the requirements at system, subsystem, unit and component levels are defined during the several design phases and then, based on that, the components, units, subsystems and finally the system are verified against their requirements as they are built.

By following that strategy, verification plans for the subsystems are being produced by the subsystems suppliers. In addition, a verification plan at system level has been elaborated by ESO. This paper focuses on the latter, i.e., the system-level requirements verification. The process to undertake this activity, which is already ongoing, and the tools supporting such process are described.

1.1 ELT programme verification process

The formal objective of the ELT verification is to assess and eventually demonstrate that the ELT system meets the Level 1 Requirements Specification (L1S), which states the system-level requirements. Embedded in this formal objective, there are some other goals as improving the overall understanding of the system from the user perspective as well as problem-fixing and fine-tuning the system to meet the required functionality and performances.

In order to accomplish this objective a verification process, which applies both at system and subsystems level, has been adopted for the ELT. This process consists of the following major phases that are defined both for the system verification (the subject of this document) and for the several subsystems verification:

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1. Verification planning
2. Verification execution and reporting
3. Verification control and close-out

The verification process covers the entire development life-cycle. During the design phase (downward branch of the V-model of project development), the planning of the verification activities is done. Starting from the final design review of the sub-systems, through the manufacturing, integration and testing phase, the verification of the technical specifications is executed (upward branch of the V-model). The process has to ensure traceability between the requirements and their verification, hence appropriate control of the process and the related documentation is in place.

The process is an incremental one, in the sense that the overall system verification strongly relies on the subsystems individual verification. Furthermore, many of the Level 1 (L1) requirements will actually be verified at subsystem level. Due to the fact that the several ELT subsystems develop at different paces, the three phases above will not be performed at the same time for all the subsystems; hence, there will be a significant overlap and no clear border between the three phases when looking at system level. In other words, the verification of some requirements may already have been closed, while the planning for others is still on-going.

2. SYSTEM REQUIREMENTS VERIFICATION APPROACH

The L1S verification approach stipulates basically that:

- The requirements of the L1S will be verified by a combination of methods, at a given temporal milestone (called verification stage) and either at system or subsystem level.
- The L1S verification will be performed following the three phases of the process (quoted in section 1.1) aiming to ensure efficient planning, execution and control.

The following sections provide further explanation on those elements of the approach.

2.1 Verification Methods

Verification of the L1 requirements will be accomplished by at least one of the following verification methods:

- Review of Design (D)
- Analysis (A)
- Inspection (I)
- Test (T)

<u>Verification by Review of Design:</u>

Verification by Review of Design consists of using approved records or evidence (e.g. design documents and reports, technical descriptions, engineering drawings) that unambiguously show that the requirement is met.

A number of L1 requirements will be verified by review of design. These requirements are basically the ones defining the overall system concept and high level architecture. The verification will consist of checking that the system architecture satisfies the requirements and that consistent subsystem concepts have been derived and specified. In practice this will be a formal checking that the required system functions have been properly implemented into the system architecture and flowed down to subsystems specifications. Checking the subsystems design will be done at subsystem level.

<u>Verification by Analysis:</u>

Verification by Analysis consists of performing theoretical or empirical evaluation using techniques such as systematic and statistical design analysis, modeling and computational simulation.

This method will be used in the cases where the following conditions are met:

- Verification by design is not enough to prove compliance

- Analysis with enough fidelity and credibility is possible
- Analysis is significantly more cost-effective than test

For certain L1 requirements a combination of analysis and test may be needed, in particular when the range of conditions applicable to the requirement is very large and fidelity of the model is checked by testing under a defined set of conditions.

Depending on when the analyses are performed as-design or as-built data will be used, i.e., the latest available consolidated data.

Section 6 provides an overview of the several models that will be in place to help in the ELT verification.

<u>Verification by Inspection:</u>

Verification by inspection consists of visual determination of physical characteristics (such as constructional features, hardware conformance to document drawing or workmanship requirements, physical conditions, software source code conformance with coding standards).

Verification by inspection will be done by checking that the actual system hardware and other deliverables include the features specified in the concerned requirements of L1S. It will also be done to check that data, documentation and calibration are provided. Also system safety features and operational requirements will usually be checked by inspection.

As a general criterion verification by inspection will be a qualitative (or simple quantitative, e.g., measuring a dimension) assessment on whether the concerned requirement has been met. When performance is specified then verification by analysis and/or test is needed.

<u>Verification by Test:</u>

Verification by test consists of measuring product performance and functions under representative conditions, or under conditions that can be clearly traced to operational ones. It includes the analysis of data derived from the test.

Verification by test will be the primary verification method when performance is to be assessed. Given that tests normally involve a significant effort in terms of resources and time verifying by test will be kept under reasonable limits.

A number of major system-level tests, aiming to assess the key ELT requirements, will be conducted. These are addressed in section 5.

As far as possible, the system-level tests should be conducted, or at least finished, on the integrated, aligned and calibrated ELT system. This implicitly asks for problem-fixing, tuning and calibrating the system to reach the specified performance as part of the tests themselves. Actually, system verification will characterize the system under operational conditions and will include calibration and tuning activities.

2.2 Verification Levels

The verification of the L1 requirements will be done either at system or subsystem level.

The second option will be exercised when enough means of verification of the concerned L1 requirement can be extracted from the verification of the subsystem(s) to which that requirement has been flowed down. Formal close-out of the verification at the lower level will be needed prior to close-out at higher level.

Verification at system level will be done when it is not possible to perform it at subsystem level.

2.3 Verification Stages

The verification stage refers to the temporal milestone by when the verification of the concerned requirement must be completed. There will be three major milestones driving the verification of the requirements to be verified at system level (some other intermediate milestones applying in particular to verification by analysis may be defined):

- L1 Verification Review (L1VR): this milestone applies to most of the requirements whose verification method is review of design. It is the milestone by when the ELT System Verification Matrix (VMX) is completed.

  The verification of the requirements subject to this milestone will be performed around the System Verification Review (SVR)

- Hand-over from AIV phase to science commissioning: this milestone applies to most of the requirements whose verification method is inspection or test. Exception to this are the requirements whose verification needs that the instruments (including post-focal AO capabilities) are in place.

  The verification of the requirements subject to this milestone will be performed during the system verification phase of AIV. Also during this period, the verification will supplement or confirm previous verification activities on sub-systems, by providing operating conditions which cannot be fully or cost-efficiently duplicated or simulated in Europe.

- Hand-over from science commissioning to operations: this milestone applies to the requirements whose verification method is inspection or test and that need that the instruments (including post-focal AO capabilities) are in place.

  The verification of the requirements subject to this milestone will be performed during the Commissioning period.

The milestone applicable to the requirements to be verified at subsystem level will be the closure of the concerned subsystem verification.

3. SYSTEM REQUIREMENTS VERIFICATION PROCESS

3.1 Verification Planning

The activities related to the planning of the verification are performed on the left ("downward branch") of the system engineering V-model. A simplified flow-chart of the activities in this phase is shown in Figure 1.

During this phase, the following activities will be performed:

1. Consolidate the flow-down of the L1 requirements to lower-level technical specifications. This is important for a number of reasons: (i) making sure that the verification activities on subsystems, which are needed for the verification of L1S, are covered; (ii) allowing feeding-back the results of the subsystem verification activities to the close-out of the L1 requirements.

   The Systems Engineering (SE) team checks the incoming links for each of the L1 requirements in DOORS® (Figure 2). As shown in Figure 3, DOORS® allows to display the L1 requirements and, by using these incoming links, also the associated sub-system requirements. In this way, it will be possible – with moderate effort – to check that the flow-down is correct and all aspects of the L1S are covered. DOORS® also displays the name of the sub-systems. Thus, it also allows to check that all relevant sub-systems are covered.

2. Define for each requirement of L1S how it will be verified. This will be the content of the VMX. In particular, define the verification method(s), level and stage (see sections 2.1, 2.2 and 2.3). Additionally, a short description of the verification task will be added. Note that the VMX is part of the L1S module in DOORS® (requirements management tool used at ESO), where a dedicated view will present it in the proper format. Figure 4 shows the verification attributes and Figure 5 presents a screenshot of the VMX in DOORS®. Also, the key system-level requirements, i.e., the ones with a larger impact on the science return, will be identified.

3. Cluster requirements that are similar in terms of verification by associating them to individual verification activities. This prevents unnecessary redundancies and makes the verification process more efficient. A module in DOORS® will contain a list of all the verification activities (reviews, analyses, inspections, tests) at system level (Figure 6). Links (in DOORS®) will be established between these activities and the L1 requirements (Figure 7). This will allow to have an overview of what requirements will be verified during each of these activities.

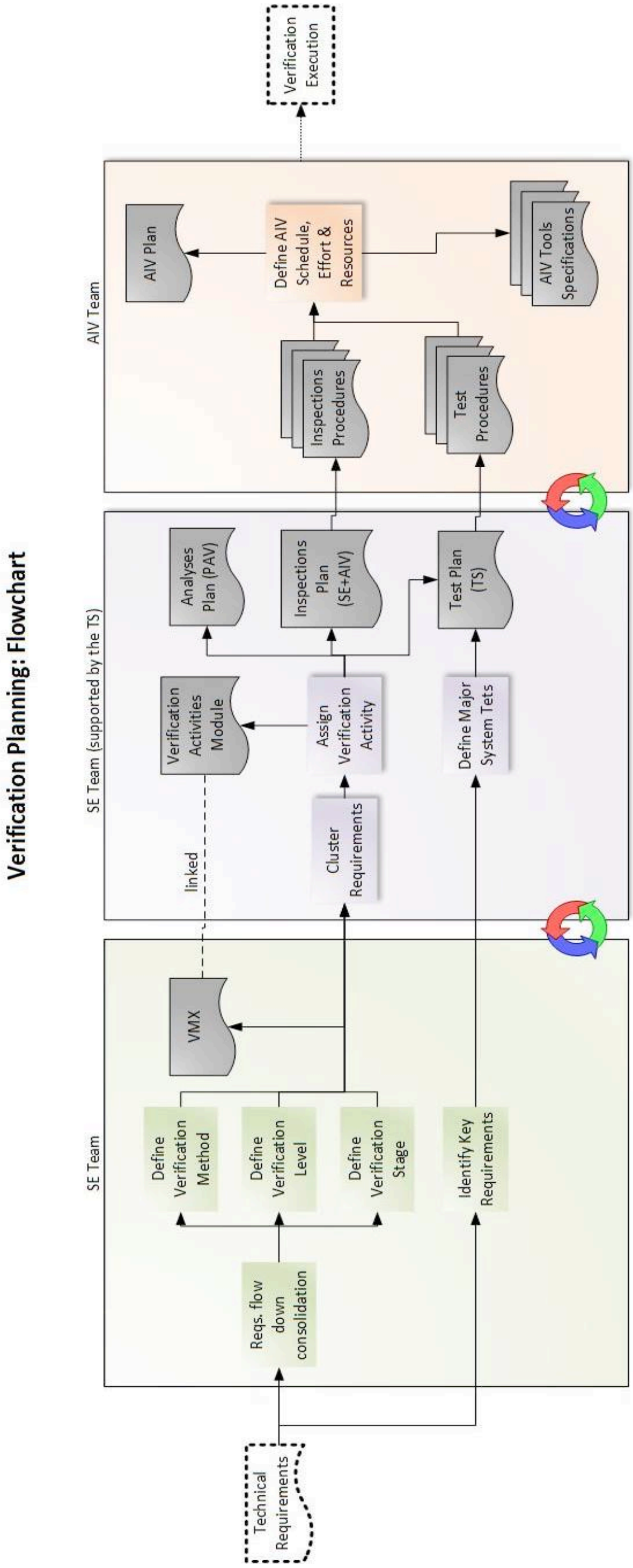


Figure 1. Flow-chart of the Verification Planning Process.

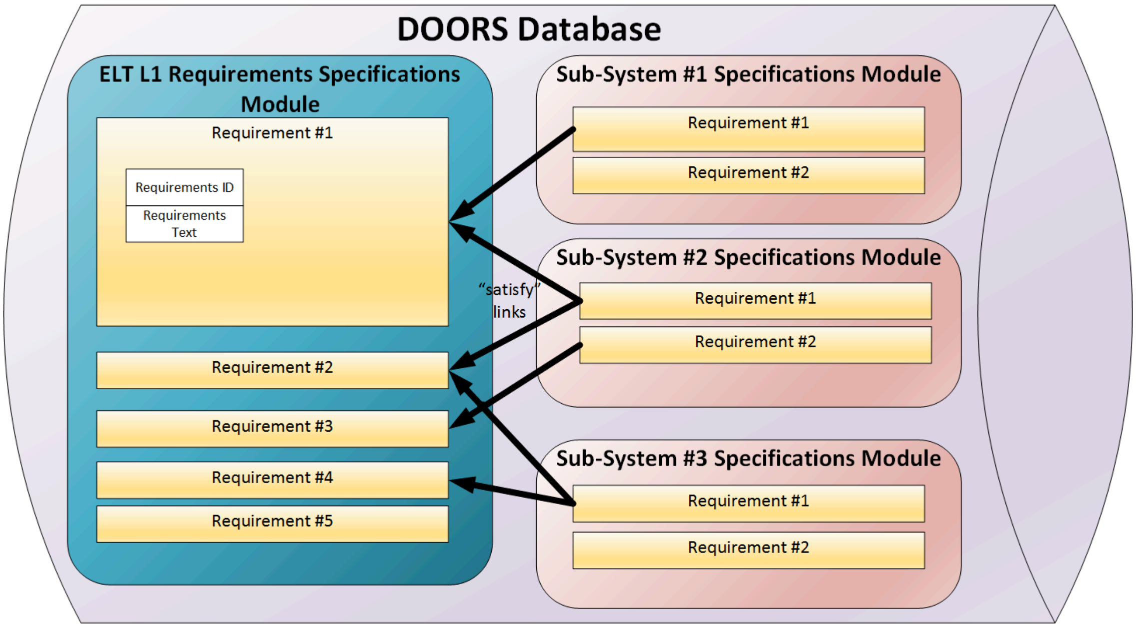


Figure 2. Illustration of the linking between L1 requirements and sub-system requirements in the DOORS® database.

Tag	Text	In-links (All modules)
	4.1.1 The Telescope	
[R-L1S-228] D/ / /	The optical system of the telescope shall be a folded three-mirror (M1, M2, M3) anastigmatic, with the beam extracted using two flat mirrors (M4, M5) sending the light towards the telescope foci along the elevation axis of the telescope (see Figure 3).	Module Name:Technical Specification for the Supply of the ELT M4 Unit Object Identifier:192 Object Text:The M4 Unit shall reflect incoming light beams towards the telescope foci, fulfilling the M4 Mirror optical prescription and optical performance requirements set herein. Module Name:ELT Optical Design Specification Object Identifier:35 Object Text:The optical solution for the EELT is a folded anastigmat, in a Nasmyth configuration. Module Name:ELT Optical Design Specification Object Identifier:36 Object Text:In this configuration, the beams are exiting the telescope after reflection on two folding flats (M4 and M5), straight towards the Nasmyth focus - see Figure 3-1.
[R-L1S-231] D/ / /	M4 shall be an adaptive mirror.	Module Name:ELT Level 1 Requirements Specification Object Identifier:657 Object Text:The telescope shall host the M4 adaptive mirror and the M5 tip-tilt mirror which will work together to provide the adaptive correction as required by the wavefront functions (sections 4.1.7 and 4.1.8.). Module Name:Technical Specification for the Supply of the ELT M4 Unit Object Identifier:203 Object Text:The M4 Adaptive Subunit shall provide real Time Shaping of the M4 Mirror optical surface shape (including the fast steering of the M4 Mirror) to compensate for wavefront errors (including but not necessarily limited to those caused by atmospheric turbulence, telescope perturbations and internal M4 deformation), and to allow optimisation of the Telescope performance. Module Name:Technical Specification for the Supply of the ELT M4 Unit Object Identifier:204 Object Text:Real Time Shaping of the M4 Mirror shall be achieved through a 'Modal Control' scheme, i.e. the M4 Mirror shall be shaped by a linear combination of orthogonal deformation modes (rigid body motions excluded). Modal control basis shall be configurable by the user so that, depending on the configuration adopted, any arbitrary set of modes relevant for AO control (e.g. identity matrix for zonal coordinates, Karuhenen-Lowe, Zernike or others) can be used.

Figure 3. Screenshot of the view in DOORS®, which is used for checking the requirements flow-down.

The Verification Activities module, apart from providing the information on how the verification of the L1 requirements will be clustered in activities, will also serve as a control tool for the verification process. As such, this module will include information on the identifier and name of the activity, its actual status and the milestone by when it must be completed, as well as an entry for comments. By using the identifier and name fields every activity can be easily tracked in the overall ELT verification plan schedule. Using the links in DOORS®, it will be possible to automatically (by means of scripts) get an overview of the verification status for every L1 requirement (see Table 2).

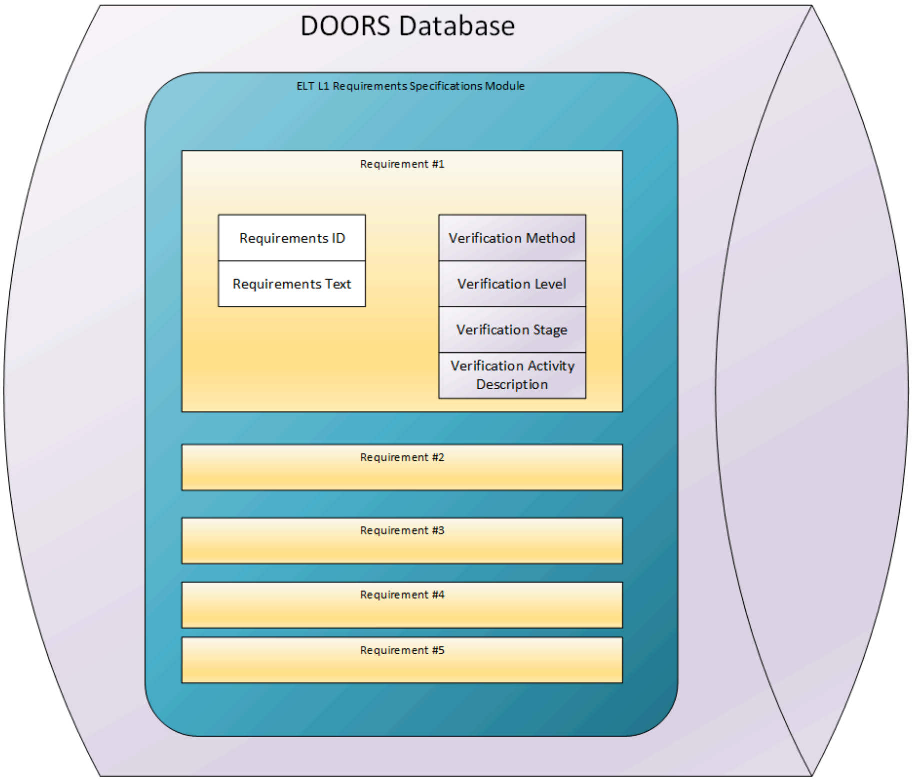


Figure 4. Illustration of the attributes of each requirement in the DOORS® database.

Tag	Text	Ver. Level	Ver. Level Details	_VM_DesignReview	_VM_Analysis	_VM_Inspection	_VM_Test	_VM_Remarks
	4.1.1 The Telescope	n/a						
[R-L1S-222] D/ /I/	The telescope shall produce an image of a selected portion of the sky (far field) and of the entrance pupil at the several Nasmyth and Coude focal planes (one at a time), as derived from the characteristics defined in this section.	System		Check that consistent concepts for the optical system, for the telescope mechanics and the control system have been derived and specified. **Stage: L1VR**		Since performance is not specified here, qualitative pointing and image checks of the telescope will suffice. Therefore, the verification of this requirement shall be clustered with the pointing and image performance tests. **Stage: AIV-system verification**		Imaging at the Coude focal planes is not part of the scope but the system design shall allow for it.
[R-L1S-223] D/ /I/	The telescope shall produce an image of up to 8 Laser Guide Starts (LGS) at the several Nasmyth focal planes (one at a time), as derived from the characteristics defined in this section.	System		Check that consistent concepts for the optical system, the telescope mechanics, the LGS unit and the control system have been derived and specified. **Stage: L1VR**		Since performance is not specified here, qualitative pointing and image checks of the telescope, including the LGS, will suffice. Therefore, the verification of this requirement shall be clustered with the pointing and image (including the LGS) performance tests. **Stage: AIV-system verification**		

Figure 5. Screenshot of the DOORS® view, which is used to define the verification attributes for each requirement.

4. Define the analyses, inspections and tests plans and procedures, as well as the way to verify the L1 requirements whose verification method is design review: after the previous step of requirements clustering, the SE team, supported by the Telescope Scientist (TS) and AIV team, will define the analyses, inspections and tests plans. In

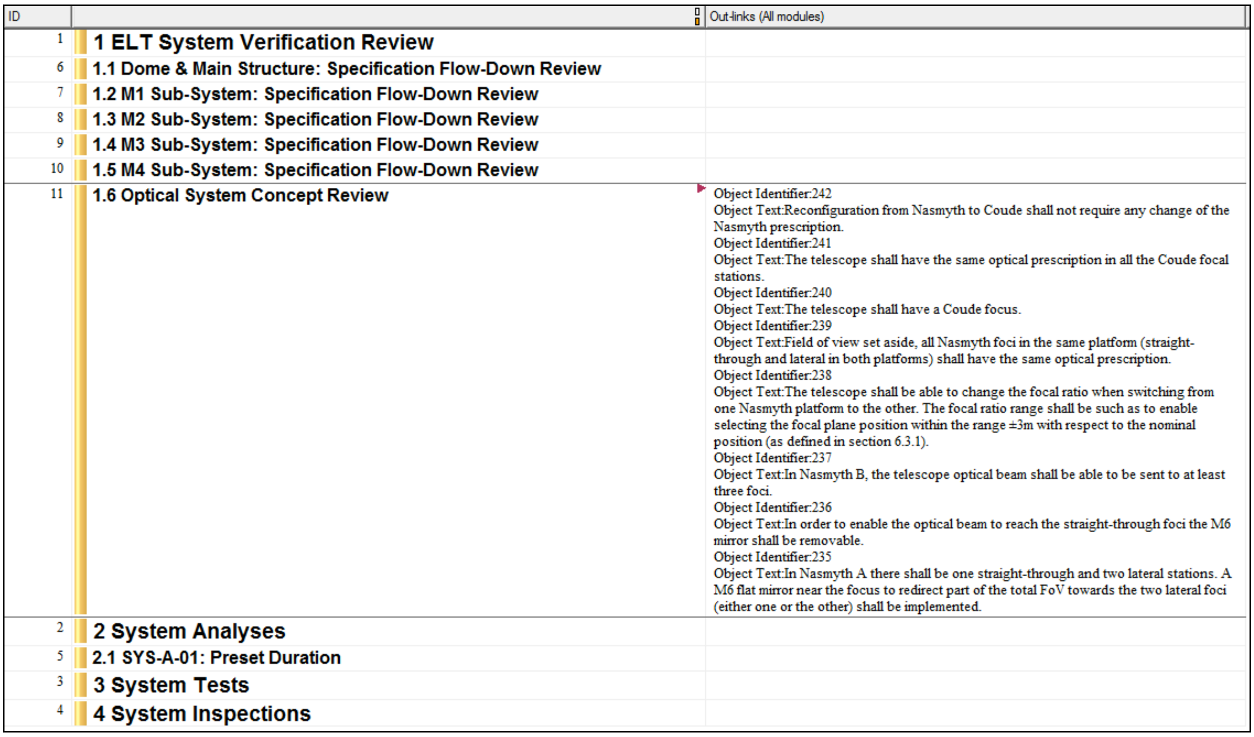
particular, the analyses plan will be done by the Performance Analysis and Verification (PAV) team, which is part of SE. These plans contain the detailed specification of the analyses, inspections and tests activities to be performed and how they will contribute to the verification of each requirement. The typical information for each activity specification is given in Table 2. The major system tests, i.e., the tests to verify the key system-level requirements, will also be defined at this point.

Regarding the verification of the L1 requirements whose verification method is design review, there will not be a design review plan as such. Instead, aiming to follow a practical approach, the status of compliance of those requirements will be directly documented in the ELT System Compliance Matrix (CMX) indicating the document(s) where compliance is demonstrated. Additional design review reports may be produced only when further explanation is needed, in which case a reference to them will be added to the CMX. The CMX can be seen as an extension of the VMX: the latter defines what is planned for verification while the former provides the information related to the execution of the verification (see Table 1).

The ELT AIV team, supported by the rest of the Programme Engineering (PE) team, will use the inspections and tests plans as input for the definition of the detailed inspections and tests procedures, with indication of the required effort and material resources. Specific AIV tools may be required that would then be identified and specified by the AIV team. As an outcome the AIV plan will be regularly updated.

All these plans and procedures will be done in MS Word®/MS Excel® using the inputs from DOORS® described in the sections above.

The L1 requirements to be verified at subsystem level should have been properly flowed down to subsystems (checking this is part of the requirements flow-down consolidation explained above). Hence, by verifying the children requirements the verification of the parent L1 requirement should be automatically done. This is the general approach but some particular cases requiring a more elaborated process may be in place (e.g., not straightforward linking from parent to children) that will be documented in the VMX by the SE team.



ID		Out-links (All modules)
1	**1 ELT System Verification Review**	
6	**1.1 Dome & Main Structure: Specification Flow-Down Review**	
7	**1.2 M1 Sub-System: Specification Flow-Down Review**	
8	**1.3 M2 Sub-System: Specification Flow-Down Review**	
9	**1.4 M3 Sub-System: Specification Flow-Down Review**	
10	**1.5 M4 Sub-System: Specification Flow-Down Review**	
11	**1.6 Optical System Concept Review**	Object Identifier:242 Object Text:Reconfiguration from Nasmyth to Coude shall not require any change of the Nasmyth prescription. Object Identifier:241 Object Text:The telescope shall have the same optical prescription in all the Coude focal stations. Object Identifier:240 Object Text:The telescope shall have a Coude focus. Object Identifier:239 Object Text:Field of view set aside, all Nasmyth foci in the same platform (straight-through and lateral in both platforms) shall have the same optical prescription. Object Identifier:238 Object Text:The telescope shall be able to change the focal ratio when switching from one Nasmyth platform to the other. The focal ratio range shall be such as to enable selecting the focal plane position within the range ±3m with respect to the nominal position (as defined in section 6.3.1). Object Identifier:237 Object Text:In Nasmyth B, the telescope optical beam shall be able to be sent to at least three foci. Object Identifier:236 Object Text:In order to enable the optical beam to reach the straight-through foci the M6 mirror shall be removable. Object Identifier:235 Object Text:In Nasmyth A there shall be one straight-through and two lateral stations. A M6 flat mirror near the focus to redirect part of the total FoV towards the two lateral foci (either one or the other) shall be implemented.
2	**2 System Analyses**	
5	**2.1 SYS-A-01: Preset Duration**	
3	**3 System Tests**	
4	**4 System Inspections**	

Figure 6. Screenshot of the "Verification Activities" DOORS® module. It shows one of the views in this module, presenting the activities and the requirements to be verified as part of each activity.

The main documents that will be produced during this phase are:

1. The VMX.
2. A template of the CMX. The CMX will be part of the L1S module in DOORS®, where a dedicated view will present it in the proper format.
3. The inspections, analyses and tests plans and procedures.
4. Updated versions of the AIV plan.
5. AIV tools specifications, if needed.

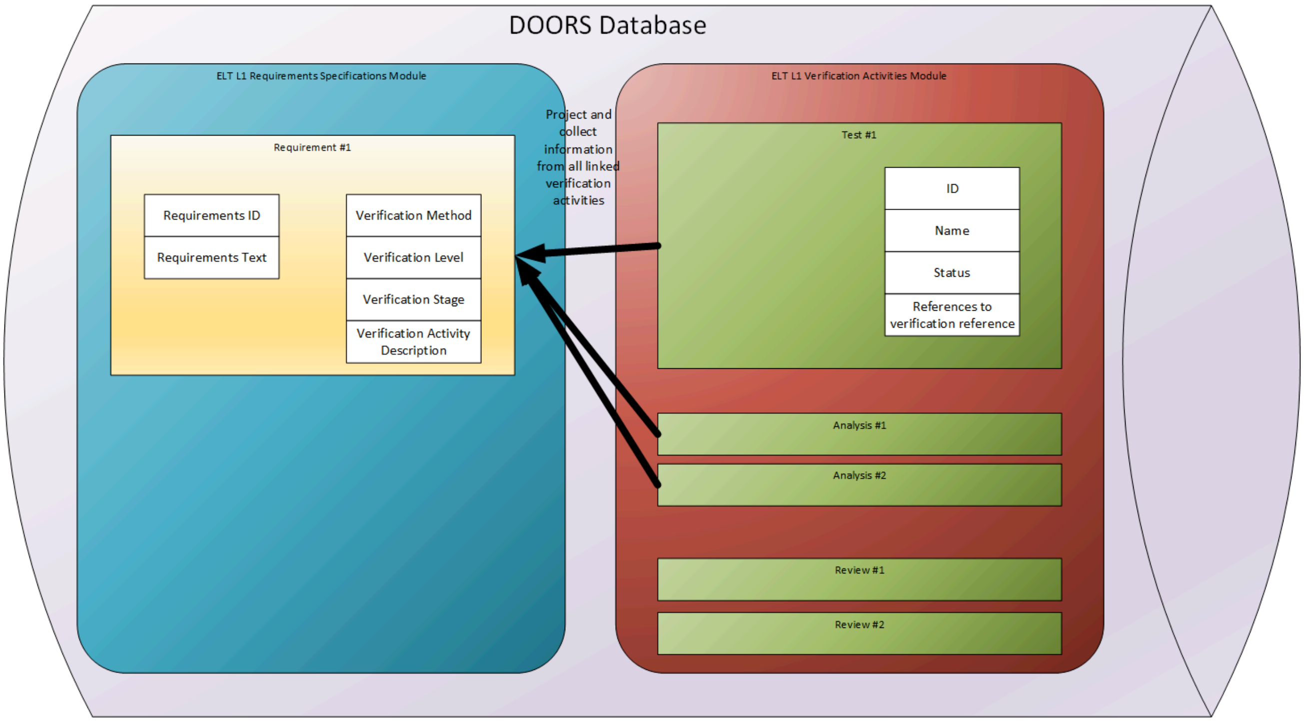


Figure 7. Illustration of the linking between the "L1S" and the "Verification Activities" modules in DOORS®.

3.2 Verification Execution and Reporting

In this phase, the verification activities, as defined in the verification planning phase, are executed and documented (see Figure 8). One of the main outcomes of this phase is the assessment of compliance.

The transition between the verification planning and verification executing phase will be gradual. The verification of some requirements will be already closed by the L1VR, while for others, e.g., the test specifications will be still under definition.

During this phase, the following activities will be performed:

1. Check the compliance of the L1 requirements to be verified at system level verified by design review. As already said, the relevant milestone here is the L1VR. This will be done in most of the cases by identifying system level documents (e.g., optical design specification, ELT thermal requirements) where the adopted design solutions are specified. In addition, in many cases a proper verification of the concerned requirements implies

checking that the affected subsystems have been consistently specified. This is why a consolidated requirements flow-down is a critical step in the overall verification process (see section 3.1).

The outcomes of this task will be documented in the CMX and, only in case further explanation is needed, in additional design review reports; the latter should be minimized to keep the effort under reasonable limits. Concerning the update of the CMX, an as precise as possible reference will be done to the section(s) and paragraph(s) of the concerned report(s) where compliance is proven. The Verification Activities DOORS® module will also be updated as needed.

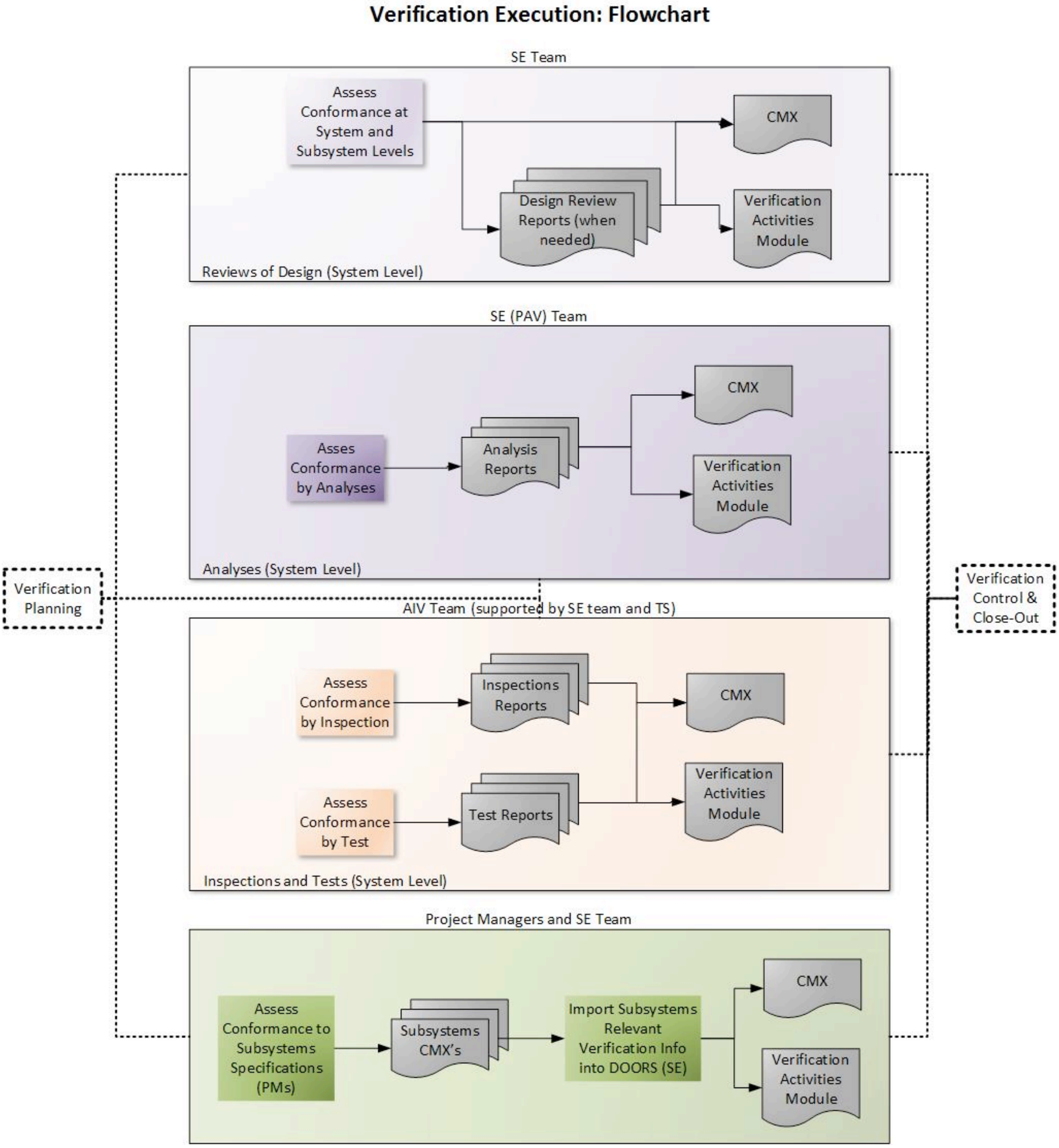


Figure 8. Illustration of the Verification Execution Process.

2. Check the compliance of the L1 requirements whose verification method is inspection, analysis or test. It means performing the inspections, analyses and tests as defined in the planning phase. The underlying verification activities will follow the detailed procedures prepared in that phase and the results will be documented in the inspection, analysis and test reports. All the work related to inspections and tests will be responsibility of the AIV team with the support of the SE team and the TS. The PAV team, which is part of SE, will be responsible for executing the analyses activities and documenting the results in the analysis reports.

   The outcomes of this task will be included in the CMX. As above, a reference as precise as possible will be done to the section(s) and paragraph(s) of the concerned report(s) where compliance is proven. The Verification Activities DOORS® module will also be updated as needed.

3. Check the verification outcomes concerning the L1 requirements that are verified at subsystem level. All the L1 requirements verified at subsystem level regardless of their verification method will be addressed in this activity. This will consist basically of checking that there is sufficient documented evidence in the outcomes of the subsystems verification, performed under the corresponding Project Manager responsibility, to proof the compliance of the concerned L1 requirements.

   In order to do so, the essential information of the subsystem compliance matrices will be imported into the corresponding subsystem specification DOORS® modules by SE team. Given that these modules are linked to the L1S module, capturing in the CMX (part of the L1S module) the relevant information on requirements to be verified at subsystem level will be straightforward. By relevant information it is meant the status of compliance as well as the reference to the proof of compliance (including section to the lowest possible level). This exercise will be performed only once, after the provisional acceptance of the concerned subsystem has been granted by ESO. In addition, in some cases, subsystems will be pre-assembled together as part of their verification before being installed in the telescope (see section 7).

   Apart from updating the CMX as explained in the previous paragraph, the Verification Activities DOORS® module will also be updated as needed.

The main documents that will be released during this phase are:

1. Design review report(s), if needed
2. Inspection, analyses and test reports
3. Updated versions of the CMX

3.3 Verification Control and Close-Out

Verification control means continuous follow-up of the progress of the verification process, including reporting of the verification results status on a continuous basis through the CMX. Verification control will extend from the beginning of the verification execution until the point in time when the verification process will be closed.

Indeed, when discussing verification execution and reporting in section 3.2 it was described how the CMX will be updated along the process with the actual status of compliance and the references to the evidence of verification for every L1 requirement. On this grounds, the CMX will be a fundamental tool to control the status of the verification process. It will be a live document which will evolve along the verification execution.

In order to provide an executive overview of the current status of the verification process, the relevant information from the CMX (e.g., status of compliance, open Request for Waiver (RfWs)) will be periodically exported by SE team into a simple Excel sheet showing some metrics of the process in a graphical way.

As pointed out also in section 3.2, following the progress of the verification process, the status of the Verification Activities DOORS® module will also be updated by SE team.

The Verification Activities module will provide a view of the status of verification by focusing on the activities rather than in the individual requirements, as it is the case of the CMX. Both documents together will play the role of the so-called Verification Control Document, which is used in some other projects.

Verification close-out will be performed by the SE team and will be formally reported in the CMX. Verification close-out of a requirement is defined as either:

- The documented and accepted evidence of compliance to this requirement. In this case the CMX will state "C" (compliant) under status of compliance.
- Or the acceptance of the RfW(s) associated to this requirement. In this case the CMX will state "W" (waived) under status of compliance.

Before final close-out of requirements, the documented verification information providing evidence of compliance (e.g. test reports, analysis reports, design review reports when needed, inspection reports) will have to be released in the ESO Documentation Archive System. The same applies to the forms documenting acceptance of the concerned RfWs.

The verification of a requirement will not be closed if its status of compliance is "NC" (non-compliant). If the reason for the deviation can not be fixed then an accepted RfW will be needed before closing out.

Any change to a requirement whose verification close-out has already taken place, or any change to a related proof of compliance, will require a re-verification of the requirement.

The ELT System Verification process will be considered closed only when the verification of all the L1 requirements will be closed. This implicitly means that no open RfWs may remain in the final issue of the CMX. This last issue will document the closing out of the verification process.

4. VERIFICATION DATABASE & DOCUMENTATION

In Figure 9 the relationship of the DOORS® database and the documents used along the verification process is presented.

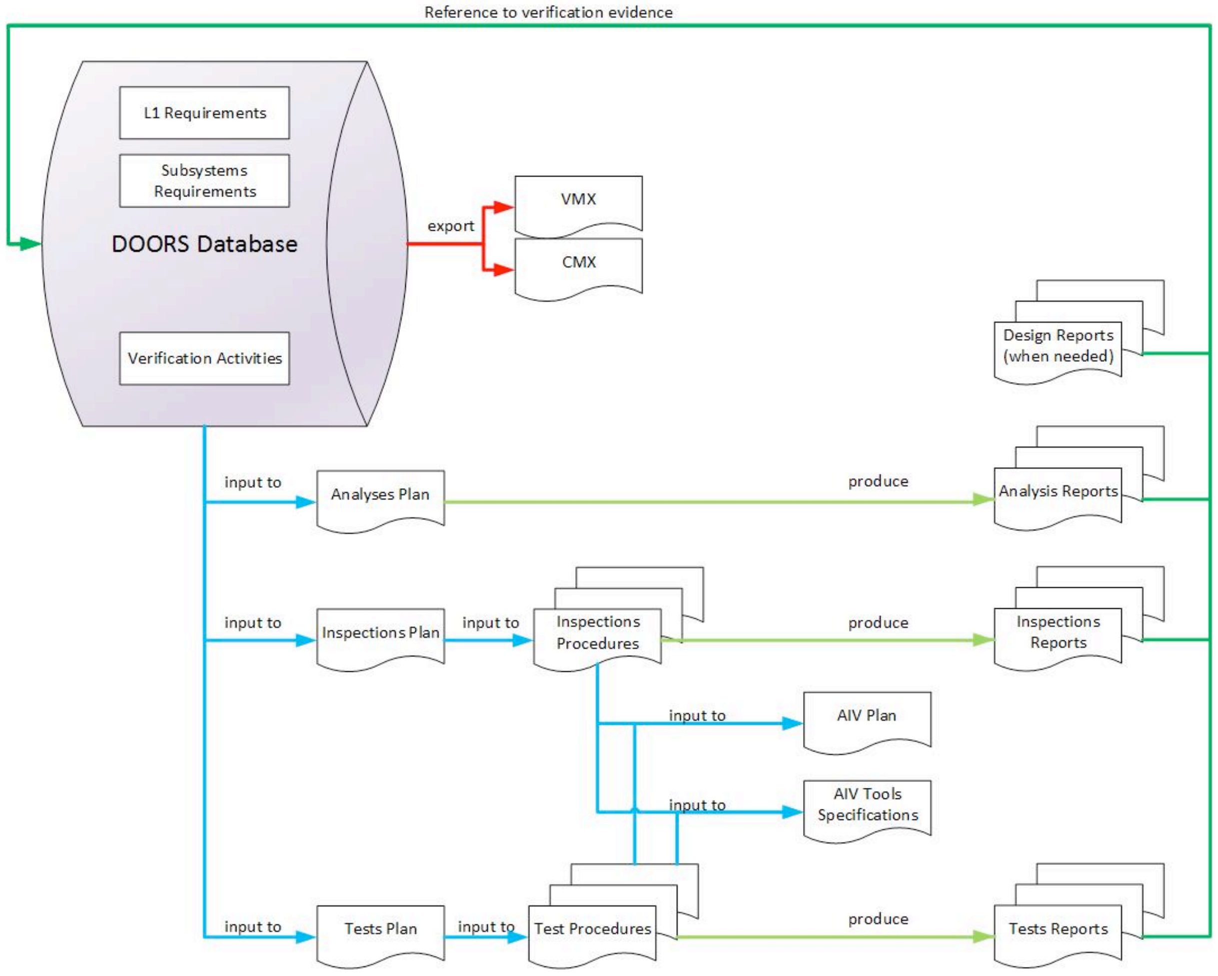


Figure 9. The relationship of the documents and DOORS® database related to the verification process.

In the following the two main tools to control the verification process are described. Table 1 lists the (minimum) contents of the CMX. Note that some of these contents are also in the VMX (as already expressed, the CMX can be seen as an extension of the CMX following the execution of the verification process). Table 2 shows the (minimum) contents of the verification activity (inspection / test / analysis) specifications defined in the Verification Activities module.

<table>
<tr><th>CMX Attributes</th><th>Comment</th></tr>
<tr><td>Requirement identifier</td><td rowspan="7">Will be defined during the “Verification Planning” phase.
This content is also in the VMX.</td></tr>
<tr><td>Requirement text</td></tr>
<tr><td>Verification method (Review, Inspection, Analysis, Test)</td></tr>
<tr><td>Verification level (Subsystem, System)</td></tr>
<tr><td>Verification stage (milestone)</td></tr>
<tr><td>Short description of the verification task</td></tr>
<tr><td>Verification remarks</td></tr>
<tr><td>Compliance status (C, NC, W)</td><td rowspan="4">Will be added during the “Verification Execution and Reporting” and “Verification Control and Close-Out” phases</td></tr>
<tr><td>Reference to the proof of compliance (relevant section of the analysis, inspection or test report). Also include references to RfW in case of non-conformance.</td></tr>
<tr><td>Verification status (Open, Closed)</td></tr>
<tr><td>Compliance remarks</td></tr>
</table>

Table 1. Minimum contents of the CMX.

Verification Activity Attributes	Comment
Activity identifier	
Activity name	
Status (to be done, ongoing, completed, cancelled, to be repeated)	
Identifier of the requirements concerned by the activity	Generated with a DOORS® script
Text of the requirements concerned by the activity	Generated with a DOORS® script
Verification level (Subsystem, System)	Generated with a DOORS® script
Verification stage (milestone)	Generated with a DOORS® script
Verification method (Review, Inspection, Analysis, Test)	Generated with a DOORS® script
Reference to the verification results (relevant section of the analysis, inspection or test report)	Generated with a DOORS® script
Comments	

Table 2. Minimum contents of the activity (inspection / test / analysis) specifications defined in the Verification Activities DOORS® module.

5. VERIFICATION OF THE KEY ELT REQUIREMENTS

The key ELT requirements are those that while having a significant weight in the ELT to efficiently satisfy the users' needs, meeting them is challenging. They are directly derived from the main science needs and their fulfilment will be a must for the success of the ELT programme. Therefore, special relevance will be given to the verification of these key requirements.

A final assessment of compliance will have to be done by test and will only be possible once the system will be integrated and calibrated, late in the AIV phase. Therefore, in order to mitigate the technical risk associated to these requirements, the verification will make extensive use of analysis starting as early as possible in the development of the ELT (actually, significant analysis work has already been done at the time of writing this document).

The tests to verify these key requirements will be tagged as major system tests in the VMX and defined in detail in the Test Plan. Most of these requirements are planned to be verified during the system verification phase of AIV (see section 2.3). Those requirements needing the participation of an instrument and a post-focal AO capability will be verified during science commissioning. The sequence of tests, the detailed schedule as well as the needed effort and tools will be defined in the Test Plan and Procedures.

The main key requirements and the planned way of verification are provided in the next sections.

5.1 Wavefront Control Performance

One of the most prominent cases of key requirements are those related to wavefront control performance. Many simulations based on the ELT performance model have been run in the past. A thorough update of the performance model both in terms of structure and as-design characteristics has just been completed and will be the basis for end-to-end simulations (excluding instruments) of performance. In addition to this mathematical model, a physical model of the ELT (Minuscule Extremely Large Telescope, MELT) will be in place. It will allow for checking wavefront control strategies using the actual control system hardware and algorithms. More details of the ELT performance model and MELT can be found in section 6. Apart from the verification work, already ongoing, with these models, extensive tests will be described in detailed procedures and executed during the system verification phase of AIV.

5.2 Blind Pointing Performance and Blind Image Quality

By "blind pointing" it is meant pointing the telescope to the object of interest by relying only on the telescope internal metrology without closing the guiding loop with the feedback from the sky sources provided by the optical sensors. The blind pointing performance is critical because it directly impacts efficiency of science observations. The telescope must be able to blindly point within a certain accuracy compatible with the capture range of the optical sensors of the guiding loop that will then correct for the blind pointing error by making use of optical feedback. Something similar applies to the maximum size of the (blind) punctual source spot (i.e., the blind image quality): it has to remain within the field of view of the wavefront sensors of the active optics loop that will then optimize the optical quality.

Blind pointing and blind image quality technical budgets have been built to control these requirements and to help in their verification. Allocations have been made on subsystems and the corresponding requirements have been derived. These requirements will be verified at subsystem level. Extensive tests will be done however at system level once the telescope will be assembled to determine the actual blind pointing and blind image quality performance. Given that most of the contributors to the errors are repeatable they can be considered in the telescope pointing model and compensated to a very good extent. However, to do so many pointing runs are needed, so it will take long time. The approach will be that the pointing model will be built to a certain extent during AIV and Commissioning phases, starting without science instruments but with the Telescope Test Unit (TTU) and then continuing after progressively installing the first instruments. This is a clear example of fine-tuning the system as part of the verification activities, which is one of the goals of the verification process as stated in section 1.1. The pointing model will then be continuously improved during Operations.

5.3 Blind Tracking and Guiding Performance

Similar to blind pointing, blind tracking refers to following the apparent movement of the sky objects relying only on the telescope internal metrology (e.g., encoders readings) while slow guiding refers to closing also the optical loops on sky sources (e.g., using a "guide" star). Fast guiding refers to compensating the image jitter (tip-tilt) resulting from atmosphere perturbation, wind shake on the telescope and other internal disturbances (e.g., vibrations). This is done by closing the field stabilization loop with light coming from guide stars.

Concerning blind tracking, there is no explicit L1 requirement because from the user perspective the telescope will never observe without closing the guiding loops on sky. However, blind tracking is relevant in preset (preparing the telescope for observing on a new target), from the moment the telescope finishes pointing until the new guide stars are captured in the telescope sensors and the guiding loops are closed. Hence, a technical budget on blind tracking has been prepared.

Allocations have been made on subsystems and the corresponding requirements will be verified at subsystem level. As for the blind pointing case tests at system level will be done.

Concerning guiding, only requirements on fast guiding residual (i.e., image jitter residual after field stabilization) have been defined in L1S. This residual, which is allocated to subsystems in the field stabilization technical budget, is accounted for as part of the wavefront control performance and therefore its verification will be tackled as part of the wavefront control performance verification. There is no L1 requirement on slow guiding because the field stabilization loop will always be running in science observations.

5.4 Exit Pupil Stability and Plate Scale Stability

Meeting the L1 requirements on pupil and plate scale stability is very important for the science instruments performance. As for the other key requirements two technical budgets has been built at system level and requirements derived on subsystems. The verification of the individual contributions will therefore take place at subsystem level but also verification by test on the assembled ELT (without science instruments) will take place. This will make use of the TTU.

5.5 Optical Throughput

The optical throughput of the telescope is obviously resulting from the combination of the five mirrors' reflectivity (six mirrors in the Nasmyth lateral foci). The L1 requirement will be verified by testing the reflectivity provided by the baseline coating process (protected Silver for all mirrors except Aluminum for the adaptive mirror, i.e., M4) at the nominal wavelength range of the telescope and then by assessing the overall transmission with the TTU once all the mirror units will be in place at selected wavelengths.

5.6 Emissivity and Stray-light

Emissivity and stray-light generated by the telescope and dome are sources of noise in science observations and therefore should be minimized. L1S contains requirements in this sense. The verification will be done by analysis, i.e., simulations running on numerical models built using FRED® software. In order to validate these models and to assess actual performance, it is under investigation whether a number of measurements at specific wavelengths and under given boundary conditions could be done at the telescope with the TTU and/or ad-hoc thermal cameras.

5.7 Operational Efficiency

On top of getting a good performance from the ELT, in order to maximize the science return, it is crucial to operate efficiently. There are some L1 requirements aiming to reach that goal (e.g., technical downtime, technical time, start-up and shut-down time, time to switch from one instrument to another). Technical budgets to allocate derived requirements on the concerned subsystems have been set up. Verification by analysis will be used in all the cases. In particular for the technical downtime, where verification by test is not possible, an availability model that has been built for the entire ELT will be used. Verification by test will be exercised to assess the start-up and shut-down time and the time to switch from one instrument to another.

5.8 Interfaces to the Science Instruments

On top of all the key requirements discussed above, which are actually interface requirements to instruments, the rest of the interface requirements will be verified, the method being decided on a case by case basis. As a goal, all the requirements on the interface of the instruments to the rest of the ELT should be verified before the start of commissioning of the first instrument. Some specific cases may take longer.

6. MODEL APPROACH

The verification of the ELT largely relies on modelling. A number of models have been or will be setup to be used for this purpose. These are both physical and mathematical models, as described in the following sections.

In addition to the models already mentioned above (e.g., ELT performance model, MELT, emissivity and stray-light model, technical downtime model) there will be some other models that will be used to help in the verification of specific subsystems of the ELT that are considered critical. This is the case of the ELT control model and the M1 test facility.

6.1 Physical models

Minuscule Extremely Large Telescope (MELT):

MELT[2] is a small-scale physical model of the telescope that allows for checking wavefront control strategies using the actual control system hardware and algorithms.

Key optomechanical components such as a segmented primary mirror, a secondary mirror on a hexapod, an adaptive fourth mirror, and a fast tip/tilt fifth mirror, together with their control interfaces, will be deployed on an optical bench in a way that the real telescope is emulated. The telescope control system will also be deployed on MELT, hence control schemes with the active mounts emulating the real ELT optomechanical control interfaces can also be tested. The ELT main axis control is emulated with a moveable diffraction-limited source that emits white light from the visible up to the K band through a turbulence generator. On-purpose misaligned optics will emulate the optically imperfect telescope with its optics mounted within mechanical tolerances after assembly and integration. A single conjugate adaptive optics Shack Hartmann wavefront sensor is used in closed loop with the ELT real time computer and the adaptive fourth mirror.

The main objectives of MELT are to validate the telescope control system and in particular the wavefront control algorithms and M1 phasing strategies to be compliant to the L1 wavefront control performance requirements, as well as to produce and validate key requirements for the Phasing and Diagnostic Station (PDS).

ELT Control Model:

The ELT control model is developed at ESO by building a scale-1 copy of selected aspects of the ELT Control System infrastructure including simulators. This includes in particular a replica of the Central Control System (CCS) and the Local Control Systems (LCSs) hardware, on which the CCS and the LCSs software will be running.

The CCS is developed by ESO while the LCSs, in charge of controlling the several ELT subsystems (e.g., Dome, Main Structure, mirror units), are developed by the contractors delivering those subsystems. The ELT control model allows for assessing the interfaces from the CCS to the several LCSs and for assessing the functionality and performance of both the CCS and the LCSs. It also provides services to support their continuous integration and test and will provide technical support to the Observatory during the ELT operation.

The ELT control model does not intend to emulate the subsystems (e.g., does not include a model of the subsystem) but only the interface to the CCS, so it will not be possible to check the control loop performance. Note that MELT is a complement to the ELT control model because, as explained above, it allows for emulating some critical ELT subsystems and actually testing the relevant control loops (e.g., wavefront control loops).

M1 Test Facility:

The M1 test facility is a full scale physical model of a part of M1, including not only the segment assemblies and their supporting mechanical frames but also the M1 cell. A full "flower" of M1, i.e., seven segments is under construction. The M1 test facility will be used for assessing the elements of M1 (segment assemblies, fixed frames, positioning actuators, edge sensors and M1 cell and M1 LCS), the interfaces between them and also the accessibility and handling of those elements. M1 being a very complex subsystem composed of many components, checking the interfaces, the functionality and performance of the individual components as well as of the whole thing is considered of critical importance.

Qualification models of critical elements:

In some specific cases where the requirements defined by ESO are considered challenging or close to the state of the art, qualification models have been requested to the contractors. This is the case for instance of M4, the M1 positioning actuators, the M1 segment support and fixed frame or the M1 segment position (edge) sensors.

6.2 Mathematical Models

ELT Performance Model:

A performance model of the ELT has been produced some years ago and has recently undertaken an in-depth update to convert it into an end-to-end model. The purpose is to be able to run simulations of the performance of the complete system from the atmosphere to the telescope focal plane. Simulations of the system performance in seeing-limited and SCAO modes are now possible. Extending the model to other AO cases (e.g., Multi-Conjugated Adaptive Optics) is left for a future stage because it requires the integration of models from instruments, not available yet. On this respect, it is important to remark that by meeting the required SCAO performance it is implicitly guaranteed that the wavefront aberrations and distortion in the telescope scientific field of view will be small enough as to allow meeting the performance in other AO modes.

The performance model integrates and connects the following sub-models:

- A model of the wavefront perturbation introduced by the atmosphere (including windshake).
- A ray-tracing tool, which includes the optical surfaces and the control equipment (sensors and actuators). The positions and shapes of the optical elements can be perturbed and controlled. In particular, a complete model of the M1 unit, with the segments, edge sensors, positioning actuators and control loops is included.
- A model of the SCAO wavefront sensor and the control loops with M4 and M5 units to assess diffraction limited performance in SCAO mode.
- The FEM of the telescope structure.
- A model of the telescope control system.

The ELT performance model will allow running simulations to assess some of the key L1 requirements, in particular on SCAO wavefront control performance under the specified conditions. This is the main goal regarding the ELT system verification. In addition, the model serves as a key tool to analyze the potential impact at system level of changes (changes requests, waivers) on the subsystem requirements.

3D Model of the Dome and the Telescope:

A 3D model of the dome and the telescope main structure with the so-called hosted units (i.e., the mirror units, the Pre-Focal Station, the instruments) mounted on the latter, is being progressively assembled as soon as the main building blocks are being delivered by the corresponding contractors and instrument consortia. It is at the moment at PDR level but will evolve to reflect the final as-design (and eventually as-built) status of the concerned subsystems. This model is of paramount importance to assess the dimensional interfaces as well as to check accessibility to all the elements in the telescope and their handling. It has already demonstrated its value when assessing the access to critical subsystems like M2 or M4 units, allowing for an optimization of the concerned requirements and the derived design solutions. Figure 10 shows a snapshot of the model.

Figure 10. Snapshot of the ELT 3D model showing a view of Nasmyth A with the instruments and the Pre-Focal Station.

Finite Element Model (FEM) of the populated Nasmyth platform:

Following a similar approach to the one of the 3D model, a FEM of the telescope Nasmyth platform with the instruments and the Pre-Focal Station mounted on it is being developed by connecting the individual FEM models produced by the telescope main structure contractor, by the instrument consortia and by ESO in the case of the Pre-Focal Station (whose contractor has just been awarded). The aim is to assess the mechanical interfaces in terms of load capacity and stiffness as well as to analyze the static and quasi-static deflections of the instruments with respect to the Pre-Focal Station. Earthquake analysis is another objective.

Other specific models:

Some additional mathematical models have been built (or are under development) to address specific areas of concern, where verification by analysis is deemed important. This is the case of:

- A Computational Fluid Dynamics (CFD) model under development for simulating (to a certain extent) local seeing in the telescope chamber.
- An emissivity and stray-light model, which has been used to assess the L1 requirements on telescope self-emission and on stray-light. It considers the telescope and the inner part of the dome.
- A technical downtime model used to build the ELT non-availability budget, which allocates contributions from subsystems to the L1 requirement on ELT technical downtime, and hence to define the requirements on this respect on the subsystems.
- A vibrations model used to build the ELT vibrations budget, which allocates contributions from subsystems to the overall vibrations requirement, and hence to define the requirements on the concerned subsystems.

7. PRE-ASSEMBLY OF SUBSYSTEMS

There are some ELT units that are procured not as a single contractual item but in separated elements under different contracts. Therefore, it is ESO responsibility to integrate them and verify that the whole unit performs as expected. This is typically the case of the mirror units:

- The M1 unit is composed of several elements which are contracted separately or developed in house (the glass segments, the segment support, the edge sensors, the positioning actuators, the M1 local control system).
- The M2 unit and the M3 unit are composed of the mirror on one side and the cell on the other.
- The M5 unit is composed of the mirror assembly and the tip-tilt stage.

In these cases, in order to reduce not only the risk of mismatches and therefore the effort required on site when assembling the several elements, it is planned to conduct a pre-assembly by the acceptance of the concerned elements. This is actually an intermediate verification activity that takes place before the final integration in the telescope, mainly to check that the elements fit and to assess the integration procedure.

For instance, M2 and M3 mirrors are intended to be assembled into their corresponding cells in Europe before the shipment to the Observatory. Basic tests would then be conducted on the assembled unit, which will then be separated again in cell and mirror before shipment to the Observatory. In addition, a basic set of requirements on the unit derived from L1S will be defined by the corresponding ELT project manager. These requirements will be assessed by the AIV team after integration of all the elements, as a previous step to declare “internal acceptance’ of the M2 and M3 units (note that no contractor is involved in this process). A similar approach will be followed with the M5 unit.

In the case of M1, as already explained in section 6.1, the M1 test facility will be used at ESO to assemble the elements of the M1 mirror well before starting the integration at the Observatory.

The case of the control system, which is developed in house, deserves special attention when it comes to verification. As discussed in section 6.1, a control model will be used to fully assess the functionality and performance as the development progresses.

8. CONCLUSIONS

The overall approach, process and tools to verify the system-level requirements of the ESO ELT has been presented. All those elements together form the system verification plan. When preparing this plan, one has to find a proper balance between the objectives of the verification activity and the associated cost and effort. From this perspective, the approach is based on the following principles:

- Whenever possible, verification of system-level requirements relies on subsystem-level verification.
- Verification by review of design is the chosen method when it is deemed enough to prove compliance.
- Verification by analysis is the selected method when verification by review of design is not enough and when models with sufficient fidelity and credibility are economically feasible and more cost-effective that tests.
- Verification by test is in place whenever the previous condition is not met or when key requirements are involved. Note that in many of these cases a combination of verification by analysis and test is the selected approach: one can perform a few tests under certain boundary conditions (e.g., environmental conditions) and then, once the related models are validated by the test results, run simulations on environmental conditions that are not easy to reach in practice but still apply to the system.

As verification by analysis plays a fundamental role in the verification activity, a number of physical and mathematical models have been built (or are ongoing). These models will allow running simulations on many critical system functions and performances, in different conditions by just changing the parameters space under which these simulations are run.

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