ESO - Requirements Management (RM) in Astronomical Instrumentation

From science needs to technical specifications

Angela Cortes
Instrumentation System Engineer

EIROforum IWG Workshop on Systems Engineering 2025

Key Objectives

Why

Understand the role of requirements management in system engineering.

How

Explore how science needs are translated into technical specifications.

Examples

Examine a case study in astronomical instrumentation

Conclusions

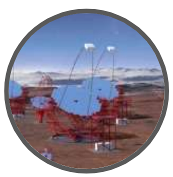
What is important for requirements

ESO Telescopes & Astronomical Instruments

Paranal

VLT & VLTI

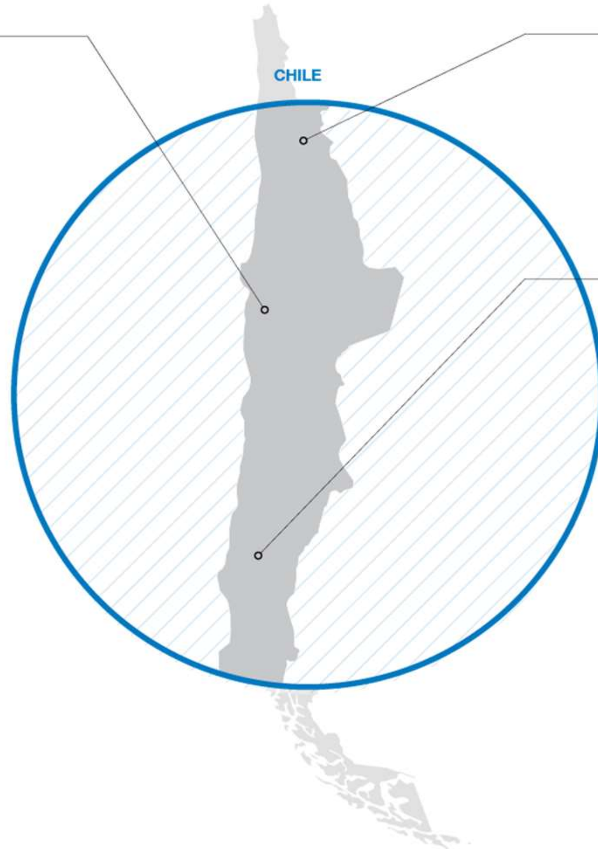
Survey & hosted Telescopes



CTA South*

Armazones

ELT*



La Silla

Telescopes at La Silla

3.6m telescope,
3.5 NTT & hosted
telescope projects

Chajnantor

ALMA

APEX

*in construction

ESO Telescopes & Astronomical Instruments

Paranal

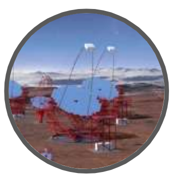
FORS2
KMOS
FLAMES
VISIR
UVES
SPHERE
ESPRESSO
PIONIER

CRIRES
XSHOOTER
HAWK-I
ERIS
MUSE
GRAVITY
MATISSE

VLT & VLTI

OmegaCAM
~~VIRCAM~~

Survey & hosted Telescopes



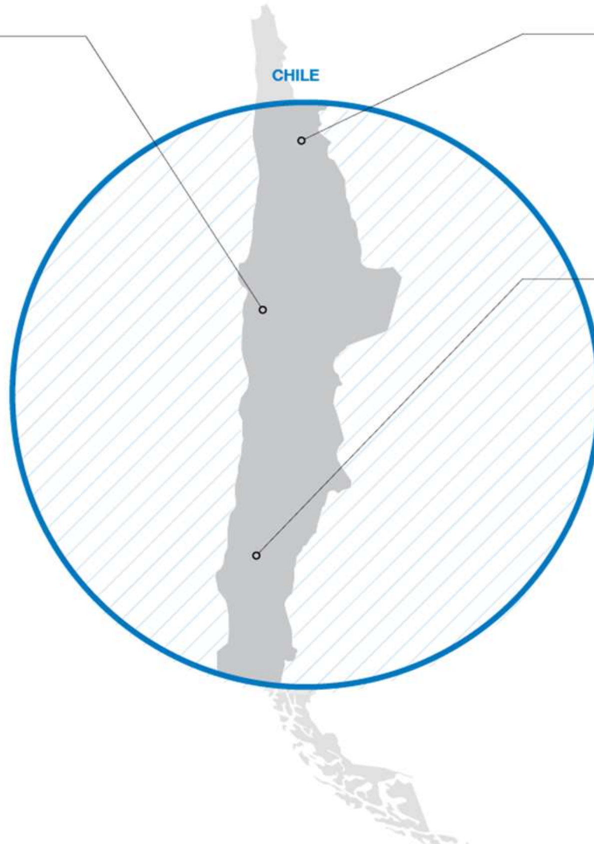
CTA South*

Armazones

ELT*

HARMONI
MICADO / MORFEO
METIS
ANDES
MOSAIC
PCS

*in construction



Chajnantor

Correlator

ALMA

SEPIA
ARTEMIS
nFLASH
CONCERTO
LASMA

APEX

La Silla

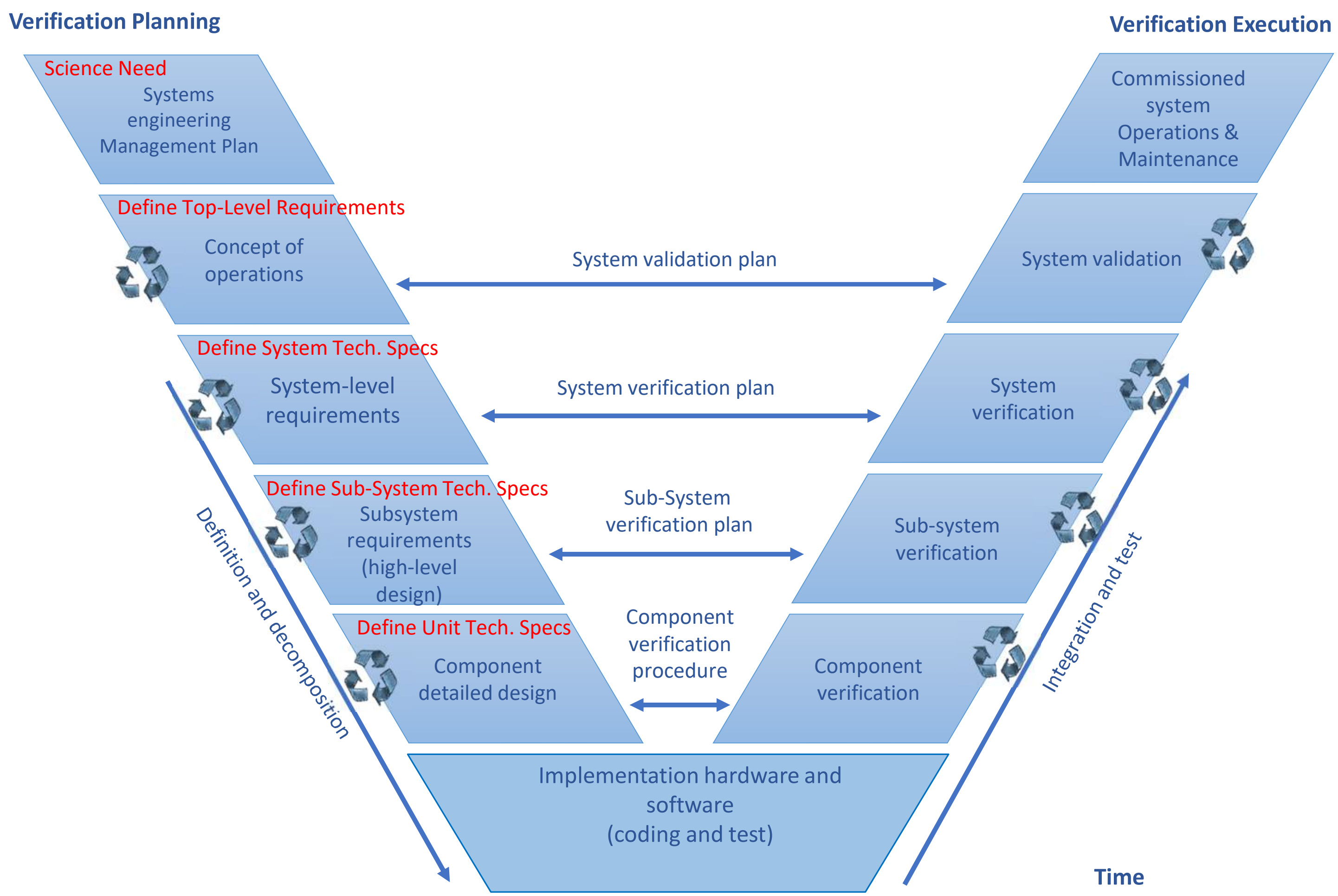
Telescopes at La Silla

3.6m telescope, 3.5 NTT & hosted telescope projects

SOFI
EMMI
EFOSC2
WFI

HARPS
NIRPS
FEROS

V Model



Verification Planning
Verification Execution
Science Need
Systems engineering Management Plan
Define Top-Level Requirements
Concept of operations
Define System Tech. Specs
System-level requirements
Define Sub-System Tech. Specs
Subsystem requirements (high-level design)
Define Unit Tech. Specs
Component detailed design
Implementation hardware and software (coding and test)
Commissioned system Operations & Maintenance
System validation
System verification
Sub-system verification
Component verification
System validation plan
System verification plan
Sub-System verification plan
Component verification procedure
Definition and decomposition
Integration and test
Time

ESO Project Phases:

Pre-Phase A:
- Identification of the science drivers and key performance metrics.
- Preliminary feasibility studies to assess technical challenges.
- Initial risk identification and resource estimation.

Phase A: Feasibility Report
- Detailed feasibility studies addressing technical, operational, and cost aspects.
- Conceptual design work that outlines the main subsystems and overall architecture.
- Develop final mission concept, and the system-level requirements (Tec. Spec.)
- Early trade-off studies to compare different design approaches.
- Preliminary risk assessment and mitigation strategies.

Phase B: PDR
- Development of detailed preliminary designs and simulations.
- Establishment of an error and performance budget (for instance, for the AO system, optics, and detectors).
- Integration of trade-off studies with respect to cost, risk, and technical performance. Also prototyping.
- Formal reviews with stakeholders to validate that the design can meet the science requirements.

Phase C: FDR
- Finalization of engineering drawings, specifications, and detailed models.
- Intensive design reviews and verification of requirements compliance.
- Detailed planning for manufacturing, assembly, integration, and testing.
- Preparation of calibration and operational plans.

Assembly, Integration & Verification

Overview

What are requirements?	• Definitions, examples
ESO requirements process	• Flow down
Challenges of requirement definition	• Flowdown and allocation • Validation and verification • Writing good requirements

Requirements Definition

Requirements describe the necessary functions and features of the system that needs to be designed, created and used. They can be related to:

- Performance (resolution, magnification, contrast,…)
- Functionalities (take visible images, take IR spectroscopy, collect sample in another planet,…)

Requirement Conditions

- Schedule (by when do we need it, be reasonable)
- Cost (budget definition)
- Survival environment (high radiation, earthquakes, extreme temperatures,..)
- Lifetime (10 years, 30 years,…), very linked to cost definition.
- Others (size, weight, …)

Understand the goal of your requirement.

- Does something similar already exist?
- Can be improved?
- Do we understand the physics behind?

Why Requirements Management Matters?

Aligns scientific goals with engineering capabilities

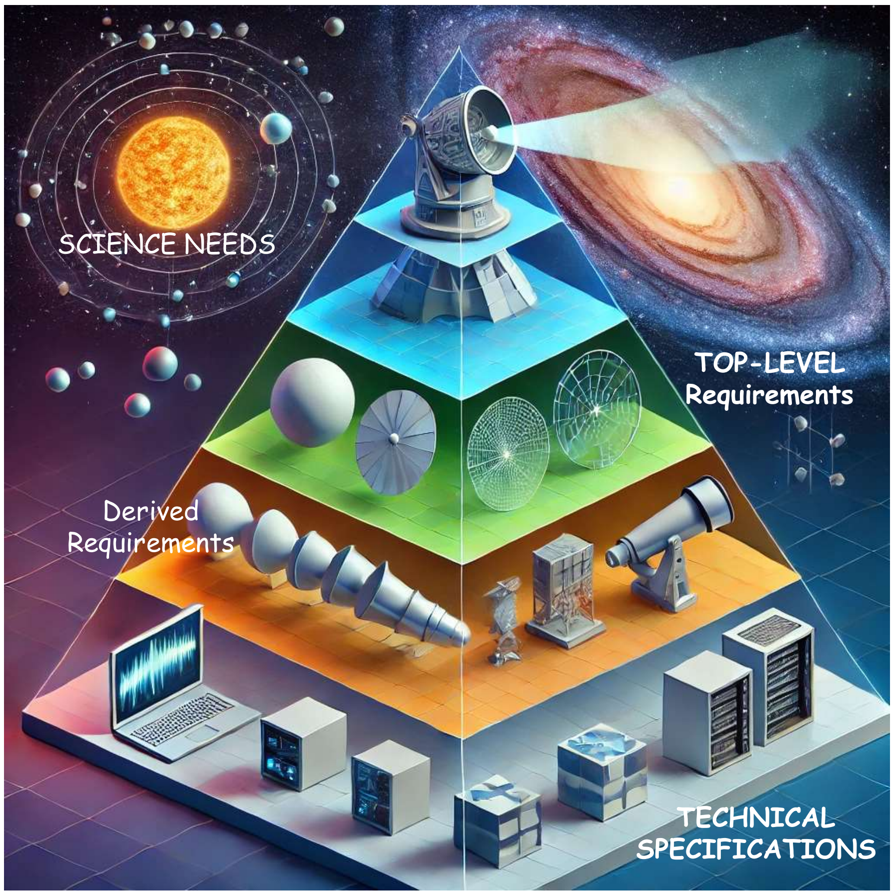
Mitigates risks of costly redesigns

Ensures traceability and accountability

Facilitates communication across multidisciplinary teams

Requirements Hierarchy

Image generated by ChatGPT



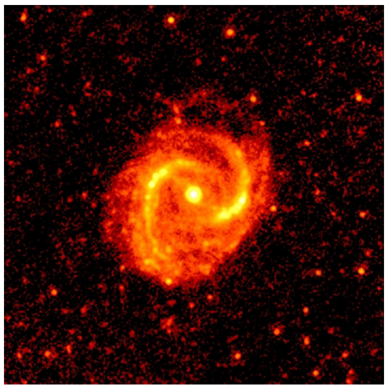
The Requirements Pyramid

1. **Science Needs:** High-level goals (e.g., detect exoplanets).
2. **Top-Level Requirements:** Translate science needs (e.g., AO correction shall be provided leading to ensquared energy of at least 15% within a 50x50 mas square aperture).
3. **Derived Requirements:** Break down into subsystems (e.g., wavefront error delivered by the AO shall be < 100 nm.). (Level 1 Req. Specification, L1S @ESO)
4. **Technical Specifications:** Component-level details (e.g., coating reflectivity > 95%).

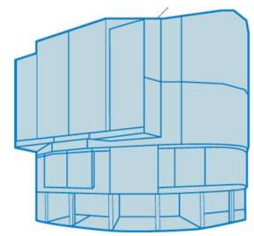
Science Needs and Their Translation

Example:

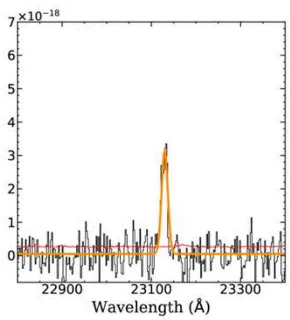
Science Need:
Detect faint galaxies in the infrared



Derived Requirement: Telescope throughput > 60% in the Ks band.



Top-Level Requirement: Sensitivity must reach 25 AB magnitude in the Ks band.



Technical Specification: Mirror coatings with reflectivity > 95% at 2.2 µm.

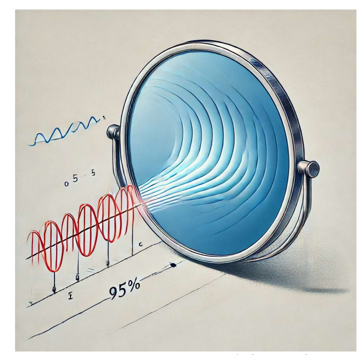


Image generated by ChatGPT

Flow-Down Process

Key Steps:

Decompose	Decompose science goals.
Define	Define performance metrics.
Allocate	Allocate budgets (e.g., error, power).
Validate	Validate allocations with simulations.
Iterate	Iterate based on feasibility.

Decompose Science Need

The community and experts find a science need that cannot be done with actual instruments

Meeting to discuss science concept and technology needs

1. Identify existing expertise
2. Agree on a list of WP
3. Draft Scope
4. Discuss organisational aspects
5. Way towards and roadmap collaboration

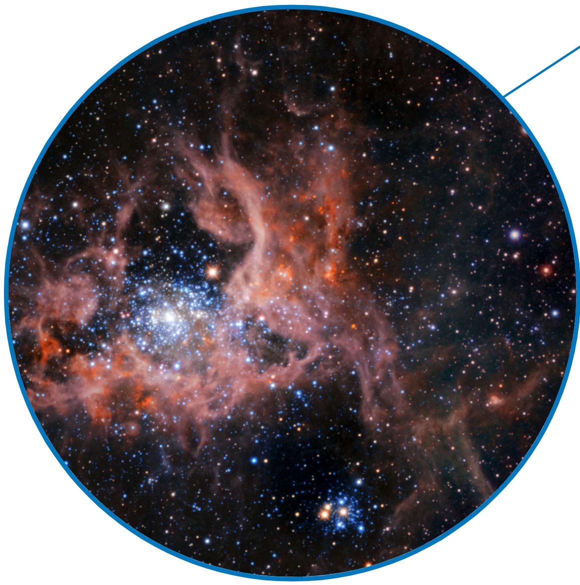
And definition of working group of experts:

- Top level Req. & definition of science cases
- XAO Wavefront Sensing and Control
- XAO DM
- XAO End-to-End simulation
- Concept studies
- System Concept

Case Study: Infrared Astronomical Instrument

Derived Requirement:

On-axis wavefront error < 100 nm at 3.3 um

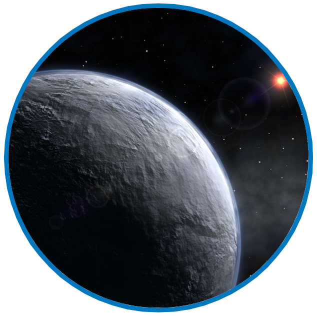


Infrared image of 30 Doradus (Tarantula Nebula) HAWK-I + VISTA

Flow-Down:

- **Telescope and Atmosphere** (seeing conditions, turbulence effects)
- **AO System** (wavefront sensor, deformable mirrors, control algorithms)
- **Instrument Optical Design** (alignment errors, optical surface quality)
- **Mechanical and Thermal Stability**

Case Study: Study Methane on extrasolar planets



Artist's impression
Credit: ESO

Science Need:
"Detect methane in the atmosphere of an extrasolar planet"

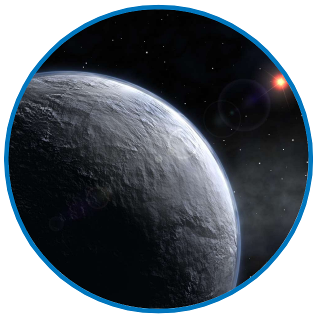
Top Level Requirements – Science Performance

- Wavelength Coverage: **near- to mid-infrared range (2.8 – 3.5 µm)**
- Spectral Resolution: **($R = \lambda/\Delta\lambda$) of at least 100,000** at 3.3 µm.
- Sensitivity: **5σ detection of a methane feature in an exoplanet atmosphere with a host star of magnitude K = 12 in 10 hours of integration**.
- Contrast and High Dynamic Range Capability: **planet-star contrast ratio better than 10^5:1** at angular separations of **0.1–0.5 arcseconds**.

Top Level Requirements - Optical and Spectroscopic Requirements

- Throughput: total system efficiency (including telescope, instrument optics, and detector quantum efficiency) shall be **≥ 20% at 3.3 µm**.
- Field of View (FoV) and Spatial Sampling: **FoV of at least 1 arcsecond** to account for adaptive optics (AO) corrections.
- Pixel scale should match the diffraction limit of a **40m telescope at 3.3 µm (~0.02 arcsec/pixel)**.

Case Study: Study Methane on extrasolar planets



Artist's impression
Credit: ESO

Science Need:
"Detect methane in the atmosphere of an extrasolar planet"

Top Level Requirements – Detector and Readout Requirements

- Detector Type and Noise Performance: **high-QE (≥80%) HgCdTe infrared detector array**, optimized for 3-5 µm.
- Readout noise: shall be **<10 e^- RMS per frame** to allow stacking of exposures.
- **Dark current < 0.01 e^-/s/pixel** at an operating temperature of **≤40 K**.
- A cryogenic cooling system (e.g., closed-cycle cooler or liquid helium) shall maintain stability within **±0.1 K**.

Top Level Requirements - Observing Mode Requirements

- High-Resolution Spectroscopy Mode.
- Cross-Correlation Spectroscopy Support.
- Polarimetry (Optional), for distinguishing between reflected starlight and thermal planetary emission.

WFE Allocations (example)

Error Source	Budget (nm RMS)	Notes
Atmospheric Turbulence (after AO correction)	60 nm	Residual error after AO compensation
Deformable Mirror Fitting Error	30 nm	Limited by actuator density and response time
Wavefront Sensor Noise	20 nm	Photon noise, detector readout noise, centroiding error
Optical Surface Errors (instrument optics)	20 nm	Mirrors, lenses, coatings, optical misalignments
Static Aberrations (telescope optics)	15 nm	Primary/secondary mirror polishing, alignment errors
Vibrations and Thermal Drifts	10 nm	Mechanical jitter, instrument flexure
Total	**~100 nm RMS**	Ensures diffraction-limited imaging

MAVIS example

<u>Top Level Requirements (TLR-14)</u>:
The AO module shall perform atmospheric turbulence correction making use of multiple natural-guide-stars (NGSes) and laser-guide-stars (LGS). **The NGSes shall be sensed such that the WFS cameras do not obstruct the science FoV and a maximum instrumental throughput is provided**.
Under stable, standard atmospheric conditions (TLR-10), **and at a zenith distance of 30°,** the average Strehl ratio (SR) for a V-band filter (performance in other, redder filters is based on the assumption of constant WFE) over the full science FoV of the camera achieved in the raw data product of the instrument over a 15 min duration observation shall be ≥10% (goal 15%) when using three m_J≈8 TT-stars (class G2) on a favourable asterism of diameter ≤40”.

<u>Derived Requirements – AO</u>

- The AO module shall deliver **unvignetted AO-corrected field of at least (30±1)x(30±1) arcseconds**
- The AO module, possibly with reduced performance scaling as expected with conditions and to be agreed with ESO, shall operate **in the best 80% (corresponding to <1 arcsecond seeing)** of seeing conditions (goal: 95%, i.e. <1.5 arcsecond seeing) and good coherence time (corresponding to >2.5 ms; MASS-DIMM value).
- The AO module shall support at least one NGS being an extended object up to 3 arcsecond FWHM
- A minimum of 11% **ensquared energy** within a 50x50 mas2 square aperture.
- AO performance for bright NGS: The average **Strehl ratio** (SR) over the full AO-corrected FoV shall be ≥8% (goal:≥12%) for three NGS with mJ≈8 and an asterism diameter ≤40 arcsec.
- The *variation* of Strehl ratio as in [#425] or FWHM as in [#426], respectively, over the full AO-corrected FoV shall be less than 10% PTV of the average, for all filters with central wavelength larger than 500nm

Example of a spec with a missing detail

R-MAVIS-SCI-6 Imaging Sensitivity

MAVIS, in a one hour total exposure time, shall be able to image an isolated point source of mV=29 with a SNR≥5.

Driving Science Case Chapters	Requirement Rationale	Other Relevant Chapters
2.5 Morphology of the first galaxies	Need to maximise volume probed, which is proportional to photometric depth; push to low mass systems beyond Hubble Ultra Deep Field (<29.5mag)	2.4, 3.3, 3.4, 4.2, 4.3, 5.2, 5.3, 5.4
3.2 Resolved stellar populations in ETG envelopes	Detect RGB of ancient stellar populations within 10Mpc requires limiting AB magnitude of V=29-30	
4.4 Stars clusters in the Local Universe	Detecting down to 0.1Msun stars in the L/SMC for IMF studies requires V>29 ABmag	
4.7 The origin of the first star clusters at high-z	Detecting lensed young massive clusters forming at z>7 requires limiting magnitudes of V>29	

Example of a spec with a missing detail

<table>
<tr><th colspan="3">R-MAVIS-SCI-6 Imaging Sensitivity</th></tr>
<tr><td colspan="3">MAVIS, in a one hour total exposure time, shall be able to image an isolated point source of mV=29 with a SNR≥5.</td></tr>
<tr><th>Driving Science Case Chapters</th><th>Requirement Rationale</th><th>Other Relevant Chapters</th></tr>
<tr><td>2.5 Morphology of the first galaxies</td><td>Need to maximise volume probed, which is proportional to photometric depth; push to low mass systems beyond Hubble Ultra Deep Field (<29.5mag)</td><td rowspan="4">2.4, 3.3, 3.4, 4.2, 4.3, 5.2, 5.3, 5.4</td></tr>
<tr><td>3.2 Resolved stellar populations in ETG envelopes</td><td>Detect RGB of ancient stellar populations within 10Mpc requires limiting AB magnitude of V=29-30</td></tr>
<tr><td>4.4 Stars clusters in the Local Universe</td><td>Detecting down to 0.1Msun stars in the L/SMC for IMF studies requires V>29 ABmag</td></tr>
<tr><td>4.7 The origin of the first star clusters at high-z</td><td>Detecting lensed young massive clusters forming at z>7 requires limiting magnitudes of V>29</td></tr>
</table>

What is missing??

⭐The definition of the window to measure the SNR ≥ 5 on pixels.

ESO Tools for Requirements Management

Capturing, tracking, and managing requirements

- IBM Engineering Requirements Management **DOORS** (Dynamic Object-Oriented Requirements System)

Model-Based Systems Engineering (MBSE) and Requirements Modeling Tools

Mainly done by the consortia:

- MORFEO – Cameo
- ANDES – MagicDraw
- METIS – Polariom

Test and Validation-Focused Tools

- DOORS

General Project and Documentation Management Tools:

- **Accruent, PDM**

Issue and Change Management Tools:

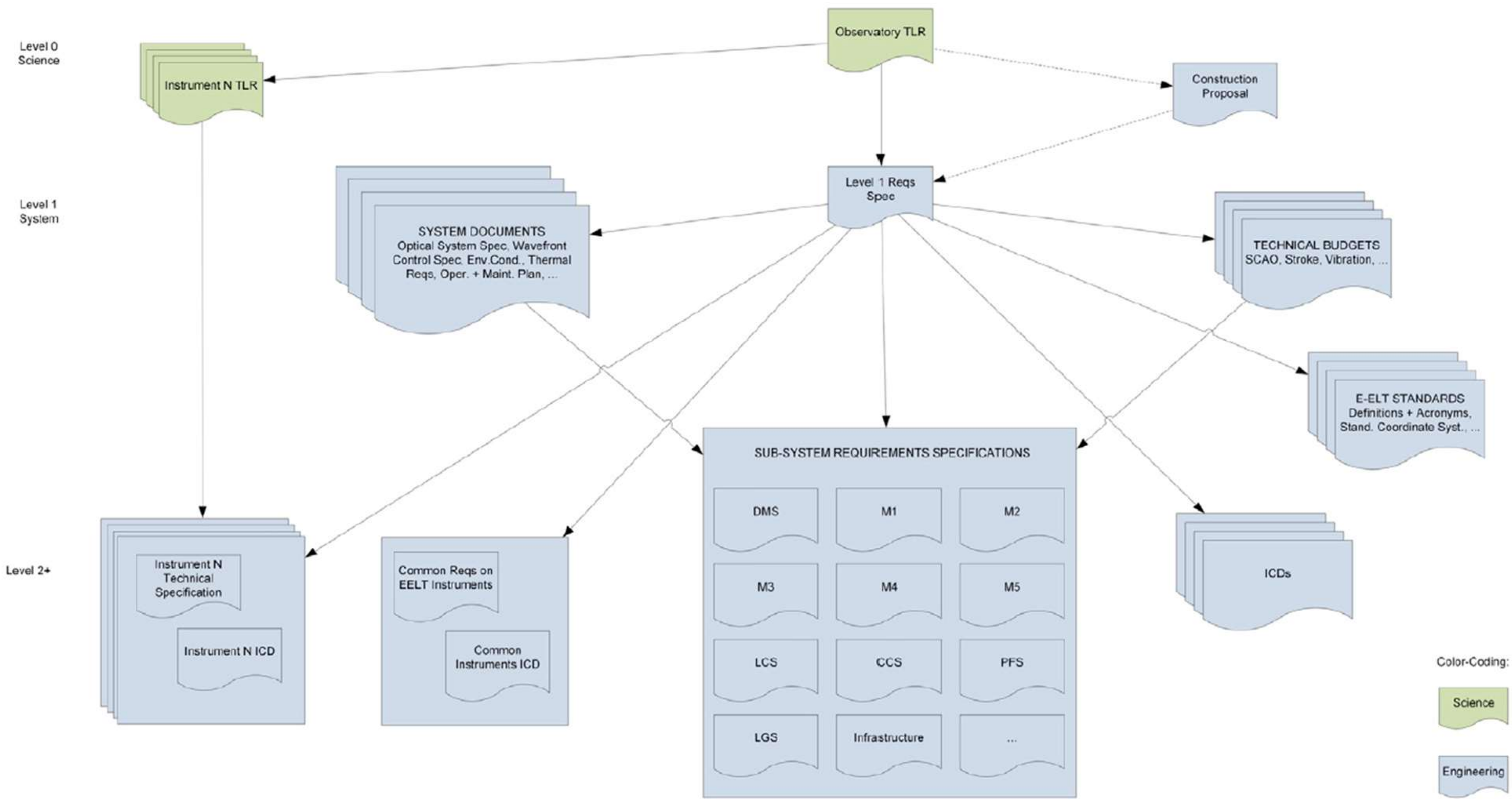
- **Jira (Atlassian)** – Widely used in agile requirement tracking and issue management.

Traceability and Compliance Tools:

Simulation and Analysis Tools (Used for Requirement Validation in Astronomy):

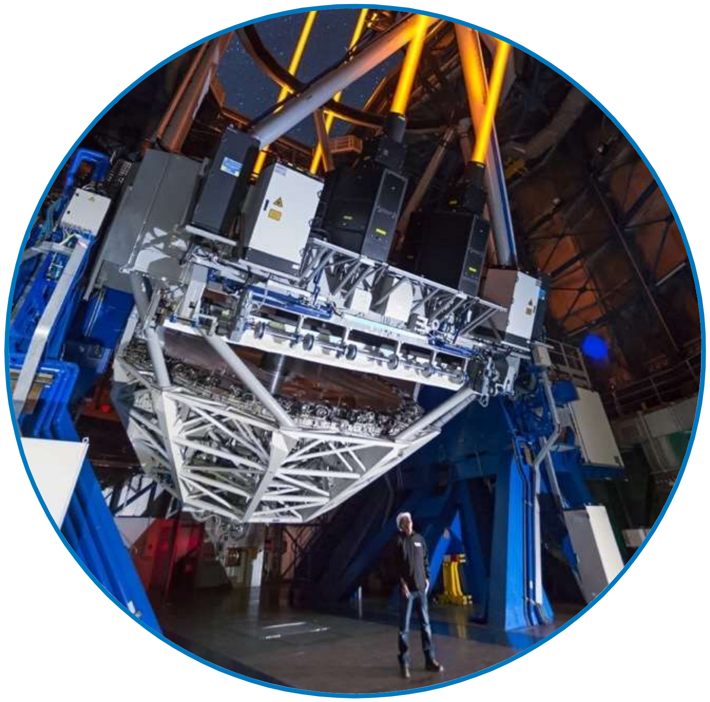
- **Zemax OpticStudio** – Used to validate optical requirements for telescopes.
- **MATLAB & Simulink** – Simulations for verifying requirements in system design.
- **ANSYS, Nastran** – Structural, thermal, and optical simulations for requirement compliance, FEA Analysis.

ESO Requirements Document Tree



Hardie et al, 2022

Challenges and Best Practices



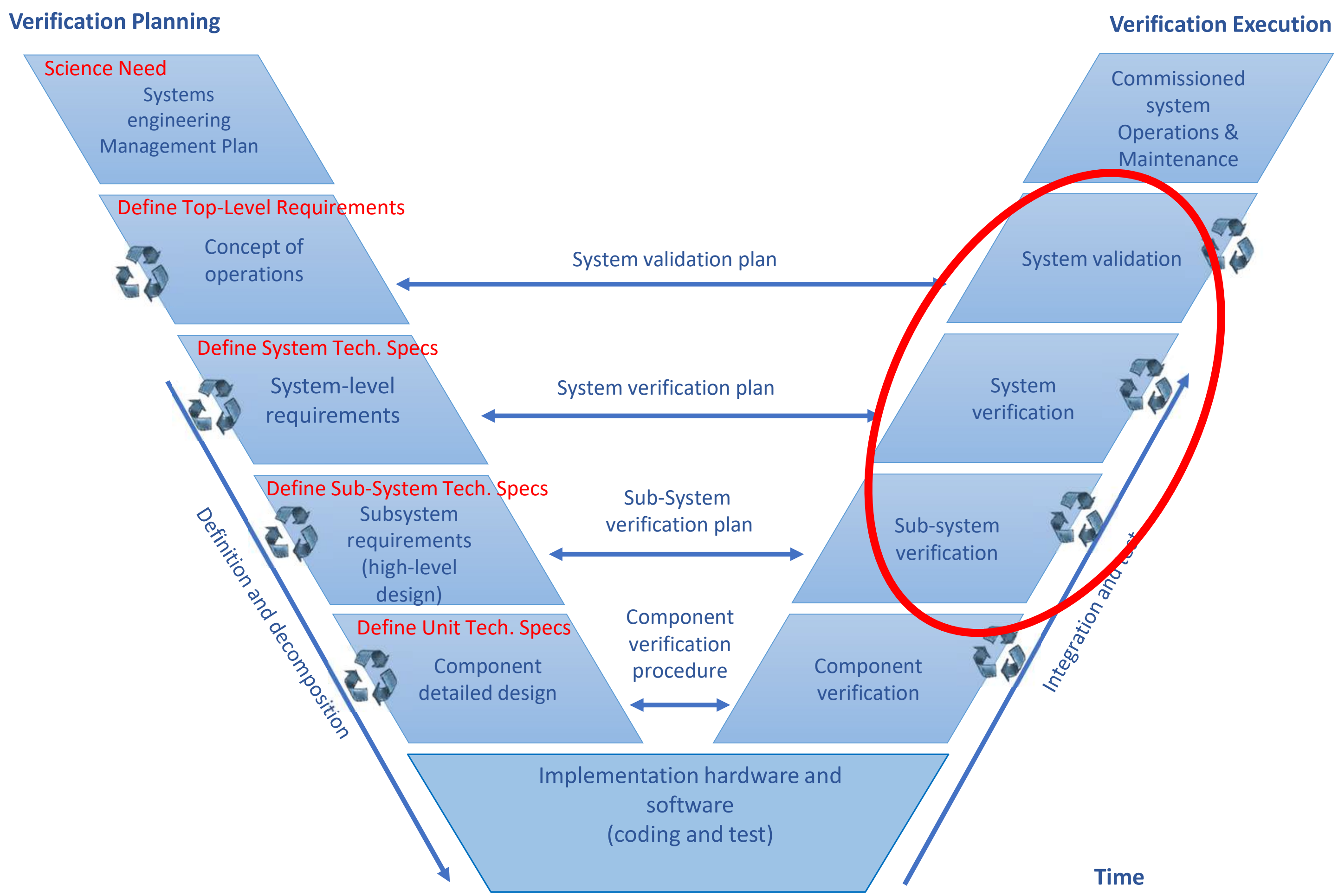
Challenges

- Conflicting stakeholder priorities
- Managing evolving requirements
- Ensuring traceability

Best Practices

- Engage stakeholders early
- Use iterative validation
- Prioritize requirements to balance cost and performance

V Model



Verification Planning
Verification Execution
Science Need
Systems engineering Management Plan
Define Top-Level Requirements
Concept of operations
Define System Tech. Specs
System-level requirements
Define Sub-System Tech. Specs
Subsystem requirements (high-level design)
Define Unit Tech. Specs
Component detailed design
Implementation hardware and software (coding and test)
Component verification
Sub-system verification
System verification
System validation
Commissioned system Operations & Maintenance
System validation plan
System verification plan
Sub-System verification plan
Component verification procedure
Definition and decomposition
Integration and test
Time

Verification and Validation (V&V)

Key Concepts:

•Verification: "Did we build it right?"

- Testing against specifications.

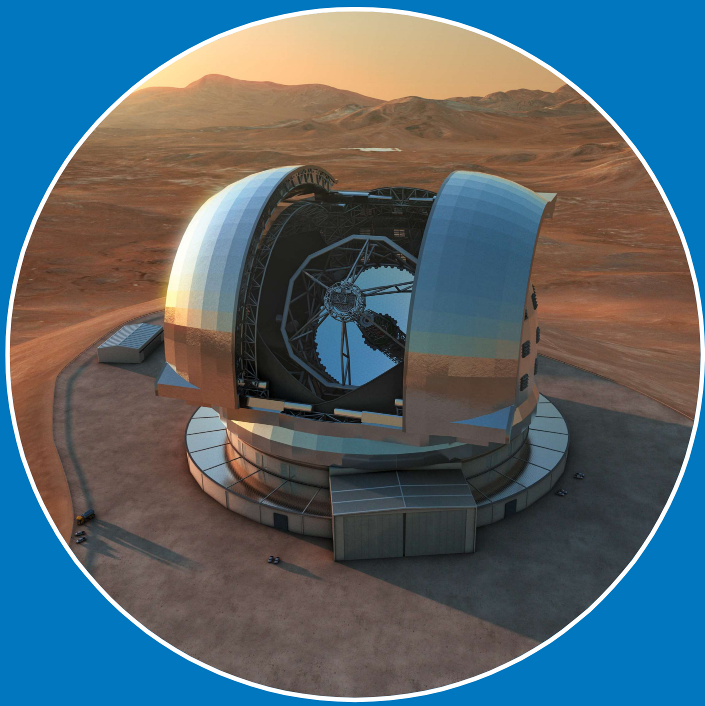
•Validation: "Did we build the right thing?"

- Ensuring it meets scientific goals.

At ESO, the verification and validation methods are defined in the Technical Requirement Specification as**:**

- **Verification by Desing** (D): using approved records or evidence (design documents and reports, technical descriptions, engineering drawings) that unambiguously show that the requirement is met.
- **Verification by Analysis** (A): performing theoretical or empirical evaluation using techniques such as systematic and statistical design analysis, modeling and computational simulation.
- **Verification by Inspection** (I): 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 Test** (T): 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.

Summary & Conclusions



Requirements management bridges science and engineering

Tools and best practices are critical for success

Use a structured hierarchy and flow-down approach

Bibliography

- Kayla Hardie, Amanda C. Santana, Andrew W. Serio, Juan C. González Herrera, Bart Fordham, Brian Walls, Brian Selvy, and Dominik Schneller "Systems engineering processes and tools for requirements management at the Extremely Large Telescopes," Journal of Astronomical Telescopes, Instruments, and Systems 8(2), 021507 (25 April 2022). https://doi.org/10.1117/1.JATIS.8.2.021507
- Hermine Schnetler, Fraser Clarke, and Myriam Rodrigues "A novel approach to the development of the HARMONI integral field spectrograph using structured systems thinking", Proc. SPIE 10705, Modeling, Systems Engineering, and Project Management for Astronomy VIII, 1070507 (10 July 2018); https://doi.org/10.1117/12.2313315
- MAVIS-SCI-SDD-0001 (D-06) MAVIS Science Case


Thank you!