5. System Engineering

5.1 Level 1 requirements

Level 1 Requirements constitute the highest level engineering requirements and are second only to Top Level Requirements, from which they are derived in part. They provide the link between the eventual user's objectives and the project and engineering frameworks, including essential characteristics.

Level 1 Requirements also include indirect ones, as well as guidelines and targets. Those may reflect constraints and objectives not directly related to scientific objectives but to technical, programmatic, or even legal considerations (e.g. compliance with legal safety standards).

At this stage, characteristics covered by OWL Level 1 Requirements are generally given two values (or two set of values), one corresponding to the biding requirement, one for the desirable (non-binding) goal.

Level 1 Requirements are documented in RD41. Items addressed in this document include:

1. Definitions and conventions, e.g. common terminology, coordinate systems;
2. Environmental conditions – the same as for the VLT until final site selection;
3. Requirements
   - 3.1. Design guidelines
   - 3.2. Optical characteristics
   - 3.3. Optical quality
   - 3.4. Atmospheric dispersion compensation
   - 3.5. Wavefront control, including accuracy requirements
   - 3.6. Structure & Kinematics
   - 3.7. Interface to instruments
   - 3.8. Local seeing, thermal control
   - 3.9. Cleanliness
   - 3.10. Enclosure characteristics
   - 3.11. Operations, including reliability, operational lifetime, science operations, maintenance
   - 3.12. Site infrastructure, including site services, offices, lodging, etc.
   - 3.13. Performance evaluation and monitoring
4. Site characterization, monitoring and preservation
5. Safety

Level 1 Requirements are essentially functional ones. However, because they must make some broad assumptions as to the technologies and concepts that may eventually be required to fulfil Top Level Requirements, they are not fully design-independent –even though every attempt should be made at removing such dependency.

Table 5-1 gives the image quality requirements in seeing-limited mode, after successive closing of individual non-adaptive control loops. These requirements are very preliminary and essentially set the maximum allowable amplitude of quasi-static, low to mid-spatial frequency terms and the maximum residual errors which will have to be compensated by adaptive optics. It should be noted a given slope requirement translates into more generous amplitude than with a smaller telescope –0.1 arc seconds of astigmatism, for instance, corresponds to a wavefront coefficient 12.5 times larger with OWL than with VLT.

In addition, non-adaptive wavefront control systems shall have such characteristics that residual telescope errors (including turbulence induced by local heat sources), which will have to be compensated by Adaptive Optics, do not exceed 20% (goal 10%) of the available adaptive correction range.

Mode	**On-axis image quality**		**Image quality off-axis (1.5 arc min)**	
	Requirement	Goal	Requirement	Goal
Open loop	1.5 arc seconds RMS	1 arc second RMS	N/A	N/A
After internal alignment	1 arc seconds RMS	0.5 arc seconds RMS	1.5 arc seconds RMS	0.5 arc seconds RMS
Idem + active centring & focusing	0.5 arc seconds RMS	0.2 arc seconds RMS	0.7 arc seconds RMS	0.3 arc seconds RMS
Idem + phasing + active deformation of flexible mirrors + field stabilization[37]	0.10 arc seconds RMS	0.08 arc seconds RMS	0.12 arc seconds RMS	0.10 arc seconds RMS

Table 5-1. Image quality requirements, non-adaptive modes.

With a view to allowing sub-mm observations without on-sky metrology, image quality on-axis shall be 1.0 arc seconds RMS (goal 0.5 arc seconds RMS) or better over a 30 minutes exposure, with the following loops running:

a. Internal alignment (running on internal metrology systems);

b. Phasing (running on position sensors);

c. Active centring (running on look-up tables);

d. Active focusing (running on look-up tables);

e. Active surfaces deformation (running on look-up tables).

Table 5-2 gives the image quality requirements after adaptive correction (first generation single conjugate, second generation dual-conjugate). In dual-conjugate mode, the maximum variation of the Strehl Ratio over the field of view shall be less than or equal to ±10%.

These requirements are in-line with the top level ones. In the event of conflict between Table 5-1 or Table 5-2 and the level 1 requirements specified in RD41, the content of RD41 shall be taken as superseding.

At the time of writing of this document, image quality requirements in Ground-Layer Adaptive Optics and Extreme Adaptive Optics modes are still under review.

Level 1 requirements also includes the hierarchy and allowable rate of occurrence of damages or major failures. The term out of operations is not meant to include preventive / regular maintenance but includes corrective maintenance if such corrective maintenance implies loss of science time.

[37] Non-adaptive field stabilization.

Star magnitude	**Seeing (arc seconds)**	**Wavefront RMS on-axis (μm)**	**Field of view (arc minutes, diameter)**
Single-conjugate adaptive optics			
13.5	0.4	0.180	N/A
	0.6	0.200	N/A
	0.8	0.230	N/A
	1.2	0.300	N/A
15.5	0.4	0.274	N/A
	0.6	0.302	N/A
	0.8	0.344	N/A
Multi-conjugate adaptive optics			
13.5	0.4	0.252	3
(integrated over all	0.6	0.234	3
guide stars)	0.8	0.302	3

Table 5-2. Image quality requirements, with first and second generation adaptive optics.

Category	Type	Definition	Max. allowable probability or rate of occurence
I	Catastrophic	*Complete loss of system or threat to personnel safety.* OR *Repair cost exceeds 10% of capital investment.*	0
II	Catastrophic	*System is out of operation for 2 months or more,* OR *Repair cost exceeds 5% of capital investment,* whichever comes first.	0.01% over 30 years
III	Critical	*System is out of operations for up to 2 months* OR *Repair cost exceeds 1% of capital investment,* whichever comes first.	0.05% over 30 years
IV	Major	System is out of operation for up to 1 calendar week.	Once every 10 years
V	Significant	System is not able to allow science time for up to 1 calendar week.	Once every 5 years
VI	Minor	System is not able to allow science time for 24 hours.	3 times per year

Table 5-3. Failure / damage hierarchy and allowable rate of occurence.

5.2 Design constraints and guidelines

Overall design constraints and guidelines are also covered in the applicable Level 1 Requirements (RD41). They are reproduced here below:

1. Reliance on proven[38] technology, materials and processes is a high priority requirement, from design to operations.
2. Reliance on serially produced parts or standard parts and assemblies is a high priority requirement.
3. Deviation from the above requirements shall only be considered

[38] At fully tested prototype level as a minimum.

a. where strictly required,

b. or where significant gains in performance, cost or schedule can reasonably be expected.

4. In such case (3.b hereabove), backup solutions shall be identified and developed at least to preliminary design level.
5. The system design and its implementation shall allow maximum possible development time for unproven technology, materials or processes –without, however, delaying the start of science operations.
6. The system design and its implementation shall allow a start of science operations as soon as possible after (technical, seeing-limited) first light, with negligible engineering overheads, reduced pupil area, and single conjugate IR Adaptive Optics with Natural Guide Stars.
7. To the possible extent, design solutions allowing progressive loss of performance in case of failure shall have preference over solutions implying significant loss of performance in case of failure.
8. From system to component level, and from the earliest phases of design inception, high priority shall be given to operation and maintenance considerations –with a view to

   - Minimizing system integration and operational resources (in particular, non-standard hardware as well as specialized human resources);
   - Facilitating maintenance and minimizing operational complexity;
   - Guaranteeing, to the maximum possible extent, system integrity and safety of human resources.

   To this end, preliminary designs, from system to component level, shall include operation and maintenance plans, including preliminary definition of related hardware and resource usage.

5.3 Complex Systems, methods and modelling

This section provides a brief overview of OWL System Engineering aspects. It starts with a broad comparison of OWL with other Complex Systems. System Engineering methods are discussed qualitatively. The flow of activities across disciplines is discussed, with emphasis on traceability and compliance verification. Requirements shall be traceable from their inception and verified at the appropriate project level, within a determined timeframe and along clear processes and pre-defined procedures. Project Documents and Project Configuration Control Procedures shall be outlined along such principles. The last part of this section deals with the quantitative aspects of System Engineering, including modelling tools.

In the following the OWL Observatory is defined as *system*, while the telescope, enclosure, instruments, Data Management, etc. are referred to as *sub-systems* (see also RD37).

5.3.1 Complex System

A consistent system engineering approach is recognized as being of paramount importance to the design of OWL. Complexity is a characteristic common to most large-scale engineering projects. Complex systems are mainly characterized by their large number of assemblies, parts, components, but also by the resources (including human resources) their design, construction, and operation require, and by the large number of interfaces and interdependencies between them [77], [78]. Breaking down into smaller and more manageable subsystems, possibly organized in hierarchical structures, implies intense, multi-directional information flow and requires efficient coordination mechanisms.

The engineering of OWL as a complex system will be conceived to achieve the following objectives:

- Ensure appropriate oversight and understanding of the system, its scientific and engineering characteristics, including underlying risks and susceptibility to failures.
- Develop tools and organizational methods to quantify, track, and visualize, system designs and to support trade-off analysis and decision-making processes.

Key element of a system approach are modelling and computer simulations. Models provide a means of understanding complex phenomena and of evaluating the overall response of the system to specified disturbances (e.g. a change of environmental condition or of a specific design characteristics). By using mathematical models along with advanced analysis tools and simulation environments, the system design and performance can be evaluated before construction begins.

OWL as a controlled opto-mechanical system will integrate the knowledge base and mathematical tools used in at least three engineering disciplines: structural mechanics, optics, and control systems. The rapidly growing computing power does not necessarily imply that an integrated model complete down to all possible details is the one-fits-all modeling tool. In practice, high accuracy and fidelity are often traded against simplicity, which often takes superseding priority. It is indeed natural to seek techniques (e.g. use of reduced models) that reduce model complexity and computational effort to a level commensurate to the level of detail required to asses an evolving design.

5.3.2 Methods

5.3.2.1 Science and Engineering.

A V-diagram (Figure 5-1) shows symbolically how Science and Engineering interface. OWL characterization is divided in 2 main structures:

- Science, the top part under the responsibility of scientists with the support of engineers.
- Engineering, the lower part under the responsibility of engineers with the support of scientists.

Both structures are involved, to variable extent, during all project phases.

System Design. The left part of the diagram corresponds to phases A and B –conceptual and preliminary / final design, respectively. Experience shows that during these phases about 80% of the project cost and technical solutions are committed. Phase A and B take typically take 20% of the project schedule. Changes of requirements and design iterations are possible until final design, but costs associated to changes tend to increase with time.

System Integration. The right part of the diagram corresponds to phases C and D. It is the counter part of the System Design. Each level of the System Design shall have a corresponding verification activity during system integration. Changes of requirements during the system integration normally generate high costs and substantial delays.

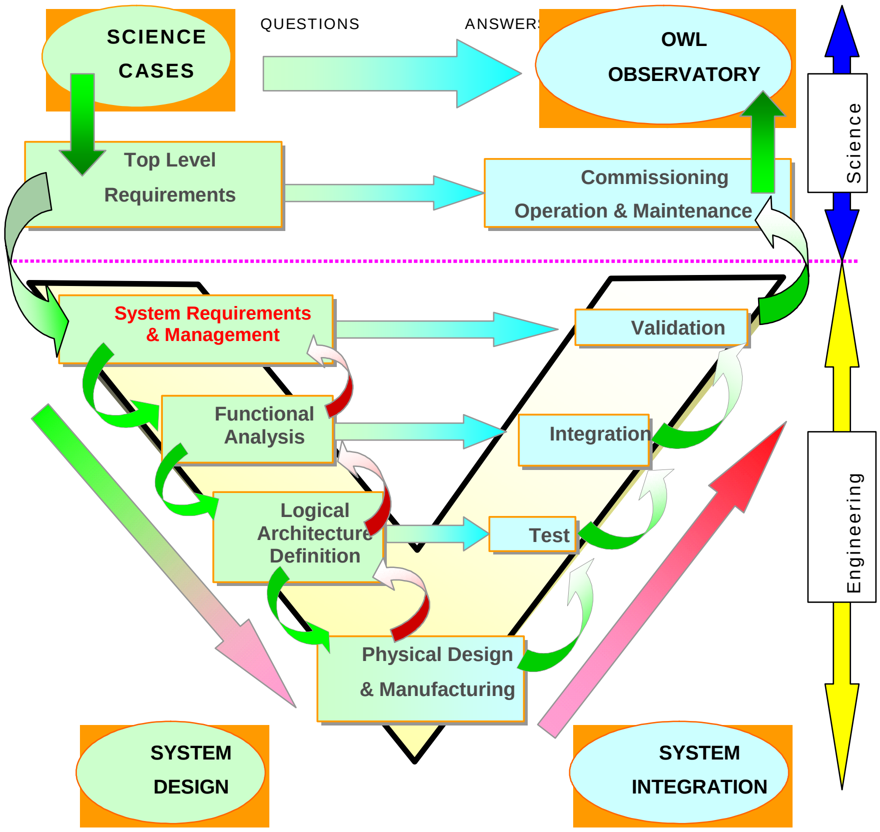

Figure 5-1 : Project V-diagram.

5.3.2.1.1 System Design

5.3.2.1.1.1 Top Level Requirements

The first tasks of the System Engineering are to interpret Top Level Requirements in terms of technical and programmatic characteristics of the the project, and derive level 1 requirements. Level 1 requirements are briefly addressed in section 5.1 and provided in RD41.

5.3.2.1.1.2 System Requirements Management

The role of the System Requirements Management is to provide a unified system engineering environment for

- Controlling requirements definitions and evolution;
- Controlling compliance with requirements;
- The setting and application of validation and certification processes;
- Ensuring optimal use of in-house experience and knowledge;
- Assessing the impact of changes on project performance and schedule;

The System Requirement Management is an iterative process which increases the understanding of requirements and generates a requirement breakdown structure (Figure 5-2).

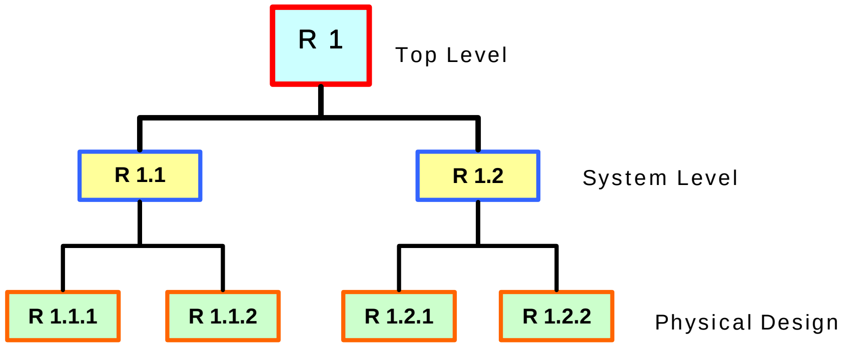

Figure 5-2: Requirements breakdown.

It is an iterative process which encompasses:

- Interpreting Top Level Requirements, translating into system definitions;
- Capture candidate technical and non-technical requirements;
- Breaking down requirements, deriving individual, non-ambiguous specifications ;
- Analysis
    - Categorizing and prioritizing requirements;
    - Establishing database attributes;
    - Establishing allocations and traceability;
    - Reconciling with, capturing decision rationale;
- Formalization
    - Formalizing traceability;
    - Allocating requirements;
    - Configuration Management;
    - Defining Interfaces requirements;
- Changes and impacts management
    - Defining requirements test & validation plan;
    - Providing Compliance and Traceability Matrices;
    - Verifying Traceability;
    - Resolving Discrepancies and facilitating agreement;
    - Establishing requirements baseline;
- Tracking and auditing evolution;
- Defining verification method(s);
- Creating and maintening baseline and definitions.

5.3.2.1.1.3 Functional Analysis

The Functional Analysis defines:

- The functional decomposition of the system;
- The functional Flow;
- The functional Data Flow.

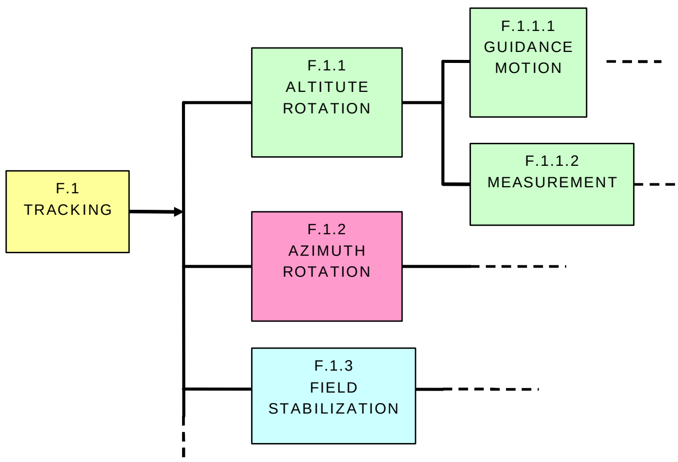

Figure 5-3: Schematic example of functional breakdown.

It is an iterative process which encompasses:

- Defining functional needs and functions requirements;
- Defining Functions, breaking down into sub-functions including their associated requirements;
- Defining detailed operational scenarios;
- Defining functional interfaces;
- Allocating requirements to functions;
- Defining acceptance criteria;
- Establishing and maintaining the functional baseline.

5.3.2.1.1.4 Logical Architecture Definition

The objectives of the Definition of the Logical Architecture are:

- To capture the pre-existing System Architecture knowledge base;
- To provide guidelines and support trade-off studies;
- To optimize Cross-Products System Re-use and Standardization;
- To share a unique system architecture across the project.

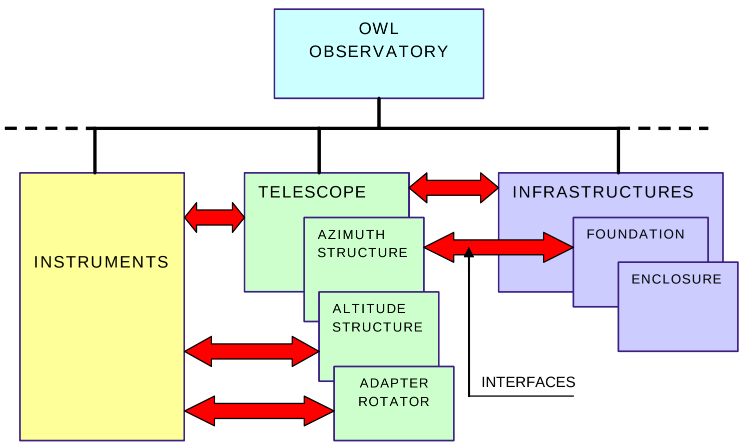

Figure 5-4. OWL architecture example.

It is an iterative process which encompasses:

- Defining the system architecture;
- Allocating functions to system architecture;
- Allocating requirements to system architecture;
- Defining/refining system interfaces (internal and external);
- Defining alternative product and processes solutions;
- Establishing a product architecture baseline

5.3.2.1.2 Physical Design & Manufacturing

Physical Design and Manufacturing is the connecting link between the system design and integration. Activities performed during Phase A of the physical design, manufacturing of prototypes, and experiments belong to the System Design, while other activities such as issuing of low level specifications, detailed development and drawings, belong to the system integration.

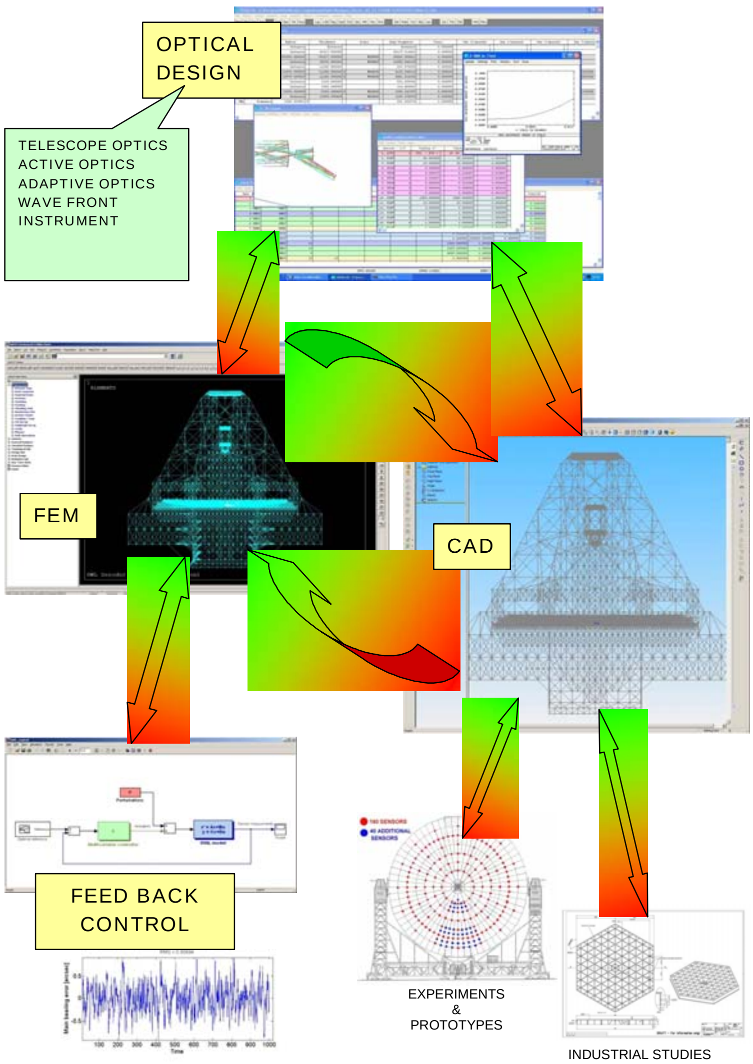

Figure 5-5: Phase A “open loop” design iterations

5.3.2.1.2.1 Physical Design

Phase A - The Physical Design performed during Phase A can be considered an *Open Loop* Design, which involves 3 major disciplines (Figure 5-5).

During this phase the Physical Design provides feed-back to:

- The system architecture;
- The functional architecture;
- The Level 1 Requirements;
- The Error Budget tree and definitions;
- The cost and schedule evaluations;

It also provides a realistic set of disturbances (see section 5.4) and hardware to be implemented into the integrated modelling (see section 5.3.3).

Phase B - The Physical Design to be performed during Phase B shall elaborate, to a higher level of details, on the work performed during Phase A. Optimal use of pre-existing knowledge base is essential. Extensive external studies and prototype activities will be integrated into the Physical Design. In-House detailed development of the Physical Design should be restricted to the fields or disciplines where ESO has mature expertise or where doing so has clear schedule or costs advantages. Interoperability of the results provided by external activities with the ESO tools (see section 5.3.3) used in the Integrated Modelling shall be taken into account.

5.3.2.1.2.2 Manufacturing

Manufacturing of parts and sub-systems shall follow established procedures, and in particular be covered by appropriate documentation (as a minimum, Statement of Work and Technical Specification).

Two types of manufacturing activities are distinguished:

- Manufacturing of prototypes, demonstrators, experiments etc. At the time of writing of this document, this type of activity has already started e.g. within the framework of the ELT Design Study (see 2.12);
- Manufacturing of parts and sub-systems. This type of manufacturing will normally start with Phase C; except where necessary for schedule reasons and where the state of the design allows for advanced manufacturing of such time-critical parts and sub-systems.

  Depending on factors such as technological risk, schedule, cost, and internal knowledge, this type of manufacturing may be based on:

  - Functional specification.
  - Conceptual designs.
  - Detailed design.

Interoperability of data packages, supplied by external contractors, with the ESO Tools (see section 5.3.2.2) used in the Integrated Modelling shall be taken into account.

5.3.2.1.3 System Integration

The System Integration is the result of two processes: the technical integration process per se, and its management at project and system level.

Technical processes include:

- Technical risk management;
- Changes Management;
  - History of the Engineering Changes;
  - Current version;

- Engineering Changes to be implemented in the near future;
- Change requests, Waivers.

Management processes include

- Risk Management (schedule, cost);
- Human resources management;
- Workflow;
- Work Breakdown Structure.
    - Operation Breakdown Structure;
    - Maintenance Breakdown Structure;
    - Cost Breakdown Structure.

To each level of the System Integration corresponds a counterpart of the System Design. These 2 parts are linked by a verification plan which includes Verification Procedures tailored to the Part, Sub-system or System to be verified.

5.3.2.2 Tools

Interoperability of results generated at ESO or supplied by external activities, is mandatory. Efficiency during the System Design, Integration and Operation largely depends on a streamlined exchange of coherent data between disciplines and entities. Appendix 7 lists the major software tools currently used at ESO.

5.3.3 Modelling

Engineering of complex, large scale systems like OWL requires powerful and sophisticated tools within specific technical disciplines such as mechanics, optics and control engineering. In order to reliably simulate interactions, cross-coupling effects, system responses, and to evaluate global performance, integrated modelling is required. Integrated modelling is a numerical simulation technique for dynamic system analysis combining various engineering disciplines. It is considered to be an important tool to evaluate the global performance and error budgets of OWL. Crucial design decisions may be based on the results of integrated modelling simulations. However, the integrated model is not intended to replace the specialized tools and models specific to each individual discipline, e.g. finite element modelling for mechanics, ray tracing for optical design and optimization, dedicated tools for control engineering, etc. Instead, it tries to fill gaps between these specialized models. Consequently, only components and subsystems relevant to global performance should be represented within the integrated model.

It must be noted that integrated model results can be made reliable only if the complexity of the system is gradually increased and if the individual subsystems are extensively tested, and, where possible, validated independently. The subsystems models are individual toolboxes and require clear input and output definitions and clear interfaces with other subsystems.

A modular concept allows easily exchanging subsystems and increasing the level of complexity step wise. Modelling for OWL builds on the experience garnered by ESO with VLT and VLT-I end-to-end modelling.

5.3.3.1.1 Modelling Approach

The main objectives of an OWL integrated model are:

- To quantify the effect of external disturbances, including but not limited to wind load on the telescope structures and mirror segments and assess global performance (image quality).
- To demonstrate the stability and efficiency of parallel local control loops affected by sensor noise, model uncertainties, actuator dynamics and limited stroke within the global dynamic control system.

- To assess the performance of the hierarchical control loops, and especially of the optical reconstructor, which has to manage wavefront corrections and offloads across different control loops.
- To determine the optimal characteristics (bandwidth, stroke) of the individual control loops, including active hardware and metrology systems.
- To support the definition and evaluation of possible operational scenarios.

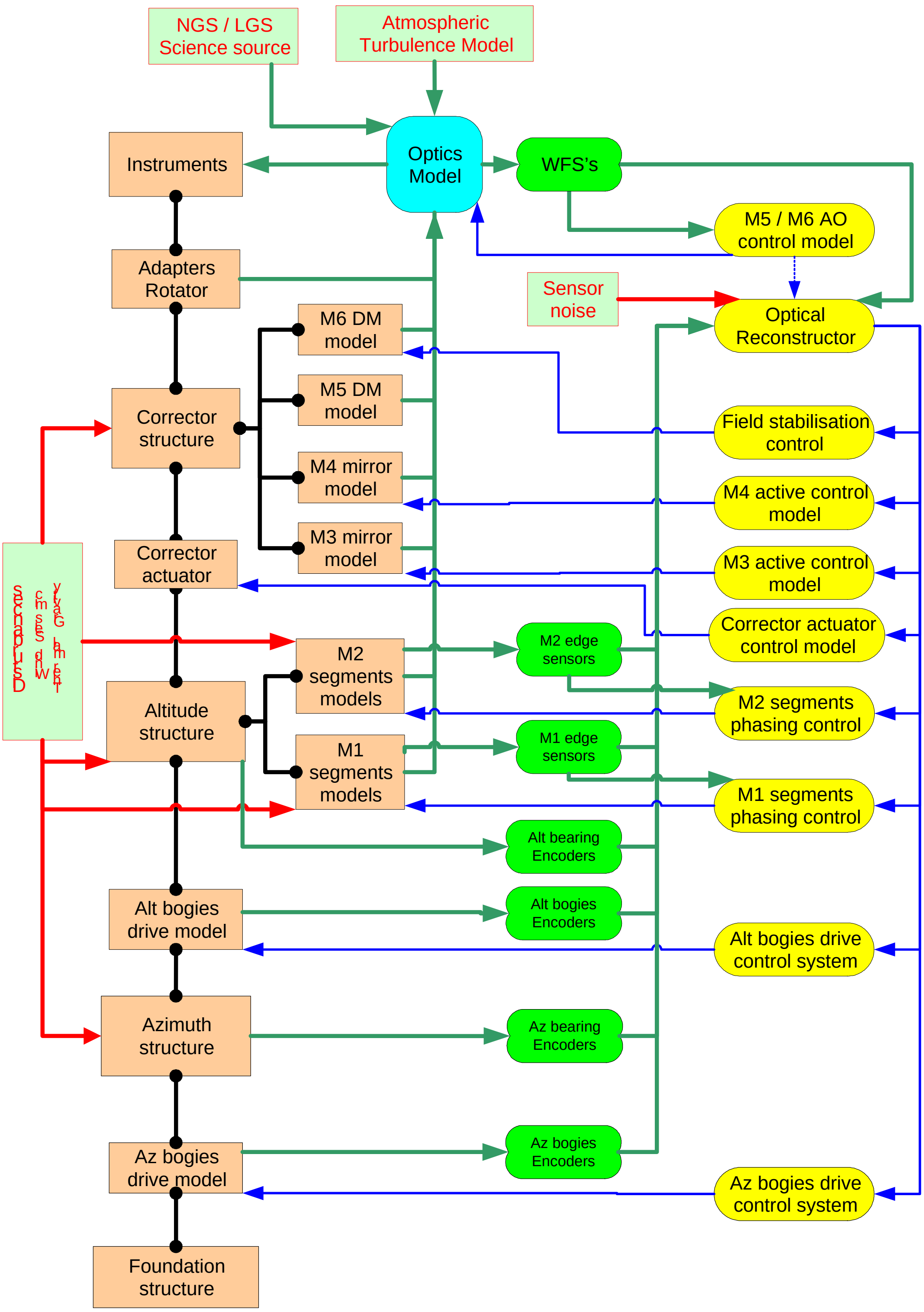

Figure 5-6: Block diagram of the OWL Integrated Model

The simulation model is realized as a state-space model, which is generated in Matlab environment. Depending on the model size and complexity, the simulation will be performed within Matlab or the model will be exported to a suitable modelling environment, which could rely on using a high-end computer or on parallelization using a PC-cluster if required.

Figure 5-6 shows a preliminary block diagram of the OWL integrated model. The diagram layout is driven by the logical architecture of the main structural components. The telescope structure including all relevant masses and elastic components will be modelled in ANSYS FEM. The complete finite element model includes sub-models for the foundation, azimuth structure, altitude structure with the segmented mirrors M1 and M2 mounted, and the corrector structure which supports the mirrors M3, M4, M5 and M6, the adapter rotators and the instruments. The complete structural model is built in a modular way in ANSYS, based on sub-models according to clearly defined interfaces and the desired configuration, e.g. pointing, locked or controlled altitude/azimuth axis, etc. Using static and modal results from the FE-model, the dynamic model of the structure for the integrated model is generated as a reduced modal state space model by using the generation and condensation modules of the SMI toolbox[39]. Input may include, in particular:

a) External forces e.g. wind loads, seismic loads;

b) Force actuators, e.g. bogie drives: a pair of forces acting on two nodes in opposite direction, which are not directly coupled by any stiffness, i.e. the structural model contains a rigid body mode in this specific degree of freedom;

c) Displacement actuators, e.g. segment actuators, M6 tip/tilt actuators: a pair of forces acting on two nodes in opposite direction, which are directly coupled by the actuator stiffness. As such forces cause local deformation, which are in general not very well represented by the first structural modes (of a global model), a static compensation will be used (reflecting the loss of flexibility due to the modal reduction) resulting in a feed-through component in the state space model.

The outputs are expressed as linear combinations of nodal degrees of freedom and their velocities (for friction modelling), e.g. sensor signals, best-fit rigid body motions of mirrors and segments, encoder signals, etc.

The linear optical models are generated in BeamWarrior[40], which can handle both global and local coordinate systems. Hence the coupling between telescope structure and the telescope optics is done in global coordinates to avoid errors caused by transformations of coordinates. The optical model incorporates all relevant optical elements (segmented mirrors M1 and M2, active mirrors M3, M4 and tip/tilt mirror M6) as well as obscurations, and propagates the light from an unresolved point source (science source, Natural Guide Stars or Laser Guide Stars) to the image plane or the pupil. The propagation takes into account the actuation, respectively perturbation, of all optical components, i.e. rigid body motion of segments and all mirrors M3 to M6, and deformation of active mirrors (M3 and M4).

In addition to this, the integrated model includes the possibility to model the effect of active optics, using simplified models for the wavefront sensors and the active mirrors. At the time being, the simulation ends at the focal plane, but possibilities are foreseen to allow adding an instrument model at a later stage.

The adaptive optics is not introduced into the initial Integrated Model, but simplified models and assumption are used to simulate e.g. off-loading of the adaptive mirrors. However, the time history of the wavefront errors can be given to a detailed AO simulation, which currently does not give any direct feedback into the Integrated Model. The bandwidth difference between the Adaptive Optics (AO) and the other telescope control loops, and their impact of AO onto simulation time are the main reason for splitting both simulations. The matter will be reviewed in the design phase, and if necessary, a full coupling implemented.

---

[39] The Structural Modeling Interface (SMI) toolbox developed by ESO and the Technical University of Munich is a Matlab based software which can efficiently reduce large FE models and create state space models used in Matlab.

[40] BeamWarrior is an optical software program which has been developed by ESO and Astrium GmbH in ANSI C language. It is based on geometrical- and wave-optical models and will be extended to simulate segmented mirrors.

The Integrated Model represents the major control loops which impact global performance. These are the main axis control loops, the segment phasing control loops, the field stabilisation, the active optics and the off-loading for the adaptive optics mirrors.

A major component of an integrated model is certainly the disturbance models, where the following ones are the most important for OWL:

- Wind load models describing typical wind disturbance scenarios using either standard spectra, full scale measurements, wind tunnel data, or results from Computational Fluid Dynamics analysis. Both the spatial correlation and the temporal spectrum should be representative for the modelled site (see section 5.4.1.1).
- Quasi-static loads (gravity and thermal deformations) and micro-seismic effects are expected to be less critical for the dynamic simulation of the telescope performance. However, if relevant, these loads can be added at a later stage.
- Suitable atmospheric turbulence models like Kolmogorov turbulence or phase screens, depending on the modelling of the WFS and the design of the optical reconstructor (see section 5.4.1.1)
- Friction models for friction drives.
- Sensors read-out noise, drift and background noise.
- Other errors such as actuators non-linearity, hysteresis, modelling errors.

In order to assemble the components and eventually the complete model, scripts are provided using the relevant configuration information stored in a configuration data file. Scripts and functions for post-processing are provided to generate:

- Optical characteristics such as Point Spread Functions, wavefront visualizations at different locations in the optical train, wavefront fit coefficients, etc.
- Error budget contributions;
- Power Spectral Density of various outputs.

Components, tools and scripts developed within the framework of the ELT Design Study (see A-1.10 and RD525) and which can be easily adapted to the OWL Integrated Model will be incorporated accordingly.

5.3.3.1.2 Architecture Concept

This section addresses the concept of OWL Integrated Model architecture. For all major disciplines the subsystems modules and their interfaces are described in more detail.

The structural subsystem includes the modules listed in Table 5-4. The optics model provides the relation between the inputs and outputs as described in Table 5-5. The control loops represented in the OWL integrated model are listed in Table 5-6.

The full Integrated Model is not built at once, but gradually assembled from otherwise verified and validated components. Intermediate models and simulations (Table 5-7) are used to generate an eventual reliable integrated model (see also Figure 5-6). At the time of writing this document steps no. 1 a) to 3 a) of Table 5-7 are completed.

To ensure credibility and fidelity of the Integrated Model, validation of the global model and of its individual components, subsystems, scripts and tools is mandatory. Typical validation methods are briefly indicated in the Table 5-8.

Mechanical substructure	Input load	Structural Interface	Local control system	Position monitoring	Output
Foundation	Seismic load	Az bogies Az bearing	Az Bogies control	Encoder	
Azimuth structure	Wind load Bogie driving forces	Az bogies Alt bogies Alt bearings Az bearing	Az Bogies control Alt Bogies control	Linear encoders Linear encoders Encoders Encoder	Bogie normal forces, positions and velocities Central bearing rotation
Altitude structure	Wind load	Alt bogies	Alt Bogies control	Linear encoders	Main bearing rotation
	Bogie driving forces	Corrector support	Corrector actuator control	Encoders	Bogie normal forces, positions and velocities
	M1 actuators	M1 segments	M1 phasing control	M1 edge sensors	M1 edge sensors
	M2 actuators	M2 segments	M2 phasing control	M2 edge sensors	M2 edge sensors
Corrector	Corrector actuator	Corrector support	Corrector actuator control	Encoders	Corrector position
	M3 actuators	M3 support	M3 active control		M3 position
	M4 actuators	M4 support	M4 active control		M4 position
		M5 support			
	M6 tip/tilt actuators	M6 support	M6 tip/tilt control		M6 position
		Instruments			
Instruments		Corrector			Image plane position

Table 5-4. Structural subsystem.

Subsystem	Input	Interface	Output
M1 & M2 segments	Position	M1 and M2 structure	
M3 and M4	Position and surface deformation	M3 and M4 structure	
M5 and M6	Position	M5 and M6 structure	
	Surface deformation	M5 and M6 AO control model	
Instrument entrance	Position	Instrument structure	WFE

Table 5-5. Optic model, inputs and outputs.

Control group	Control loop	Control system / dynamics involved	Sensor	Actuator	Controller
Main axes control	Azimuth axis	Telescope structure	Azimuth encoder	Azimuth bogies	Feedback controller + feed forward friction compensation
	Altitude axis		Altitude encoder	Altitude bogies	
Segment phasing	M1 phasing	M1 segments / Telescope structure	Edge sensors + WFS	Segment actuators	Local feedback + optical reconstructor command
	M2 phasing	M2 segments / Telescope structure			
Field stabilization		M6 unit / Telescope structure or decoupled	WFS	M6 tip/tilt actuators	Feedback + optical reconstructor command
Active optics	M3/M4 active optics	M3/M4 active support model	WFS	M3/M4 active supports	Optical reconstructor command
Optical reconstructor		All control loops above	WFS + edge sensors + AO command	-	

Table 5-6. Control loops.

Step	Major simulation	Substep
1	Main axes control (tracking) for frontal wind load lateral wind load with pointing to zenith, 30, 45, 60 deg, respectively.	a) Altitude axis control b) Azimuth axis control c) Altitude + azimuth axis control
2	Field stabilization with M6	a) Fixed backside structure b) OWL structure
3	Segment phasing with wind load on segments	a) Single segment control (including noise) b) Small area of segments on a simplified backside structure using segment position information c) Small area of segments on a simplified backside structure using (fast) edge sensors (including sensor noise models and drift) and (slow) segment position information (WFS)\ d) M2 segment control on the OWL structure e) M1 segment control on the OWL structure
4	Main axes control and segment phasing	a) Only step 1 + step 3 b) Simplified Optical reconstructor c) WFS-based reconstructor
5	Full model	a) Without AO off-loading b) With AO off-loading c) Increase gradually the level of detail for different components

Table 5-7. Integrated Model - Intermediate steps.

Component	Validation method
Mechanical structure	FE Analyses, hand-calculations, tests
Foundation stiffness	Soil measurements, FE analyses
Bogies friction	Tests
Wind loading	Wind tunnel, full scale measurements, CFD analysis
Seismic loading	Measurements on Paranal
Edge sensors noise	Tests of capacitive sensors
Segments control	APE
Idem + active optics + field stabilization	APE
BeamWarrior	Analyses, comparison with Zemax
ANSYS	Standard FE program
SMI toolbox	FE Analyses

Table 5-8. Integrated Model validation methods.

5.3.3.2 DOORS Model, System requirements management

A software tool will be used to manage the requirements and links between them. The current tool is the *Dynamic Object Oriented Requirements System* (DOORS)

OWL observatory requirements are provisionally broken down into 3 hierarchical levels:

1. Top Level Requirements generated by the Science Cases..
2. System Requirements (Level 1 requirements. Level 2 requirements. etc.)
3. Design Specifications. (Low level specifications, Drawings, Etc.)

Each level shall conform to Regulations, Standards, Acceptance tests.

The high complexity of the project requires a consistent system requirement management, which shall take the following issues into account:

- Limits of individuals to assimilate the whole system down to all its parts.
- Evolution of scientific requirements, technologies, and site characteristics, increasing the number of system or sub-systems options.
- Duration of the project which may reach 20 years. Turn over of personnel is inevitable
- Development of the budget.
- Development of the schedule.

System requirement management is necessary to effectively manage and control the evolving design and integration of OWL observatory. The benefit of the system requirement management are:

- Traceability from scientific requirements to implementation.
- Impact assessment of proposed changes.
- Controlled access to current project information.
- Migration of information between personnel.
- Change control.
- Human resources management.

5.4 Disturbances Characterization

This section provides a overview of OWL System Engineering aspects related to the disturbances which will influence the performance and the integrity of OWL during its complete lifetime. The environment, the system and the human induced disturbances effect the telescope performances, while the survival load cases effect its integrity.

5.4.1 Environment

The disturbances discussed in this section effects the operation of the Telescope and are generated by the natural environment in which the telescope is integrated. The main environmental disturbances are: Wind, Atmosperic Turbulence, Temperature and Microseismicity.

5.4.1.1 Wind

OWL will be affected by wind disturbances in several ways:

- Pointing and tracking by the large scale wind torques on the whole structure.
- Deformations of the structure generating misalignments of the optical components by large scale wind pressures. Here the optical components are regarded as undeformable rigid bodies.
- Deformations of the large segmented mirrors by large scale pressure variations over the area of the whole mirror causing deformations of the supporting cell structure.
- Differential rigid body movements of neighbouring segments caused by pressure variations with scales of the order of a segment.
- Deformations of individual segments due to small scale pressure variations.

For a design of the actuators and the control algorithms which correct the effects of theses disturbances one needs information about the static and dynamic characteristics of the wind loads. For telescopes the relevant range of the turbulence characteristics and scales is extremely wide, including very large scales in undisturbed wind flow (open air) and relatively small scales generated by the interaction of the wind with the structural parts of the telescope or of structures which are in front of the telescope.

The basis for such information will be well established models applicable to the geometry of a telescope in an open air environment (sections 5.4.1.1.1.1 and 5.4.1.1.1.2). In addition, there are three other sources of information. First, computer simulations which can give information about time averaged pressure fields as well as dynamic properties, but are not capable to reach the interesting regime of small scale and high frequency fluctuations (section 6.4.1.1.2), second, wind tunnel tests which have to cope with the large reduction factors of up to 100 imposed by the proposed size of 100 m for the telescope and a size of a model of the order of 1 m in the wind tunnel (section 5.4.1.1.4), and third, full scale measurement at existing large radio telescopes like the 76 meter telescope at Jodrell Bank (section 5.4.1.1.3).

5.4.1.1.1 Wind characterization from literature

5.4.1.1.1.1 Wind Velocity, integral length and turbulence intensity Profiles

In an undisturbed boundary layer the characteristics of velocity and pressure variations can be described by standard models like the von Karman spectrum and the Taylor hypothesis. At any given height *z* above the ground only three parameters are required in the context of these models: first, the time–averaged or mean wind speed $\overline{U}(z)$, second, the turbulence intensity *I*, and third, an integral lenghts *L* describing roughly the size of the largest eddies. For telescopes like OWL which reach heights of about 100m above the ground level values for these parameters have to given for different heights.

The mean wind velocity can be modelled by a power law. This is shown together with an alternative logarithmic model in Figure 5-7 a surface roughness similar to that at Paranal, a height of the boundary layer of of 270 m, and a velocity of 10 m/s at a height of 10 m.

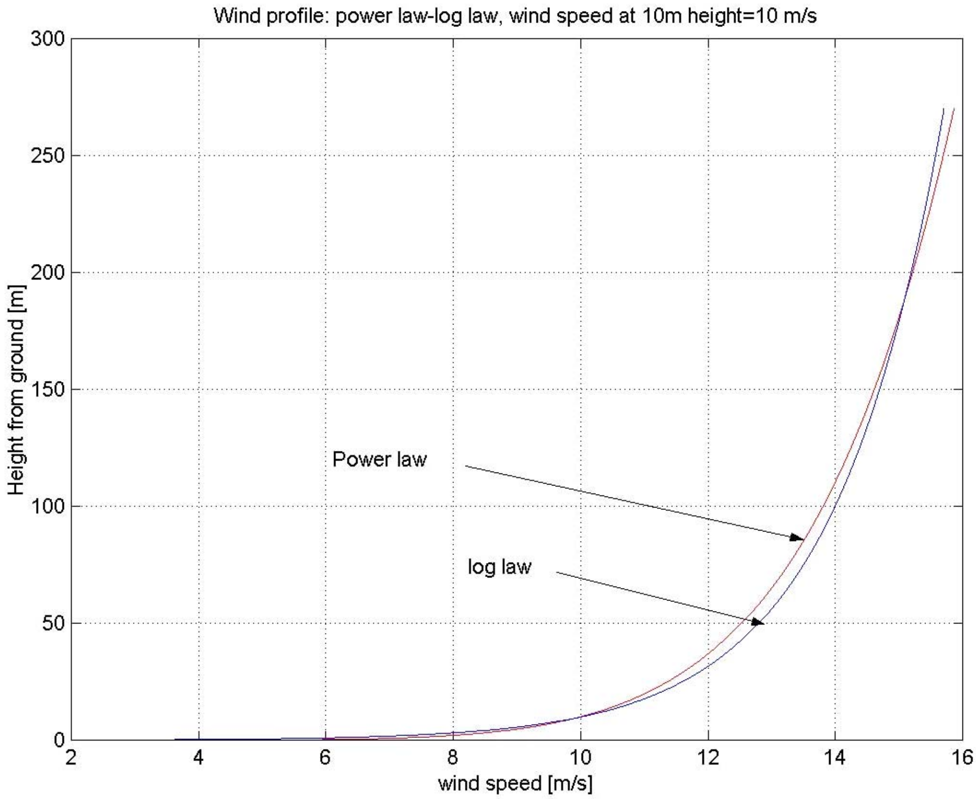

Figure 5-7: Relationship between the height above the ground and the mean velocity

The values for the three parameters $\overline{U}(z)$, *I* and *L* used in this study for heights from 16 to 130 meters are approximately 11m/s to 14 m/s for the mean wind speed, 0.16 to 0.12 for the turbulence intensity, and 80 m to 100 m for the integral length.

5.4.1.1.1.2 Power Spectral Density

Wind action is a stochastic phenomenon which is conveniently described by the Power Spectral Densities (PSD) of the wind speed and the aerodynamic pressure on the surfaces and by correlation functions for these parameters.The pressure field will strongly depend on the orientation of the telescope with respect to the wind direction, the zenith distance of the pointing, and the location on the mirror. One may have the following wind load cases :

- When the telescope is pointing into the wind the characteristics of the incoming wind are not significantly modified on the telescope surface.The power spectra and correlations of the pressure fields should therefore be similar to the ones in the boundary layer.
- When the telescope is pointing away from the wind or towards the zenith there will be recirculation zones at the edges of the mirror with different power spectra and correlation functions.
- Parts of the mirror will be obstructed by the structure supporting the secondary mirror. In some telescopes this structure is a truss sructure and the turbulence behind it may have the characteristics of grid turbulence with an integral length *L* of the order of the grid size.

At the VLT ESO had good experience with using the von Karman spectrum representing the wind-energy content over a large frequency range. The spectrum depends only on the previously introduced parameters $\overline{U}$ *L* and *I*:

$$S_U(f) = (I\overline{U})^2(4L/\overline{U})(1+70.78(fL/\overline{U})^2)^{-5/6}$$

Two parameters derived from this expression are the zero frequency energy f_0 and the corner frequency f_c. The latter marks the beginning of the the inertial range in which the energy content decreases with a power of –5/3 of the frequency:

$$f_0 = 4LI^2U$$

$$f_c = \overline{U}/(L \cdot 70.78^{1/2}).$$

Adapting the values for the parameters f_0 and f_c the von Karman model can, in a first approximation, also be applied to other types of conditions like for example to the grid turbulence expected downwind from the suppert structures. To properly simulate these situations one has to retrieve information on the integral length and on the turbulence intensity of such flows. This will be done in the framework of the ELT study, WP 8300, and also in the future development of OWL.

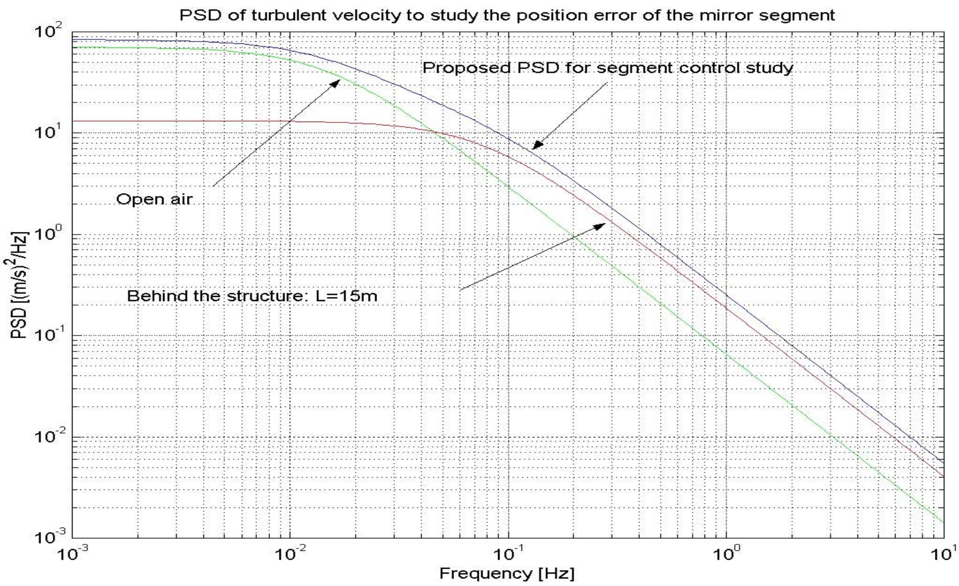

Figure 5-8: Model velocity-PSD close to the M1 segments

For the time being it has been decided to approximate the PSD on the complete structure, on the primary and the secondary mirror by making assumptions about the integral length and turbulence intensity of the flows and assuming that the different flows affecting the loads on the different parts are statistically independent from each other, and that therefore the corresponding PSDs can be added up. These assumptions are certainly not fully justified. However, we believe that they result in somewhat conservative PSDs, overestimating the effects of the wind on the telescope.

Three different PSD have been generated for the study of the control systems of the axes, the primary and the secondary mirror. For the control of the axes five PSD have been generated for five different heights, as well as an average PSD for simplified control analyses.

The PSD of the turbulent velocities at the level of M1 is shown in Figure 5-8 by the curve labeled ‘open air’. For any wind direction most of the segments of M1 and M2 will be behind the support structure for the secondary mirror and the corrector, that is they will be affected by grid turbulence. The integral length is set to L = 15 m which is roughly the size of the gaps in the grid, and the other parameters to $\overline{U}$ = 10m/s and I = 0.15. The corresponding PSD for M1 is shown in Figure 5-8 by the red curve.

The PSDs of the forces are derived from the PSDs of the velocities:

$$S_F(f) = 4(\overline{F}/\overline{U})^2 S_U(f)\chi_a(f)\ ,$$

where F is the static force calculated as $F = 0.5 \cdot c_D \overline{U}^2 A\rho$, c_D is the drag coefficient of the area *A*, and ρ the air density. For the aerodynamic attenuation function χ_a, which models the statistical averaging of the small eddies on large surfaces, the following semi-empirical formula has been used for the design of the VLT and in this study:

$$\chi_a = (1 + 2f\sqrt{A}/\overline{U})^{-1}\ .$$

Examples for averaged PSDs for a unit force with A=5, 10, and 8000 m^2 , the latter applicable for the control of the main axes, are shown in Figure 5-9

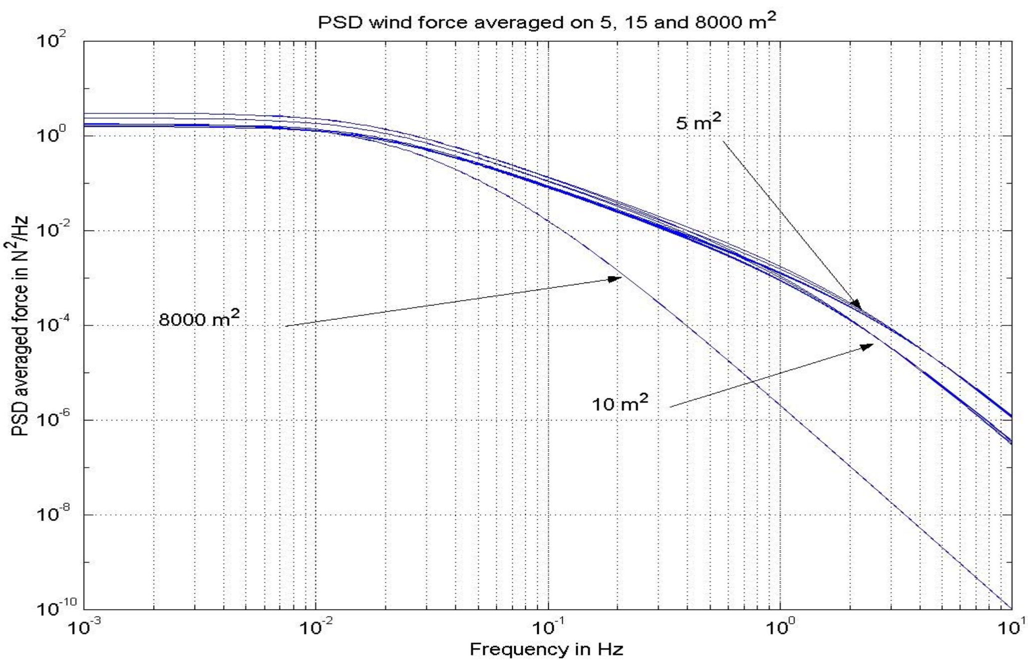

Figure 5-9: Force PSD averaged over three different areas

5.4.1.1.2 Computational Fluid Dynamics (CFD)

Computational fluid dynamics programs can be used to calculate characteristics of flows in arbitrary geometries. One type, the so-called direct numerical simulations (DNS), is capable of delivering both average flow properties as well as dynamic properties as time series and power spectral densities. However, the information is only reliable up to a certain frequency which is determined by the size of the volume elements and the average wind speeds.

During 2001 and 2002 ESO placed an industrial study to calculate PSDs for the actual OWL geometry using the PowerFLOW® code. The largest volume elements had edge sizes 4 m and the smallest ones of 0.4 m. With a wind speed of 10 m/s this limits the frequencies up to which reliable information can be extractred to about 5 Hz. Figure 5-10 shows an instantaneous pressure field on the primary mirror and the lower parts of the structure for the wind coming from the left. Apparently, the average wind speed is strongly reduced behind the M2 support structure.

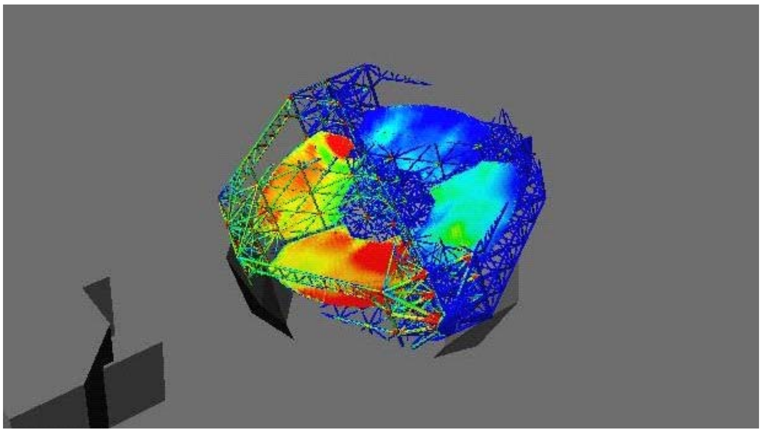

Figure 5-10: Instantaneous pressure field on M1

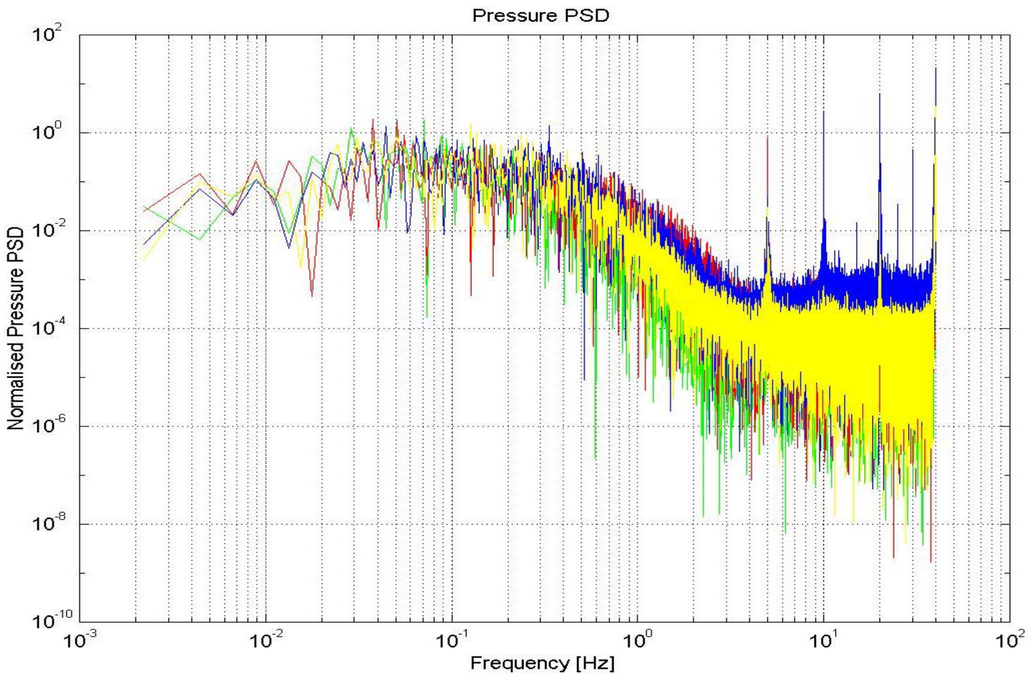

Figure 5-11: Comparison of PSDs obtained by CFD with model PSDs

Figure 5-11 shows the pressure PSD on one location on M1. The maximum frequencies for which the PSD is above the noise level is, as expected of the order of 4 Hz. The corner frequency is a approximately 0.3Hz which is much higher than expected in a free boundary layer. The reason fro this is that the turbulence in the computer simulation is primarily generated by the building in front of the telescope and by structures around M1.

CFD calculations can not give information over the whole range of frequencies which are of interest for the telescope design. However, for large scales it seems to be possible to calculate the corner frequency, if one assumes that for higher frequencies the PSD follows the -7/3 law for the pressures. Small scale PSDs have to calculated with smaller, more detailed models. In the ELT study, Work Package 8300, CFD codes will be used simulate the complete system including the site, the enclosure and the telescope, and to compare the results with measurements in a wind tunnel.

5.4.1.1.3 Full scale measurements

Pressure fluctuations are measured on the surface of the 76 m radio telescope at Jodrell Bank. The expected load cases, depending on the orientation of the telescope with respect to the wind, have been listed in section 5.4.1.1.1.2.

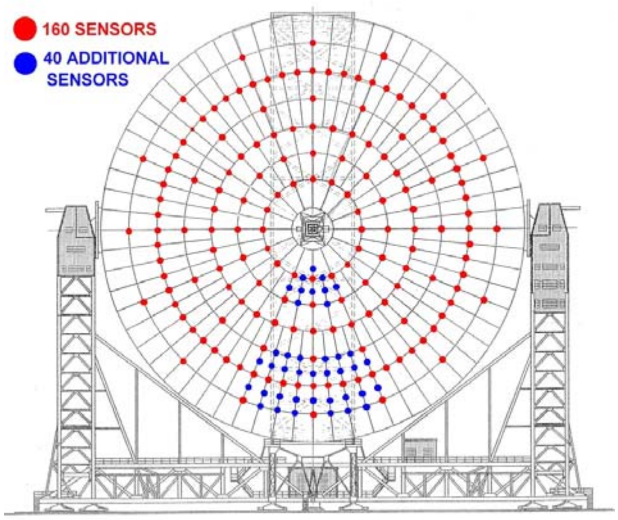

Figure 5-12: JBO Lovell Radio Telescope with pressure sensors

To measure the overall pressure distribution 160 pressure sensors are distributed over the mirror as shown in Figure 5-12.They are located in the gaps between the panels of the reflector. In addition, 40 sensors will be distributed over the smaller areas, to measure pressure variations over a smaller scale. The 76 m radio telescope at Jodrell Bank is an ideal candidate for such measurements.

- It is located on a plain which guarantees that for most of the time the incoming wind in the turbulent boundary layer has reasonably well known characteristics. To measure the wind speed and its orientation and to check the power spectrum an ultrasonic anemometer will be installed on a mast at a height of 20 m. above the ground at a location where the wind flow is not affected by the telescope or other buildings.
- The front surface is not, at least when the telescope is pointing into the wind, obstructed by parts of the telescope structure or other infrastructure in front of it.

ESO is very grateful to the staff at Jodrell Bank for the permission to perform these measurements at their telescope and for generous assistance during the setup of the measuring devices. The sensors have been designed and installed by the firm PSP Technologien im Bauwesen in Aachen.

At a height of approximately 50 m above the ground and a wind speed of 10 m/s the corner frequency of von Karman power spectrum is expected to be at approximately 0.02 Hz. Figure 5-13 shows the power spectrum of the pressure fluctuations measured on the reflector at a distance of 20 m from its center and an angle of 35 degrees counting counterclockwise from the top. The elevation was 58 degrees, the azimuth angle 1 degree, the wind speed 10 m/sec, the wind direction 330 degrees, the sampling 8 kHz, and the total measuring time 73 minutes. The limitation to frequencies of approximately 30 Hz is due to the dynamic range of the measuring chain. The corner frequency is close to the expected corner frequency and the slope in the inertial regime is very close to the expected slope of -7/3, shown in the figure by the red line. The measurements therefore show that at least for the measured configuration the assumptions underlying the von Karman spectrum are satisfied.

Measurements for other configurations and wind conditions will be done in the near future. PSDs at all locations, correlation functions between the pressures at all locations, and correlation functions based on filtered time series, where the high-bandpass filter describes the capability to correct aberrations up to given frequencies, will be calculated.

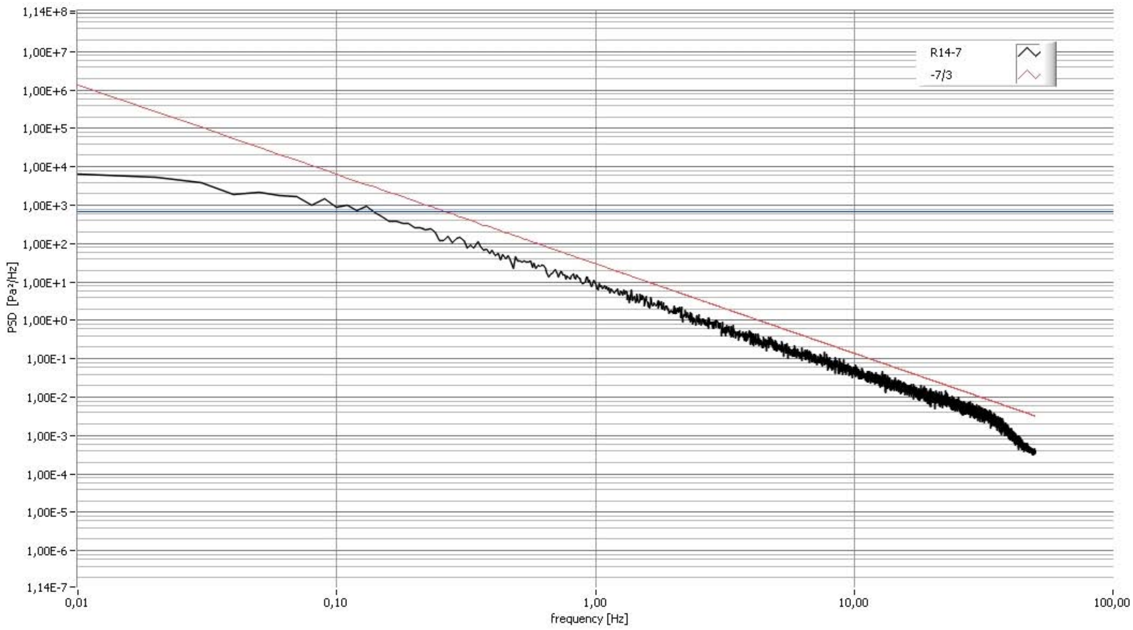

Figure 5-13 : Pressure power spectrum on the reflector of the Jodrell Bank Telescope

5.4.1.1.4 Wind tunnel measurements

The wind speed used in the wind tunnel measurements will approximately be the same as the ones in the full scale measurements. The integral length will be of the order of 1 m and therefore about 100 times smaller than in the full scale measurements. Therefore also the Reynolds number will be 100 times smaller. To keep at least the other important dimensionless parameter, the Strouhal number, at the same value as the one characterising the full scale measurements, the highest detectable frequencies should be 100 times higher than the highest detectable frequencies in the full scale measurements, that is they should be of the order of 1000 Hz. Wind tunnel measurements have been done by two institutes under ESO contract to check up to which frequencies wall pressures can be measured by standard pressure sensors. At both institutes a circular plate with a diameter of 500 mm was placed in a boundary layer wind tunnel with widths of approximately 2.5 m and heights of approximately 2 meters. The plates were inclined by 18 degrees with respect to the horizontal position towards the wind and the center was at 500 mm above the ground. The most important measured parameter was the power spectral density. For frequencies up to 100 Hz the results of the two measurements were in good agreement decreasing in the inertial regime above 10 Hz with a slope of -7/3 as expected from Kolmogorov theory. But, in the equally important interval between 100 Hz and 1000 Hz, the power spectral density was flat or even had a local maximum in one of the measurements whereas it continued to decline with the -7/3 slope in the other measurement. In both measurements the signals were above the noise level over the whole frequency interval. An additional problem was caused by acoustic waves which are created by the wind generator in the tunnel. Fortunately they seem to have well defined peaks and can therefore be eliminated numerically during the processing of the data. Figure 5-14 shows the PSD of pressure fluctuations measured in the wind tunnel at the center of the plate. The curve is an average of 732 measurements of 300 s duration, with a sampling rate of 10 kHz, and a wind speed 20 m/s. The red line shows the -7/3 slope expected from Kolmogorov turbulence in the inertial regime.

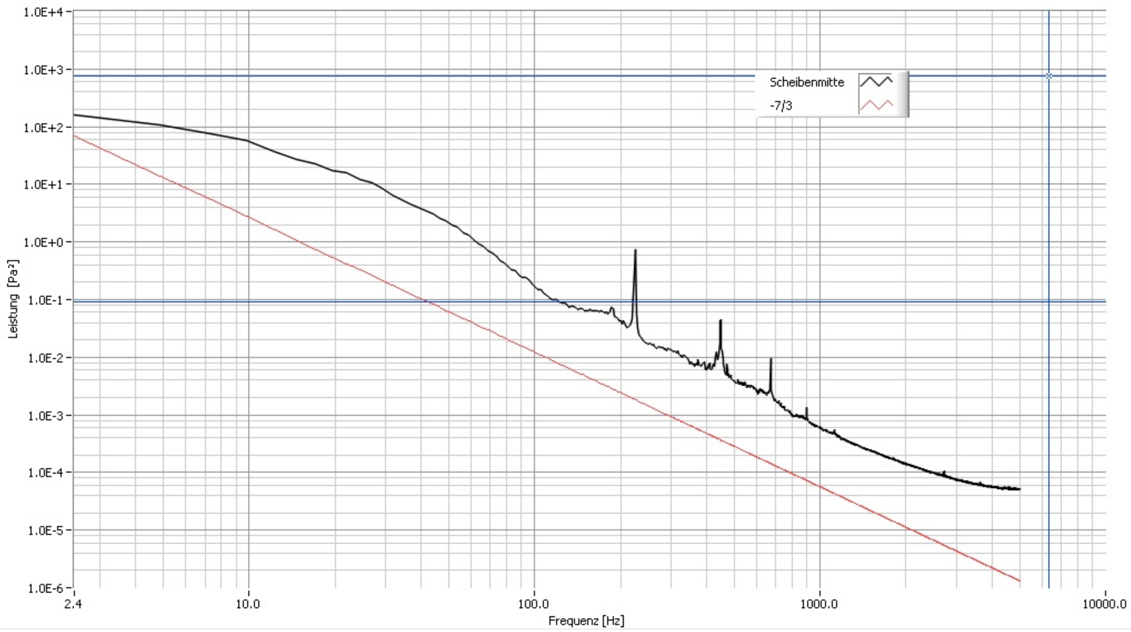

Figure 5-14: Pressure PSD measured in a wind tunnel

The conclusions are that pressure fluctuations can reliably be measured in wind tunnel experiments up to frequencies of approximately 1500 Hz. However, the discrepancies between the two measurements in the frequency interval between 100 Hz and 1000 Hz have to be explained before continuing with wind tunnel measurements using a 1:70 model of the Jodrell Bank Radio Telescope.

5.4.1.2 Atmospheric turbulence (AO)

While wind load is handled by several active systems as detailed in section 5.4.1.1, correcting the effects of atmospheric turbulence is the task of adaptive optics. The overlap area between the two techniques can be described in terms of spatial and temporal frequency range as shown on Figure 5-15. In the case of the atmospheric turbulence, the perturbations on the incoming wavefront are described in terms of amplitude and phase fluctuations.

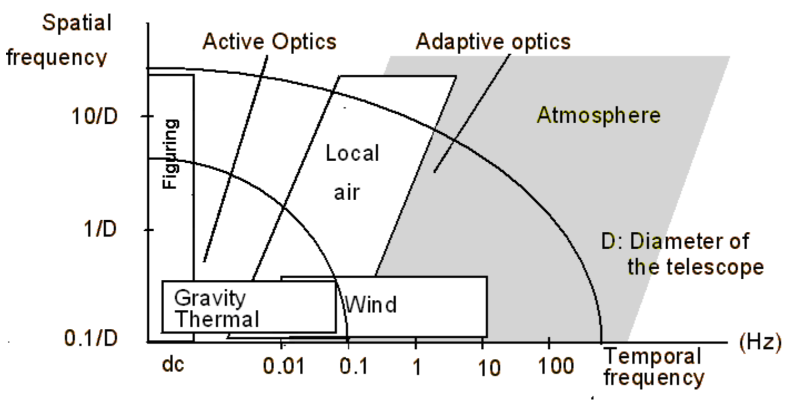

Figure 5-15. Respective areas of action of active and adaptive optical systems as a function of the spatial and temporal frequency of the perturbations

The amplitude fluctuations are the result of flux inhomogeneities in the pupil plane due to interference patterns of waves refracted within the various turbulence layers. This so-called ‘flying shadow’ pupil plane pattern translates into to the scintillation of the stellar flux in the focal plane. The scintillation cannot be corrected by adaptive optics techniques and is even considered as a noise source in the wave front sensing process. The scintillation increases with smaller apertures and is highly chromatic. It is generally characterized by an index defined as the long term normalized variance of the flux of a stellar source integrated over the pupil.

Within the inertial range, the wave front phase fluctuations are of Kolmogorov type (i.e.: the power density spectrum of the index of refraction fluctuations decays as the 11/3rd power of the spatial frequency) for any developed isotropic turbulence as encountered in the free atmosphere. Thanks to this, it is sufficient to know the distribution along the path of the index of refraction structure coefficient of the atmosphere Cn^2 ($m^{-1/3}$) to fully characterize the wave front phase perturbations at any wavelength. The inertial range is limited on the one end by the outer scale of the turbulence L_0 (m, typically 10^1 to 10^2, no site dependency proven) and, on the other end, by the inner scale l_0 (m, typically 10^{-3}, site independent) where the energy is turned into heat dissipation because of viscosity forces. For telescopes of diameter (or interferometers of baseline) larger than the outer scale L_0, the effects of the turbulence are less severe than predicted by the Kolmogorov distribution because of a saturation of the power spectrum as shown in the example of Figure 5-16. The characterization of the wavefront for scales comparable to OWL diameter is one of the tasks assigned to the ELT Design Study site monitoring work package (see appendix A-1.9)..

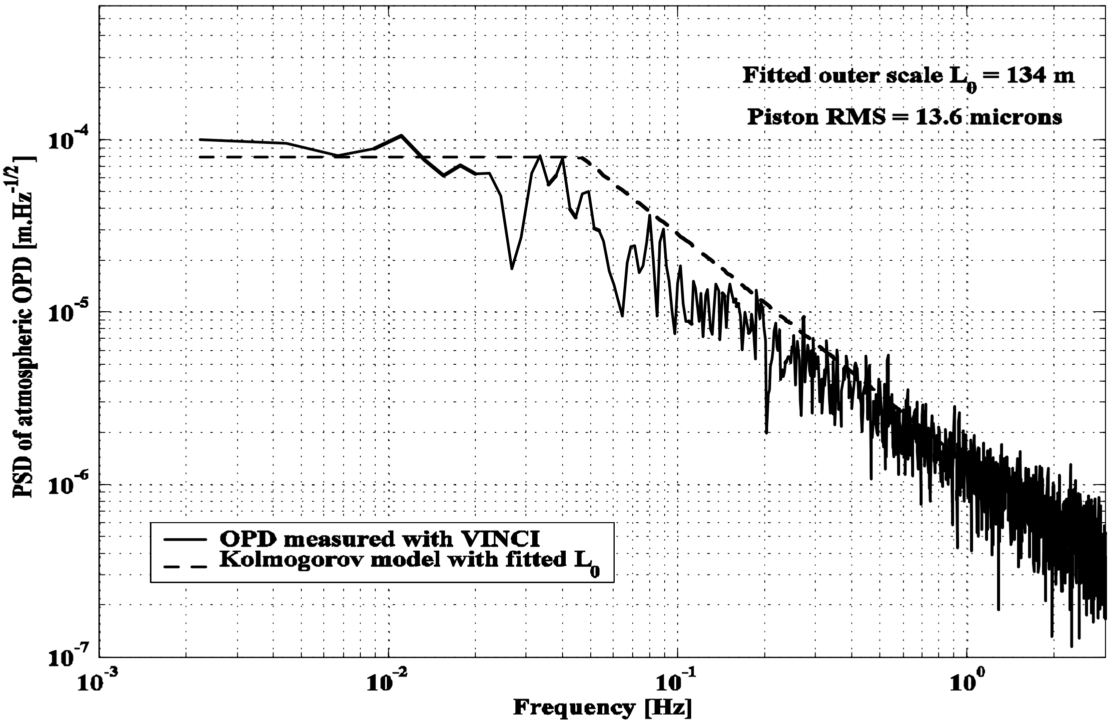

Figure 5-16: VLTI-Vinci Optical path difference power spectrum and Kolmogorov model saturation for aperture distances larger than the outer scale L_0 (credit. E. di Folco, ESO 2004)

For classical adaptive optics techniques which sense and correct the wave front at the entrance pupil of the telescope, it is enough to characterize the wave front by the atmospheric perturbations integrated over the whole light path. In the tri-dimensional space, the relevant parameters are the overall radius of coherence r_0 (m), its coherence time τ_0 (s) and its angular coherence θ_0 (arcsec). While r_0 and τ_0 constrain the design in terms of number of actuators and velocity of the control loop, θ_0 determines both the size of the corrected field and the availability of natural guide stars for wave front sensing measured as sky coverage (%). θ_0 can be generalized to the case of MCAO to explain the larger corrected field of view [123].The limitation in sky coverage can (at least on 8-10m class telescopes) be alleviated by the adjunction of artificial laser guide stars. The wavefront coherence radius r_0 can also be translated into seeing, defined as the focal image angular size (FWHM, full width at half maximum, arcsec) before AO correction. The efficiency of the AO correction is measured in terms of Strehl, which is the ratio of the achieved maximum image intensity to its theoretical value at the diffraction limit. For GLAO systems (see 8.2.2), another metric, the ensquared energy within a given pixel size is used. In the evaluation of the performance of the proposed AO systems (see section 8), two models for the atmospheric conditions are taken, corresponding to good atmospheric turbulence conditions (about 20-30% best conditions) and bad turbulence conditions (~70% worst conditions). These models have different r_0, θ_0, τ_0 to allow to see the impact on the performance of the AO.

For designing more elaborated, or partial adaptive optics systems based on techniques such as MCAO (see 8.3.1) and GLAO (see 8.2.2), it is necessary to know the vertical distribution of the atmospheric C_n^2 (h). The instruments and methods developed for this purpose are described in section 14.2.3.

For reference, waiting for the final site selection, median values of the various atmospheric parameters expected at a suitable candidate are given in Table 5-9

Atmospheric Turbulence Parameters	Range of median
Seeing (arcsec at zenith and 5000A)	0.6-0.8
r_0 (m at zenith and 5000A)	0.13-0.17
tau_0 (s at zenith and 5000A)	0.003-0.010
$theta_0$ (arcsec at zenith and 5000A)	2-4

Table 5-9: Typical expected median values of the atmospheric turbulence parameters based on the experience at existing observatories.

The effect of L_0 on the AO is to reduce the required stroke for the deformable mirror(s), since low spatial frequencies (which would carry large amplitudes) are reduced. Also, for a telescope the size of OWL, the seeing limited PSF changes significantly due to L_0, and a very small diffraction peak (containing only a very small fraction of the energy) can appear [122]. In the AO simulations, the Paranal median value of 25m for L_0 was taken [121]. The effects of L_0 on the AO performance is studied in RD26.

5.4.1.3 Temperature, humidity, rain, snow, ice, dust, radiation

As the observatory site has not been selected yet, the environmental conditions at Paranal are assumed. Apart from the temperature variation, which is defined in more detail in the next chapter, Table 5-10 summarizes the relative humidity, rain fall, snow and ice height, dust as well as the air pressure and air density conditions on Paranal.

Temperature variation - The objective of the Paranal temperature measurements described in RD34 is to provide experimental information to calibrate the thermal models (see section 9.5.3) which are used during the following project phases:

- System Design.
- System Integration.
- Commissioning.
- Operation.

In the Paranal experiment the temporal surface temperatures of a typical part of steel pipe, as used in the OWL framework structure (1m diameter, 10 mm wall thickness, 2 m long) has been measured. The steel pipe was placed on the telescope platform of the Paranal observatory, and the evolution of its temperature over several days measured at various points and under different conditions. Also environmental parameters, such as wind speed and direction, relative humidity and ambient temperature were measured simultaneously, to be able to correlate them with the pipe temperatures

The pipe was placed on a 1,6 m high steel structure, see Figure 5-17. Measurements were done in different configurations:

- Exposed to sun radiation, with inner air volume stagnating.
- Exposed to sun radiation, with inner air flow.
- Protected to sun radiation, with inner air volume stagnating

The measurement results also aimed at evaluating the time the passive system needs to reach thermal equilibrium between ambient and pipe surface temperature. Figure 5-18 shows a typical temperature evolution over several days at the ambient conditions shown in Figure 5-19. As expected the inside and outside surface temperatures are very close to each other. Moreover, soon after the sunset the steel structure temperature goes below ambient temperature.

Environmental condition	**Paranal**
Relative humidity operational range Max. relative humidity (with condensation)	5 % to 90 % 90 %
Max. rain precipitation in 1 hour Max. rain precipitation in 24 hours Rainfall in 1 year Wind speed for blowing rain	100 mm N/A 100 mm 18 m/s
Max. operational snow height (enclosure only) Max. survival snow height (enclosure only)	65 mm 65 mm
Max. operational ice height (enclosure only) Max. survival ice height (enclosure only)	50 mm 50 mm
Dust contamination	TBD
Sun radiation (enclosure only)	1120 W/m^2
Air pressure Air density	750 mb +/- 50 mb 0.96 kg/m^3

Table 5-10: Various environmental conditions on Paranal.

Figure 5-17: Steel pipe exposed to sun radiation

The steel pipe has been painted in matte-black on the outside surface. OWL will cope radiation effects (heating during the day and cooling during the night) by a proper selection of surface treatments and paints. The telescope structure will be treated with low emissivity coating/paint The design of the observatory platform will ensure low solar absorption during the day (white concrete or white traffic paint).

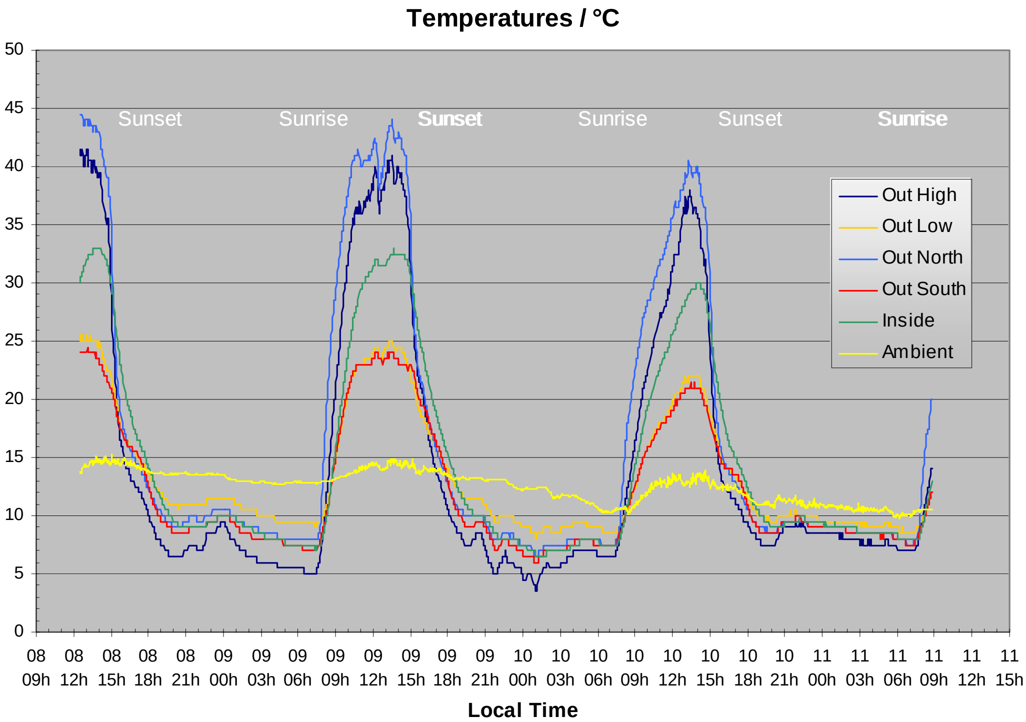

Figure 5-18: Temperature evolution

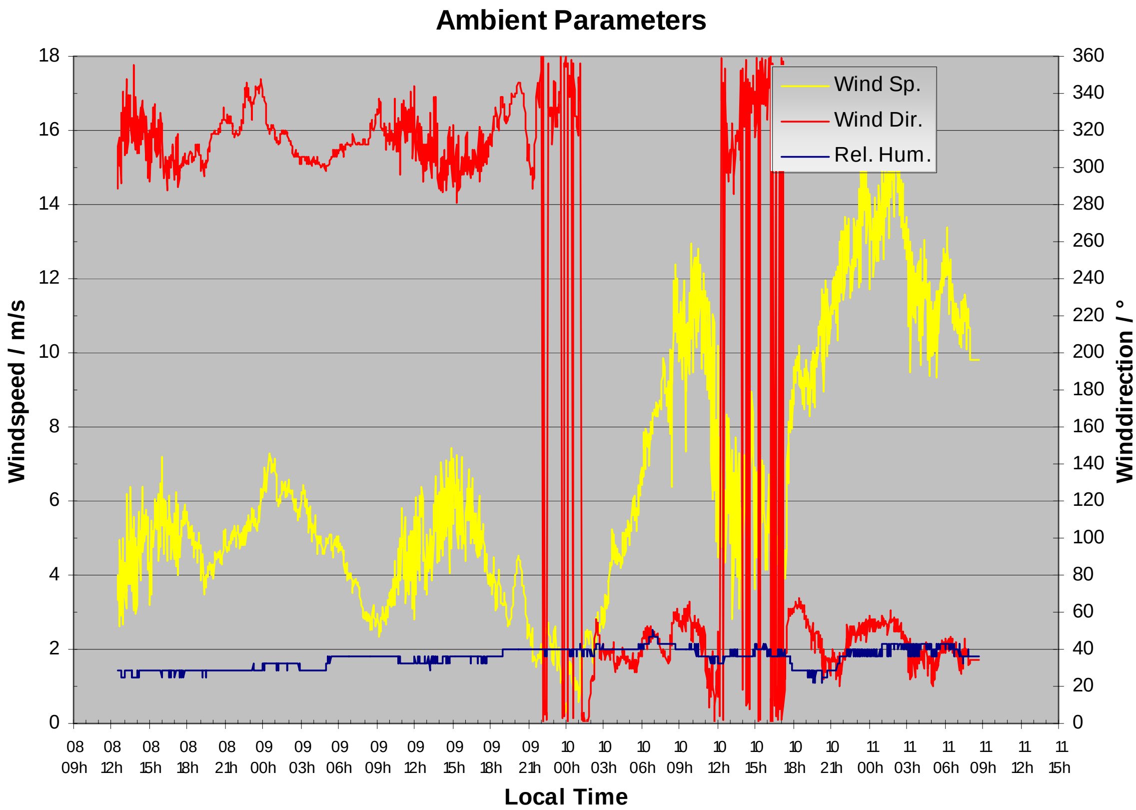

Figure 5-19: Environmental conditions.

The temperature definitions (see Table 5-11) to be applied for the thermal analyses are based on the Paranal conditions and the thermal pipe experiment.

Environmental condition	Paranal
Temperature operational	0 to +15 °C
Typical temperature gradient at night time	0.7 °C/h
Average air temperature difference between day and night	4 °C

Table 5-11: Temperature conditions on Paranal.

5.4.1.4 Microseismicity

The microseismic noise is a complex disturbance which is transmitted to the telescope via the foundation and may affect the operation of the telescope. The main sources of this phenomena can be natural, human and system induced. Detailed analyses on microseismicity will be performed progressively according to the available data, which will be acquired in the next phases.

5.4.2 System Induced Disturbances

Once the system is put into operation, it will inevitably generate self-disturbances in the various sub-systems. Typical sources of these disturbances are electro-mechanical devices installed on the telescope itself or in its vicinity. Detailed analyses will be performed progressively according to the available data, which will be acquired in the next phases.

5.4.3 Human induced disturbance

An observatory is a manned base. The activities of several individuals and the services provided for thems will introduce disturbances to the environment and to the operation of the telescope. The positive experience gained at the Paranal Observatory will be fully used for defining measures to minimize the impact on the performance of the telescope.

5.4.3.1 Camp, hotel, sewage, transport, etc

The hotel will host personnel working during day time as well as astronomers on duty at night This will cause activities going on almost around the clock.that need to be coordinated or restricted to avoidserious impacts on the observations. To minimise interactions between the support installations like the hotel, the offices, and the workshops on the one hand and the telescope on the other hand, the two areas will be located at different heights and as far apart as economically reasonable.

Starting at sunset, the transport of persons and goods will be restricted inside the observatory area and forbidden on the telescope platform. The disturbances to the environment introduced by sewage and sanitary installations will be avoided by using closed loop treatment plants as on Paranal.

To avoid vibrations spreading to the telescope area any equipment generating vibrations will be mounted on independent foundations and on damping devices to reduce spourious noise to specified levels.

5.4.3.2 Power generation

Power generation, depending on which system will be selected, is a source of acoustic, thermal and vibrational disturbances.

OWL will probably require at total power supply of 14 MW, which can be supplied by four power generators designed to produce 4.5 MW each at an altitude of 300 m. As for Paranal, the installation will be far from the telescope area in an acoustically insulated enclosure. The transformers close to the area of the technical buildings will be mounted on mechanically damped foundations.

5.4.3.3 Light pollution

At sunset all the buildings will be obscured using blinders. Any vehicle traffic will use parking lights only. For this reason the roads will be equipped with weak side lights radiating at road level only.

5.4.4 Survival load case of the opto-mechanical elements

The characterization of the survival load case depends on the environmental conditions of the observatory site. As the site has not yet been selected, two typical observing sites with different environmental and geotechnical characteristics are used as a basis for the characterization of the disturbances and the definition of the load cases:

Site 1: Ventarrones 2837 m, Northern Chile

Site 2: Observatory Roque de Los Muchachos, La Palma in the Canary Islands

This selection does not imply a pre-selection of these sites.To guarantee the safety of the system and the subsystems under survival loads detailed stress analyses have to be performed in more advanced design phases of the project. The stress analysis shall combine the individual design loads and conditions according to standard norms, whereby for specific subsystems or components different load combinations may apply.

The result of the load combinations shall be evaluated for the maximum stress criteria, e.g. yield strength for metallic material, rupture strength for brittle material (glass, glass ceramics) and CFRP strength criteria for CFRP material. More details about the criteria for mechanical acceptability can be found in RD49.

5.4.4.1 Earthquake

Apart from relatively small earthquakes which might occur several times during the lifetime of the observatory the following two types of earthquake categories characterized by their probability of occurrence have been defined:

- Operating Basis Earthquake (OBE): Earthquake of moderate size but with high probability of occurrence
- Maximum Likely Earthquake (MLE): Earthquake of large magnitude, but with lower probability of occurrence

The characteristic earthquake parameters are defined in Table 5-12. Based on these parameters the acceleration response spectra are determined according to the currently applicable European Standard (Eurocode 8, “Design of structures for earthquake resistance”, Part 1, BS EN 1998-1:2004). Different damping ratios are assumed for the telescope structure and the enclosure. Due to its larger deformations the enclosure structure can dissipate more energy than the telescope which justifies the higher damping ratio of 2 %. The damping ratio for the telescope structure under MLE and 0.34 g is assumed to be 1.5 %.

The earthquake and geotechnical characteristics of site 1 are assumed to comply with those specified on Paranal. The corresponding disturbances have the worst horizontal and vertical response spectra for the telescope structure, shown in Figure 5-20. The maximum spectral accelerations in this case are 1.14 g in vertical and 1.06 g in horizontal direction, respectively. According to the spectra the frequency bands for the peak accelerations are between 2 and 6.3 Hz for the horizontal and between 6.3 and 20 Hz for the vertical component. In order to take into account the magnification effects of the structure’s resonance frequencies, the final verification of the earthquake compliance shall be done with the Response Spectrum analysis technique as defined in Eurocode 8.

In addition it has to be taken into account that the earthquake may occur at any configuration of the telescope and the enclosure.

Subsystems like instruments, mirror units, electronic boxes, handling devices, etc. must also be verified against earthquake events occurring at the observatory. In many cases this verification can be carried out independently from the telescope structure. The appropriate requirements and method are described in RD49.

Characteristics	**OBE**		**MLE**	
	Site 1	Site 2	Site 1	Site 2
Peak ground horizontal acceleration	0.24 g	0.04 g	0.34 g	0.04 g
Probability of exceedance	50 %	50 %	10 %	10 %
Repetition period	25 years	25 years	100 years	100 years
Duration	65 s	65 s	200 s	200 s
Ground type[41]	A	A	A	A
Damping ratio[42] (Telescope structure)	1.0 %	1.0 %	1.5 %	1.0 %
Damping ratio (Enclosure structure)	2.0 %	2.0 %	2.0 %	2.0 %

Table 5-12: Earthquake characteristics for two different sites.

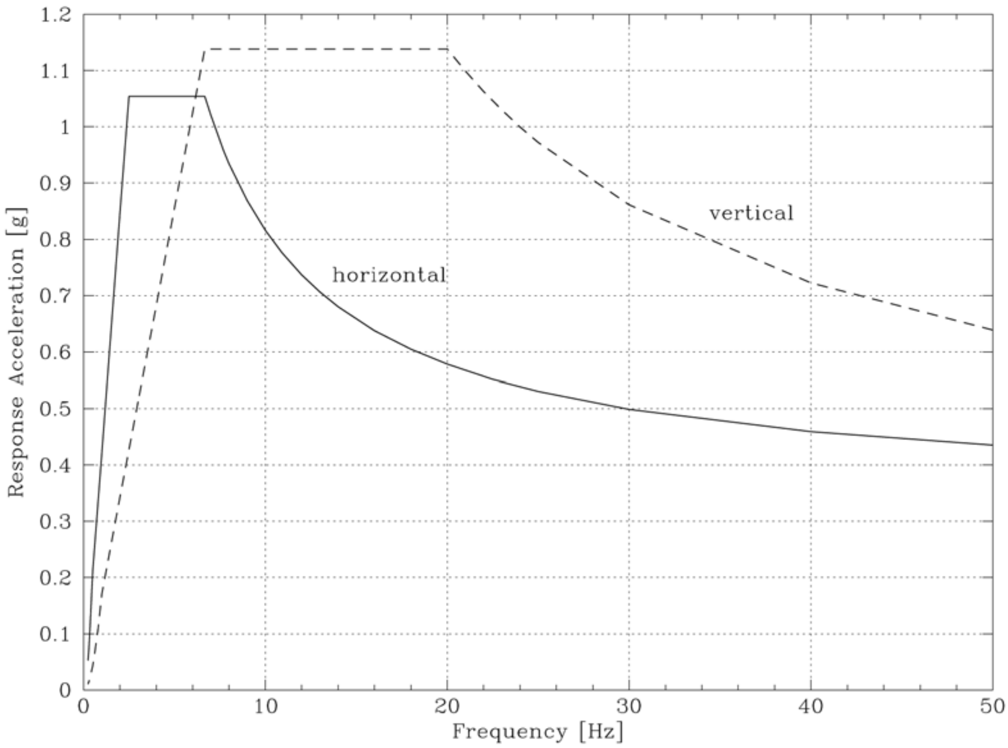

Figure 5-20: Acceleration response spectrum (Telescope, MLE, 0.34 g, 1.5 % damping).

5.4.4.2 Wind

Subsystems like the telescope and the enclosure structure shall withstand the survival maximum wind speeds. The enclosure shall protect the telescope and return to nominal performance once the wind speed has returned to its operational level. As listed in Table 5-13 different survival wind speeds are specified for the telescope and the enclosure for both sites. These survival wind speeds have been estimated from measurements performed on these

[41] Ground type A is defined as rock or other rock-like geological formation.

[42] Damping ratio is the percentage of critical damping.

sites. The values in the table are 1.5 times the highest wind speeds ever recorded since the beginning of the site testing.

Subsystem	Survival wind speed in [m/s]	
	Site 1	Site 2
Telescope	27	27
Enclosure	51	67

Table 5-13: Survival wind speed for telescope and enclosure structure.

It is assumed, that at wind speed above 27 m/s the enclosure is fully closed and protects the telescope. The force distribution caused by survival wind loads may be derived from applicable standard norms or from adequate CFD analyses. For the verification of the safety under survival loads hese forces may be applied as quasi-static loads.

5.4.4.3 Temperature

The performance of the telescope and the subsystems has to be verified under extreme temperature conditions which may occur during the installation of the telescope and of the enclosure as well as during the operation. The latter may occur as an accidental scenario, e.g. the enclosure cannot be closed during the day. Table 5-14 summarizes the survival temperature conditions for site 1 and 2 for both the telescope and the enclosure structure.

Subsystem	Air Temperature survival	
	Site 1	Site 2
Air temperature [°C]	-10 to +30	-10 to +35
Sun radiation [W/m^2]	1120	1200

Table 5-14: Survival temperature conditions for the telescope and enclosure structure.

5.5 Error budgets

OWL error budgets shall include, as a minimum, image quality, pointing, emissivity and reliability budgets. The emissivity budget is provided in section 6.3.4 and will not be recalled here. At the time of writing of this document, the pointing budget has not been addressed yet; there is however no à priori concern about meeting the requirement of 1 (goal 0.5) arc second RMS (see RD41). Establishing a sound and realistic reliability budget requires more studies then available yet, in particular in the area of adaptive mirrors. Those are either ongoing or planned for in the design phase. Preliminary analysis have however been performed with a view to understanding the system susceptibility to individual failures, e.g. phasing failures (see RD21) or failures in the segments maintenance line (RD5).

In view of the different possible modes of operation (seeing-limited, single or multi-conjugate adaptive optics, extreme adaptive optics, etc.), several distinct optical quality budgets must be drawn, including:

1. Optical quality in “blind” mode i.e. without on-sky metrology. The underlying scientific rationale is daytime, sub-mm observations. In blind mode, wavefront control loops are

closed on internal metrology (phasing, pre-alignment) or iterated on the basis of look-up tables. The optical quality budget in blind mode applies on-axis only.

2. Optical quality in seeing-limited mode. This mode assumes that all non-adaptive wavefront control loops are closed (on local metrology or on-sky, as applicable). The optical quality in seeing-limited mode not only sets the performance requirements for such science applications that do not require adaptive correction, but also the maximum allowable telescope residual errors that will have to be compensated by adaptive optics in more demanding modes. The optical quality budget in seeing-limited mode applies to the total science field of view (3 arc minutes). Active optics wavefront sensing in the entire 10 arc minutes field of view must however be taken into account when assessing image quality within the science field of view.

3. Optical quality in Single Conjugate Adaptive Optics (SCAO) mode. This mode assumes that all non-adaptive wavefront control loops are closed (on local metrology or on-sky, as applicable) first, followed by the single conjugate adaptive optics loop, with M6 as the correcting element. The M6 adaptive shell is assumed to compensate not only for atmospheric turbulence but also for

   3.1. quasi-static residual errors with a spatial frequency of up to ~0.5 m^{-1} in the entrance pupil i.e. 50 cycles per pupil diameter[43];

   3.2. fast, small amplitude (less than ~0.5 arc seconds RMS) tracking errors.

   The optical quality budget in SCAO mode applies on-axis only. Active optics wavefront sensing in the entire 10 arc minutes field of view must however be taken into account when assessing image quality on-axis.

4. Optical quality in Ground Layer Adaptive Optics (GLAO) mode. The active elements and assumptions are the same as in SCAO mode, with the following exceptions:

   4.1. overall quality requirements are relaxed as this mode aims at seeing reduction, not diffraction limited resolution;

   4.2. the GLAO mode budget applies to a 6 arc minutes field of view (diameter) and includes PSF stability.

5. Optical quality in Multi-Object Adaptive Optics (MOAO) mode. At the time of writing of this document the underlying requirements still need to be clarified. It is expected that the MOAO error budget will closely resemble the GLAO one, with tighter allocations for diffraction-limited resolution but extended correction capability for very high spatial frequency errors.

6. Optical quality in Multi-Conjugate Adaptive Optics (MCAO) mode. This mode assumes adaptive compensation with M6 and M5 adaptive shells. The MCAO mode budget applies to a 3 arc minutes field of view (diameter) and includes PSF stability. As for SCAO, quasi-static errors up to 50 cycles per pupil diameter are to be compensated by the AO units. The MCAO mode includes PSF stability requirements.

7. Optical quality in Extreme Adaptive Optics (XAO) mode. This mode assumes first-order adptive correction by M6 shell, and post-focal, very high spatial frequency AO correction. The XAO budget applies to the on-axis image quality only. Active optics wavefront sensing in the entire 10 arc minutes field of view must however be taken into account when assessing image quality within the science field of view. The XAO budget closely resembles the SCAO one, however with extended correction capability for minor quasi-DC residuals up to 250 cycles per pupil diameter[44].

The structure of the error budget is identical for all modes and given in Table 5-15. The budget is broken down according to major subsystems and functions. A subsystem allocation (e.g. M1 error budget) does not include errors associated to related control systems (e.g. phasing), which

[43] Or one actuator every ~1-m. For comparison, the VLT active primary mirrors are theoretically able to provide correction up to ~5 cycles per pupil diameter and have an optical quality of ~30 nm RMS wavefront (best 17 nm) after active correction.

[44] Or one actuator every ~20 cm in the entrance pupil.

are treated separately in the error allocation of this specific control system. In other terms, the M1 error budget assumes a perfect phasing; phasing residuals are to be found in the allocation to phasing, and include environmental factors e.g. wind. The error budget before closing said control system sets the maximum amplitude that will be passed on to it. Contingency is managed at system level.

No	Position
1.	As-designed
2.	M1
3.	M2
4.	M3
5.	M4
6.	M5
7.	M6
8.	Corrector (rigid body)
9.	Environment
10.	Tracking
11.	Non-AO wavefront control
11.1.	Pre-alignment
11.2.	Phasing
11.3.	Active focusing
11.4.	Active centring
11.5.	Active surfaces deformations
11.6.	Field stabilisation
12.	Ground layer AO
13.	Single conjugate AO
14.	Dual conjugate AO
15.	Multi-Object AO
16.	Extreme AO (XAO)

Table 5-15. Image quality budget - main positions.

A preliminary image quality budget in SCAO mode is given in Table 5-16. It is potentially the most demanding as the adaptive optics correction capability in this mode provides limited compensation –if any- for relatively high spatial frequencies such as the print-through of M1 segments support, the residual M4 polishing errors. This budget is the result of a first top-down iteration. Error budgets in the other modes are currently under elaboration.

Table 5-16. OWL Image quality budget in SCAO mode.

OWL ERROR BUDGET v. 0.1 System error budget after closing non-adaptive and single-conjugate adaptive loops					Active loops		
						X	Pre-alignment
						X	Phasing
						X	Active focusing
						X	Active centring
						X	Active surfaces deformation
CRITERION RMS wavefront amplitude	**On-axis**		**Off-axis**			X	Field stabilisation
UNITS nm							Ground layer AO (M6)
OFF-AXIS 1.5 arc minutes						X	Single conjugate AO (M6)
REQUIREMENT	**180**		**N/A**				Dual conjugate AO (M5+M6)
TOTAL BUDGET	**175**		**N/A**				Multi-Object AO (M6 + post-focal AO)
Contingency	**43**		**N/A**				Extreme AO (XAO)
As-designed	0		N/A				
M1	68		N/A				
M2	52		N/A				
M3	43		N/A				
M4	77		N/A				
M5	54		N/A				
M6	50		N/A				
Corrector (rigid body)	9		N/A				
Environment	25		N/A				
Tracking	14		N/A				
Non-AO wavefront control	42		N/A				
Pre-alignment		0		N/A			
Phasing		42		N/A			
Active focusing		0		N/A			
Active centring		0		N/A			
Active surfaces deformations		0		N/A			
Field stabilisation		0		N/A			
Ground layer AO	0		N/A				
Single conjugate AO	87		N/A				
Dual conjugate AO	0		N/A				
Multi-Object AO	0		N/A				
Extreme AO (XAO)	0		N/A				

As-designed	**0**				**0**				
M1	**68**				**0**				
Rigid body		10				0			
Overall curvature			5				0		
Segments average curvature				0				N/A	*Amplitude & frequency low enough for full AO correction*
Integration				0				N/A	*Amplitude & frequency low enough for full AO correction*
Gravity				0				N/A	*Amplitude & frequency low enough for full AO correction*
Thermal				0				N/A	*Amplitude & frequency low enough for full AO correction*
Wind				5				N/A	*Uncorrected residual only (>~ 100Hz)*
Lateral decentres			5				0		
Integration				0				N/A	*Amplitude & frequency low enough for full AO correction*
Gravity				0				N/A	*Amplitude & frequency low enough for full AO correction*
Thermal				0				N/A	*Amplitude & frequency low enough for full AO correction*
Wind				5				N/A	*Uncorrected residual only (>~ 100Hz)*
Tip-tilt			5				0		
Integration				0				N/A	*Amplitude & frequency low enough for full AO correction*
Gravity				0				N/A	*Amplitude & frequency low enough for full AO correction*
Thermal				0				N/A	*Amplitude & frequency low enough for full AO correction*
Wind				5				N/A	*Uncorrected residual only (>~ 100Hz)*
Piston			5				0		
Integration				0				N/A	*Amplitude & frequency low enough for full AO correction*
Gravity				0				N/A	*Amplitude & frequency low enough for full AO correction*
Thermal				0				N/A	*Amplitude & frequency low enough for full AO correction*
Wind				5				N/A	*Uncorrected residual only (>~ 100Hz)*
Segments		62				0			
Substrates			35				0		
In-segment CTE inhomogeneities				35				N/A	*Mostly effect of through-thickness CTE gradient*
Inter-segments CTE inhomogeneities				5				N/A	
Polishing			32				0		
All terms except edge misfigure				30				N/A	*Over full pupil; individual segments may exceed*
Edge misfigure				12				N/A	*Assumes edge misfigure <1 fringe over 10 mm*

OWL Image quality budget in SCAO mode (continued)

Axial supports			31					0			
Print-through				25					N/A		*Gravity; assumed to be mostly polished out.*
Thermal				10					N/A		
Integration				15					N/A		
Bonding stresses					5					N/A	
I/F dimensional errors					10					N/A	
I/F force & moments errors					10					N/A	
Lateral supports			26					0			
Print-through				20					N/A		
Thermal				10					N/A		
Integration				12					0		
Bonding stresses					5					N/A	
I/F dimensional errors					8					N/A	
I/F force & moments errors					8					N/A	
Mirror seeing		25					N/A				
M2	**52**					**0**					
Rigid body		13					0				
Overall curvature			5					0			
Segments average curvature				0					N/A		*Amplitude & frequency low enough for full AO correction*
Integration				0					N/A		*Amplitude & frequency low enough for full AO correction*
Gravity				0					N/A		*Amplitude & frequency low enough for full AO correction*
Thermal				0					N/A		*Amplitude & frequency low enough for full AO correction*
Wind				5					N/A		*Uncorrected residual only (>~ 100Hz)*
Lateral decentres			5					0			
Integration				0					N/A		*Amplitude & frequency low enough for full AO correction*
Gravity				0					N/A		*Amplitude & frequency low enough for full AO correction*
Thermal				0					N/A		*Amplitude & frequency low enough for full AO correction*
Wind				5					N/A		*Uncorrected residual only (>~ 100Hz)*
Tip-tilt			5					0			
Integration				0					N/A		*Amplitude & frequency low enough for full AO correction*
Gravity				0					N/A		*Amplitude & frequency low enough for full AO correction*
Thermal				0					N/A		*Amplitude & frequency low enough for full AO correction*
Wind				5					N/A		*Uncorrected residual only (>~ 100Hz)*
Piston			10					0			
Integration				0					N/A		*Amplitude & frequency low enough for full AO correction*
Gravity				0					N/A		*Amplitude & frequency low enough for full AO correction*
Thermal				0					N/A		*Amplitude & frequency low enough for full AO correction*
Wind				10					N/A		*Uncorrected residual only (>~ 100Hz)*

OWL Image quality budget in SCAO mode (continued)

Segments		43					0				*Effect twice larger than with M1*
Substrates			16					0			
In-segment CTE inhomogeneities				15					N/A		*Most corrected by M6 (~6-7 actuators / M2 segment diameter)*
Inter-segments CTE inhomogeneities				5					N/A		*Idem*
Polishing			32					0			
All terms except edge misfigure				30					N/A		*Over full pupil; individual segments may exceed*
Edge misfigure				12					N/A		*Assumes edge misfigure <1 fringe over 10 mm*
Axial supports			21					0			
Print-through				15					N/A		*Assumed to be mostly polished out; corrected by M6*
Thermal				5					N/A		*Partially corrected by M6*
Integration				14					0		
Bonding stresses					8					N/A	*Partially corrected by M6*
I/F dimensional errors					8					N/A	*Partially corrected by M6*
I/F force & moments errors					8					N/A	*Partially corrected by M6*
Lateral supports			11					0			
Print-through				8					N/A		*Partially corrected by M6*
Thermal				8					N/A		*Partially corrected by M6*
Integration				12					0		
Bonding stresses					5					N/A	*Partially corrected by M6*
I/F dimensional errors					8					N/A	*Partially corrected by M6*
I/F force & moments errors					8					N/A	*Partially corrected by M6*
Mirror seeing		25					N/A				
M3	**43**					**0**					
Rigid body		9					0				*Within corrector considered as rigid body*
Lateral decentres			5					0			
Integration				0					N/A		*Amplitude & frequency low enough for full AO correction*
Gravity				0					N/A		*Amplitude & frequency low enough for full AO correction*
Thermal				0					N/A		*Amplitude & frequency low enough for full AO correction*
Wind				5					N/A		*Uncorrected residual only (>~ 100Hz)*
Tip-tilt			5					0			
Integration				0					N/A		*Amplitude & frequency low enough for full AO correction*
Gravity				0					N/A		*Amplitude & frequency low enough for full AO correction*
Thermal				0					N/A		*Amplitude & frequency low enough for full AO correction*
Wind				5					N/A		*Uncorrected residual only (>~ 100Hz)*
Piston			5					0			
Integration				0					N/A		*Amplitude & frequency low enough for full AO correction*
Gravity				0					N/A		*Amplitude & frequency low enough for full AO correction*
Thermal				0					N/A		*Amplitude & frequency low enough for full AO correction*
Wind				5					N/A		*Uncorrected residual only (>~ 100Hz)*

OWL Image quality budget in SCAO mode (continued)

Mirror misfigure		37					0				
Substrate - CTE inhomogeneity			10					N/A			*Mostly compensated by active optics*
Polishing			30					0			*Assumes polishing support = operational support*
Matching				5					N/A		*Mostly corrected by active optics and M6*
Other terms				30					N/A		*Comparable to VLT M1 (not best)*
Axial supports			14					0			
Print-through				10					N/A		*Mostly polished out*
Thermal				5					N/A		
Integration				9					0		
Bonding stresses					5					N/A	*Mostly compensated by AO*
I/F dimensional errors					5					N/A	*Mostly compensated by AO*
I/F force & moments errors					5					N/A	*Mostly compensated by AO*
Lateral supports			11					0			
Print-through				10					N/A		*Mostly compensated by AO*
Thermal				5					N/A		*Mostly compensated by AO*
Integration				14					0		
Bonding stresses					8					N/A	*Mostly compensated by AO*
I/F dimensional errors					8					N/A	*Mostly compensated by AO*
I/F force & moments errors					8					N/A	*Mostly compensated by AO*
Mirror seeing		20					N/A				*Some AO compensation expected*
M4	**77**					**0**					
Rigid body		9					0				*Within corrector considered as rigid body*
Lateral decentres			5					0			
Integration				0					N/A		*Amplitude & frequency low enough for full AO correction*
Gravity				0					N/A		*Amplitude & frequency low enough for full AO correction*
Thermal				0					N/A		*Amplitude & frequency low enough for full AO correction*
Wind				5					N/A		*Uncorrected residual only (>~ 100Hz)*
Tip-tilt			5					0			
Integration				0					N/A		*Amplitude & frequency low enough for full AO correction*
Gravity				0					N/A		*Amplitude & frequency low enough for full AO correction*
Thermal				0					N/A		*Amplitude & frequency low enough for full AO correction*
Wind				5					N/A		*Uncorrected residual only (>~ 100Hz)*
Piston			5					0			
Integration				0					N/A		*Amplitude & frequency low enough for full AO correction*
Gravity				0					N/A		*Amplitude & frequency low enough for full AO correction*
Thermal				0					N/A		*Amplitude & frequency low enough for full AO correction*
Wind				5					N/A		*Uncorrected residual only (>~ 100Hz)*

OWL Image quality budget in SCAO mode (continued)

Mirror misfigure		74					0				
Substrate - CTE inhomogeneity			10					N/A			*Mostly compensated by active optics*
Polishing			71					0			*Assumes polishing support = operational support*
Matching				10					N/A		*Mostly corrected by active optics and M6*
Other terms				70					N/A		*Comparable to VLT M1 (not best)*
Axial supports			14					0			
Print-through				10					N/A		*Mostly polished out*
Thermal				5					N/A		
Integration				9					0		
Bonding stresses					5					N/A	*Mostly compensated by AO*
I/F dimensional errors					5					N/A	*Mostly compensated by AO*
I/F force & moments errors					5					N/A	*Mostly compensated by AO*
Lateral supports			11					0			
Print-through				10					N/A		*Mostly compensated by AO*
Thermal				5					N/A		*Mostly compensated by AO*
Integration				12					0		
Bonding stresses					5					N/A	*Mostly compensated by AO*
I/F dimensional errors					5					N/A	*Mostly compensated by AO*
I/F force & moments errors					10					N/A	*Mostly compensated by AO*
Mirror seeing		20					N/A				*Some AO compensation expected*
M5	**54**					**0**					
Rigid body		9					0				*Within corrector considered as rigid body*
Lateral decentres			5					0			
Integration				0					N/A		*Amplitude & frequency low enough for full AO correction*
Gravity				0					N/A		*Amplitude & frequency low enough for full AO correction*
Thermal				0					N/A		*Amplitude & frequency low enough for full AO correction*
Wind				5					N/A		*Uncorrected residual only (>~ 100Hz)*
Tip-tilt			5					0			
Integration				0					N/A		*Amplitude & frequency low enough for full AO correction*
Gravity				0					N/A		*Amplitude & frequency low enough for full AO correction*
Thermal				0					N/A		*Amplitude & frequency low enough for full AO correction*
Wind				5					N/A		*Uncorrected residual only (>~ 100Hz)*
Piston			5					0			
Integration				0					N/A		*Amplitude & frequency low enough for full AO correction*
Gravity				0					N/A		*Amplitude & frequency low enough for full AO correction*
Thermal				0					N/A		*Amplitude & frequency low enough for full AO correction*
Wind				5					N/A		*Uncorrected residual only (>~ 100Hz)*

OWL Image quality budget in SCAO mode (continued)

Mirror misfigure		47					0				
Substrate - CTE inhomogeneity			10					N/A			*Mostly compensated by active optics*
Polishing			35					0			*Assumes polishing support = operational support*
Matching				5					N/A		*Mostly corrected by active optics and M6*
Other terms				35					N/A		*Comparable to VLT M1 (not best)*
Axial supports			22					0			
Print-through				10					N/A		*Mostly polished out*
Thermal				10					N/A		
Integration				17					0		
Bonding stresses					10					N/A	*Mostly compensated by AO*
I/F dimensional errors					10					N/A	*Mostly compensated by AO*
I/F force & moments errors					10					N/A	*Mostly compensated by AO*
Lateral supports			18					0			
Print-through				15					N/A		*Mostly compensated by AO*
Thermal				10					N/A		*Mostly compensated by AO*
Integration				17					0		
Bonding stresses					10					N/A	*Mostly compensated by AO*
I/F dimensional errors					10					N/A	*Mostly compensated by AO*
I/F force & moments errors					10					N/A	*Mostly compensated by AO*
Mirror seeing		25					N/A				*Some AO compensation expected*
M6	**50**					**0**					
Rigid body		7					0				*Within corrector considered as rigid body*
Lateral decentres			0					0			
Integration				0					N/A		*Flat mirror*
Gravity				0					N/A		*Flat mirror*
Thermal				0					N/A		*Flat mirror*
Wind				0					N/A		*Flat mirror*
Tip-tilt			5					0			
Integration				0					N/A		*Amplitude & frequency low enough for full AO correction*
Gravity				0					N/A		*Amplitude & frequency low enough for full AO correction*
Thermal				0					N/A		*Amplitude & frequency low enough for full AO correction*
Wind				5					N/A		*Uncorrected residual only (>~ 100Hz)*
Piston			5					0			
Integration				0					N/A		*Amplitude & frequency low enough for full AO correction*
Gravity				0					N/A		*Amplitude & frequency low enough for full AO correction*
Thermal				0					N/A		*Amplitude & frequency low enough for full AO correction*
Wind				5					N/A		*Uncorrected residual only (>~ 100Hz)*

OWL Image quality budget in SCAO mode (continued)

Mirror misfigure		43					0				
Substrate - CTE inhomogeneity			5					N/A			*Mostly compensated by active optics*
Polishing			25					0			*Assumes polishing support = operational support*
Matching				0					N/A		*Mostly corrected by active optics and M6*
Other terms				25					N/A		*Comparable to VLT M1 (not best)*
Axial supports			29					0			
Print-through				20					N/A		*Mostly polished out*
Thermal				10					N/A		
Integration				19					0		
Bonding stresses					15					N/A	*Mostly compensated by AO*
I/F dimensional errors					5					N/A	*Mostly compensated by AO*
I/F force & moments errors					10					N/A	*Mostly compensated by AO*
Lateral supports			18					0			
Print-through				15					N/A		*Mostly compensated by AO*
Thermal				10					N/A		*Mostly compensated by AO*
Integration				15					0		
Bonding stresses					10					N/A	*Mostly compensated by AO*
I/F dimensional errors					5					N/A	*Mostly compensated by AO*
I/F force & moments errors					10					N/A	*Mostly compensated by AO*
Mirror seeing		25					N/A				*Some AO compensation expected*
Corrector (rigid body)	**9**					**0**					
Lateral decentres		5					0				
Integration			0					N/A			*Amplitude & frequency low enough for full AO correction*
Gravity			0					N/A			*Amplitude & frequency low enough for full AO correction*
Thermal			0					N/A			*Amplitude & frequency low enough for full AO correction*
Wind			5					N/A			*Uncorrected residual only (>~ 100Hz)*
Tip-tilt		5					0				
Integration			0					N/A			*Amplitude & frequency low enough for full AO correction*
Gravity			0					N/A			*Amplitude & frequency low enough for full AO correction*
Thermal			0					N/A			*Amplitude & frequency low enough for full AO correction*
Wind			5					N/A			*Uncorrected residual only (>~ 100Hz)*
Piston		5					0				
Integration			0					N/A			*Amplitude & frequency low enough for full AO correction*
Gravity			0					N/A			*Amplitude & frequency low enough for full AO correction*
Thermal			0					N/A			*Amplitude & frequency low enough for full AO correction*
Wind			5					N/A			*Uncorrected residual only (>~ 100Hz)*

OWL Image quality budget in SCAO mode (continued)

Environment	**25**			**0**			
Local heat sources		20			N/A		
Telescope seeing		15			N/A		*Telescope structure*
Tracking	**14**			**0**			
Friction		10			N/A		*Mostly compensated by field stabilisation (incl. fast thin shell)*
Wind		10			N/A		*Mostly compensated by field stabilisation (incl. fast thin shell)*
Metrology (encoders)		0			N/A		*Amplitude & frequency low enough for full AO correction*
Non-AO wavefront control	**42**			**0**			
Pre-alignment		**0**			**0**		
Metrology			0			N/A	*Amplitude & frequency low enough for full AO correction*
Actuation			0			N/A	*Amplitude & frequency low enough for full AO correction*
Phasing		**42**			**0**		
Metrology (incl. signal processing)			20			N/A	*Excluding on-sky metrology (calibration)*
Calibration			10			N/A	*Assumes bright star (v < 8)*
M1 segments actuation			25			N/A	*Incl. wind and after AO correction*
M2 segments actuation			25			N/A	*Incl. wind and after AO correction*
Active focusing		**0**			**0**		
Metrology (incl. signal processing)			0			N/A	*Amplitude & frequency low enough for full AO correction*
Actuation			0			N/A	*Amplitude & frequency low enough for full AO correction*
Active centring		**0**			**0**		
Metrology (incl. signal processing)			0			N/A	*Amplitude & frequency low enough for full AO correction*
Actuation			0			N/A	*Amplitude & frequency low enough for full AO correction*
Active surfaces deformations		**0**			**0**		
Metrology (incl. signal processing)			0			N/A	*Amplitude & frequency low enough for full AO correction*
Fitting			0			N/A	*Amplitude & frequency low enough for full AO correction*
M3 force actuation			0			N/A	*Amplitude & frequency low enough for full AO correction*
M4 force actuation			0			N/A	*Amplitude & frequency low enough for full AO correction*
Field stabilisation		**0**			**0**		
Metrology			0			N/A	*Amplitude & frequency low enough for full AO correction*
Actuation			0			N/A	*Amplitude & frequency low enough for full AO correction*

OWL Image quality budget in SCAO mode (continued)

Ground layer AO	**0**	**0**	
Metrology (incl. signal processing)	N/A	N/A	
Non-common path	N/A	N/A	
M6 actuation	N/A	N/A	
Single conjugate AO	**87**	**0**	
Metrology (incl. signal processing)	85	N/A	
Non-common path	10	N/A	
M6 actuation	15	N/A	
Dual conjugate AO	**0**	**0**	
Metrology (incl. signal processing)	N/A	N/A	
Non-common path	N/A	N/A	
M5 actuation	N/A	N/A	
M6 actuation	N/A	N/A	
Multi-Object AO	**0**	**0**	
Metrology (incl. signal processing)	N/A	N/A	
Non-common path	N/A	N/A	
M6 actuation	N/A	N/A	
Post-focal actuation	N/A	N/A	
Extreme AO (XAO)	**0**	**0**	
Metrology (incl. signal processing)	N/A	N/A	
Non-common path	N/A	N/A	
M6 actuation	N/A	N/A	
Post-focal actuation	N/A	N/A	

OWL Image quality budget in SCAO mode (continued)

5.6 Reliability, Availability, Maintainability, Safety (RAMS)

5.6.1 Product Assurance Roles & Responsibilities

Product Assurance Tasks that ESO will take and undergo in detail in the next design phases are:

- System Safety
- Reliability Engineering
- Quality Assurance
- Review and Inspection
- Procurement Product Assurance
- Material and Process Control
- Manufacturing and process control
- NonConformance Control & Reporting:
    - Problem Reporting
    - Material Review Board
    - Failure Analysis and Corrective Action report
- EEE Parts Engineering and Electronic Packaging
- Software Quality Assurance
- Configuration Control

All the above mentioned tasks will be undertaken considering applicable and reference document such as

Failure Rates (example the ESA, PSS-01-302)

FMECA Requirements (ESA doc, PSS-01-303)

Reliability prediction of Electronic prediction (MIL-HDBK-217)

5.6.2 Safety

5.6.2.1 General

The design team will establish and implement a safety program compliant with the safety requirements. This program will be described in a dedicated section of the Product Assurance Plan of next design phase.

Compliance with the requirements below shall not relieve ESO from complying other countries national safety regulations or those where the telescope, or any related ground support equipment, is planned to be used.

5.6.2.2 Safety Assurance Program and organization

ESO will nominate a person with adequate background and experience as responsible project team member for system safety engineering tasks. Availability and access to the necessary data to adequately perform the safety tasks will be assured.

5.6.2.3 Safety assurance activities

During next detailed design phase it will be evaluated the design and operation of the telescope, identify hazards, and control measures, verify their implementation and certify that the telescope is safe and complies with the applicable safety requirements. ESO will ensure that the safety verifications are reflected in the overall OWL verification plan.

5.6.3 Reliability and Maintainability

Reliability is the probability that a system will provide its functions within specified performance limits for a specified period of time in specified conditions.

Maintainability is a characteristic of design and integration, which is expressed as the probability that a system will be retained in or restored to a specific condition within a given period of time.

Reliability and Maintainability Assurance is aimed to ensure that design reliability and maintainability will not be compromised by competing requirements such as cost and time, and to verify and provide evidence of compliance with requirements.

Maintainability requirements for software are not covered in this chapter.

Consequence Severity Categories

For the purpose of identifying failures criticality in reliability analyses, classification of Table 5-3 (section 5.1) shall be used.

By default the unclassified failures (i.e. not resulting in any of the above) are considered as negligible.

5.6.3.1 Failure Tolerance

All failure modes of criticality Category 1 shall be eliminated from the design, minimised or controlled in accordance with the applicable safety failure tolerance requirements. In addition, no single failure or operator error shall have major consequences (Category 2).

5.6.3.2 Single point failure list

Items of criticality Category 1 failures which are not maintainable, and all items with Category 2 failures will be listed in a Single Point Failure (SPF) list. The SPF list will be subjected to detailed study and formal approval. The request for approval shall be submitted with a rationale for retention explaining technical reasons and potential special provisions during development (e.g. testing), production and operation, to minimise the failure probability.

5.6.3.3 Reliability and Maintainability Data File

ESO will maintain a project reliability and maintainability data file as part of his overall product assurance documentation system. The file will contain, as a minimum, the following:

- R&M Analyses, lists, reports and input data.
- R&M recommendation status log.
- Supporting analyses and documentation.

5.6.3.3.1 Reliability Engineering

Reliability engineering will focus on the prevention, detection and correction of reliability design deficiencies. Reliability engineering will be an integral part of the item design process, including design changes. The means by which reliability engineering contributes to the design, and the level of authority and constraints on this engineering discipline, will be identified in the reliability program plan.

5.6.3.3.1.1 Reliability Analyses

<u>FMECA</u>

ESO will prepare Failure Modes Effects and Criticality Analyses according to specific procedures such as the PSS-01-303 or MIL-STD-1629A.

FMECA will be initially performed, in the early detailed project phase, at the level of system functions and/or functional paths. As the design advances, the FMECA will be refined and completed down to unit level, with the exception of safety critical circuits and circuit interfacing external elements for which FMECA will be performed down to component level.

The objectives of the FMECA shall include:

- Identification of the effects of assumed failures, including identification of hazards in support of safety analyses and to determination of the need for redundancies, inhibits or fail-safe features.
- Demonstration of compliance with applicable safety and reliability failure tolerance requirements.
- Identification of available or needed monitoring devices for the symptoms of a failure which can be observed via monitoring or telemetry.
- Identification of inputs for maintenance activities.

The following failure modes will be considered in the FMECA:

- Out of sequence operation.
- Failure to operate at prescribed time.
- Failure to cease operation at prescribed time.
- Failure during operation.
- Degradation or out of tolerance operation.
- For failure of EEE parts:
  - Short circuit,
  - Open circuit,
  - Incorrect function.
- Incorrect commands or sequence of commands.
- Incorrect software functions.

FMECA shall include consideration of hardware/software interaction to ensure that software is designed to react in an acceptable way to hardware failure (e.g. sensors). Results shall be inputs for the Software Requirements Document (SRD).

5.6.3.3.2 Maintainability Engineering

5.6.3.3.2.1 Establishment of Maintainability Requirements

Maintainability requirements that will be applied to the system, or item being developed shall be established on the basis of the system maintenance concept.

The system maintenance concept will be proposed during the next design phase.

5.6.3.3.2.2 Maintainability Inputs to Maintenance Plan

The maintainability function will provide inputs to develop a maintenance plan prepared to support the maintenance concept approved.

These inputs shall include estimates of preventive and corrective maintenance requirements (including task times and frequencies) and the proportion of failures that will be localised by automatic, semi-automatic and manual means.

5.6.3.3.2.3 Maintainability Analyses

Maintainability Prediction

Maintainability prediction shall be performed and employed as a design tool to assess and compare design alternatives with respect to specified maintainability quantitative requirements. Maintainability predictions shall be used as a basis for estimating human resource requirements.

Maintainability predictions shall be performed considering:

- The time required to diagnose (i.e. detect and isolate) item failures, the time required to remove and replace the defective item.
- The time required to return the system/subsystem to its original configuration and to perform the necessary checks.
- The item failure rates.

Maintainability Support to other Engineering Analyses

The maintainability function shall participate in the trade-off studies and support the following engineering analyses as a minimum:

a) Line Replaceable Units (LRU) optimisation, by considering safety criticality, reliability, costs, fault diagnostics capability, and unit replacement times.

b) Identification of hazards induced by maintenance activities.

c) Diagnostic alternatives to effectively detect and isolate failures at LRU level and accurately verify system restoration.

d) Use of condition monitoring methods to optimise the preventive maintenance interventions.

e) Determination of maximum number of maintenance actions that each LRU can be subjected to without degradation in performance and/or reliability.

f) Minimisation and standardisation of maintenance tools.

5.6.3.3.2.4 Maintainability Demonstration

Maintainability demonstration shall be performed to verify that the identified preventive and corrective maintenance activities can be successfully performed. In particular to verify the:

- ability to detect, diagnose, isolate and remove faulty LRU's.
- safety of maintenance actions;
- accessibility;
- repairs, when replacement is not foreseen;
- performance of inspections and tests after replacement/repair.

5.6.4 Conclusion – OWL Dependability Objective Sheet

Refinement of the following Product Assurance requirements will be part of the detailed design phase:

SAFETY

- No event relevant to the OWL telescope jeopardizing the personnel (Catastrophic event) must be expected during the OWL lifetime
- No event relevant to the OWL Telescope causing the total loss of the OWL facility (Critical event) must be expected during the OWL lifetime

AVAILABILITY

- The maximum expected probability of any event relevant to OWL causing the failure to start an observation (Major 2 event) must be [for example 15^{-2} (1.5%)]; a value of Mean Time to Repair of 8h shall be expected.
- No event relevant to the OWL telescope causing the telescope unavailability for more than 1 week. (Major 1 event) must be expected during the OWL lifetime.

RELIABILITY

- The maximum expected frequency of any event causing a forced observation interruption (Significant 2 event) must be (for example 3.0^{-4} /h), referred to the actual operating time.