Systems engineering implementation in the conceptual design phase of 4MOST

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ABSTRACT

The 4MOST Facility is a very high-multiplex, wide-field, fibre-fed spectrograph system for the VISTA telescope. Its aim is to create a world-class spectroscopic survey facility that is unique in its combination of wide-field multiplex, spectral resolution and coverage, and sensitivity. In such a complex instrumentation project, in which design and development activities are geographically distributed, a formal system engineering approach is essential for the success of the project. We present an overview of the systems engineering principles, and associated tools, implemented during the conceptual design phase, as well as the systems engineering activities planned for the preliminary design phase.

Keywords: 4MOST, VISTA, Systems Engineering, requirements, interfaces

1. INTRODUCTION

4MOST is a wide-field, high-multiplex spectroscopic survey facility under development for the VISTA telescope of the European Southern Observatory (ESO). Its main science drivers are in the fields of galactic archeology, high-energy physics, galaxy evolution and cosmology. 4MOST will in particular provide the spectroscopic complements to the large area surveys coming from space missions like Gaia, eROSITA and Euclid, and from ground-based facilities like VISTA, VST, DES, LSST and SKA. 4MOST features a 2.5 degree diameter field-of-view with ~2400 fibres in the focal plane that are configured by a fibre positioner based on the tilting spine principle. The fibres feed two types of spectrographs; ~1600 fibres go to two spectrographs with resolution R>5000 and ~800 fibres to a spectrograph with R>18,000. Both types of spectrographs are fixed-configuration, three-channel spectrographs. 4MOST will have an unique operations concept in which 5 year public surveys from both the consortium and the ESO community will be combined and observed in parallel during each exposure, resulting in more than 25 million spectra of targets spread over a large fraction of the southern sky.

It is impractical for a complex and costly facility such as 4MOST to be designed, developed, and implemented by one single institute; rather, the workload must be distributed among a consortium whose members complement each other with their experience, expertise and funding. Therefore, the definition and application of a formal systems engineering approach is crucial in achieving the scientific and cost-related goals of the project.

Section 2 of this paper introduces the systems engineering concept adopted by 4MOST, including project life-cycle, requirements engineering and interface management. Section 3 summarizes the main systems engineering activities accomplished during the first phase of the project, the Conceptual Design phase. The principal systems engineering tasks planned to be performed during the Preliminary Design Phase are described in section 4. Finally, section 5, compiles the conclusions derived from the work performed up to now.

2. SYSTEMS ENGINEERING IN 4MOST

2.1 4MOST Systems Engineering Process

The system engineering process adopted by 4MOST is based on the INCOSE definition according to which "*the systems engineering process is an iterative approach to technical management, acquisition and supply, system design, product realization, and technical evaluation at each level of the system, beginning at the top (the system level) and propagating those processes through a series of steps which eventually lead to a preferred system solution*".

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Figure 1 represents the 4MOST System Engineering Process. It corresponds to a vee model,[1] in which the left part corresponds to the system decomposition and design definition phases and the right part corresponds to the system integration and verification phases.

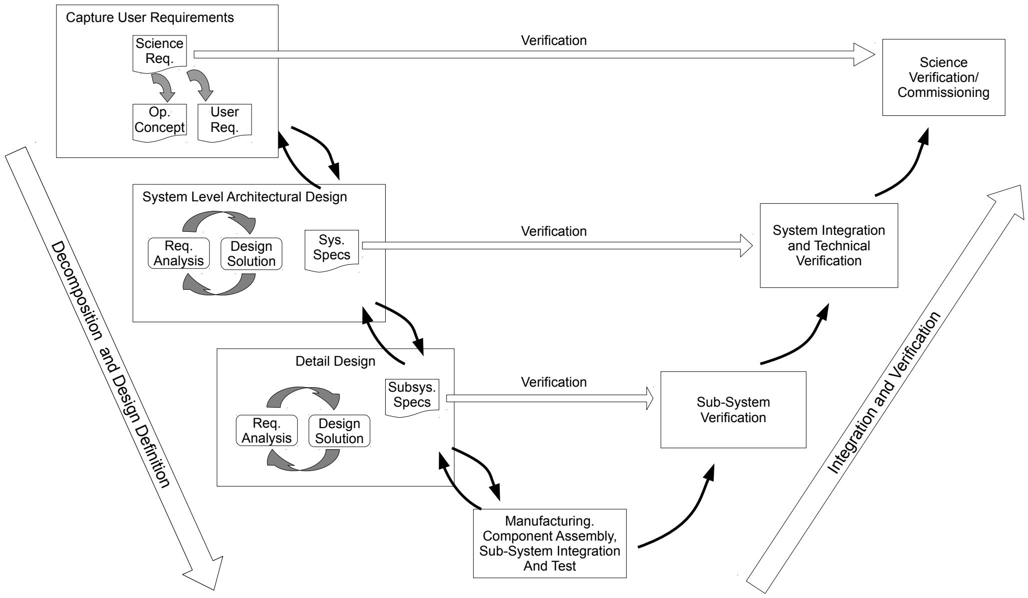

Figure 1. 4MOST System Engineering Process Vee Model

During the development phase, 4MOST science requirements evolve to a system concept that, in turn, develops into the definition of the different elements the system is made of. In the course of the integration and verification phases, the elements identified, which final design has been accepted, are constructed and verified at subsystems level to be later integrated into the system and verified as a whole.

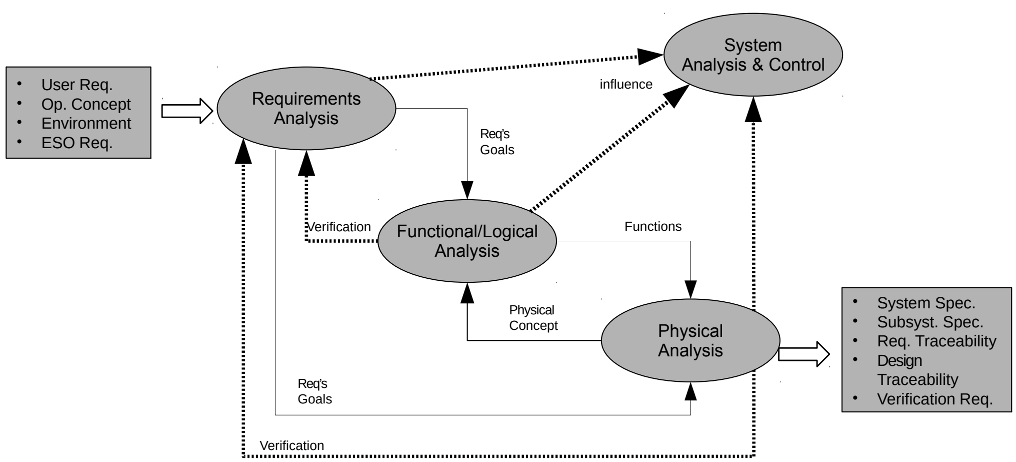

Figure 2. 4MOST System Engineering design approach[2]

In the design phases, systems engineering activities concentrate on requirement analyses, functional analyses and allocation in the physical design. They, together with system analysis and control tasks, such as interface management and decision and requirement tracking, are responsible for the generation of a set of documents fundamental for the subsequent engineering activities (e.g. system and subsystems specifications and requirement and design traceability).

The defined approach is depicted in Figure 2.

2.1.1 Project Phases

As depicted in Figure 3, 4MOST has adopted ESO project phases, and hence its life-cycle has been divided in the following phases:

- System decomposition and design definition phases
  - Conceptual Design Study Phase
  - Preliminary Design Phase
  - Final Design Phase
- System integration and verification phases
  - Manufacturing, Assembly, Integration and Verification (MAIV) Phase
  - Installation, Commissioning and Validation Phase
  - Operations Phase

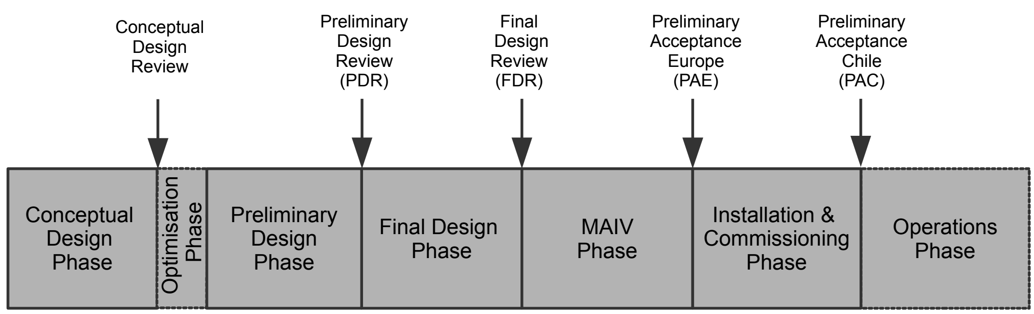

Figure 3. 4MOST Project phases and main reviews. Note that the *Operations Phase* is beyond the scope of the 4MOST systems engineering and it is shown for the sake of completeness

Each phase has one or more associated formal stage-gate reviews. The aim of these reviews is to provide a comprehensive assessment of the status of the project against targets and requirements. They give the responsible management confidence in the progress being achieved. At the end of each review, the review board shall state whether the presented design is accepted, accepted with actions or not accepted. Additionally, in the course of the different phases, a series of informal rolling reviews will be performed by the Project Office. Their objective is to progressively check the development of the system's elements in order to early identify potential problems. This will help to reduce the workload associated with formal reviews.

2.2 Requirements Engineering

Requirement definition is an essential step in the development of any project. Well-defined requirements are essential for the project manager to plan a program to be followed, engineers to know what to build, scientist to know what to expect, and to be able to validate that the system as-built satisfies the needs of the users community.

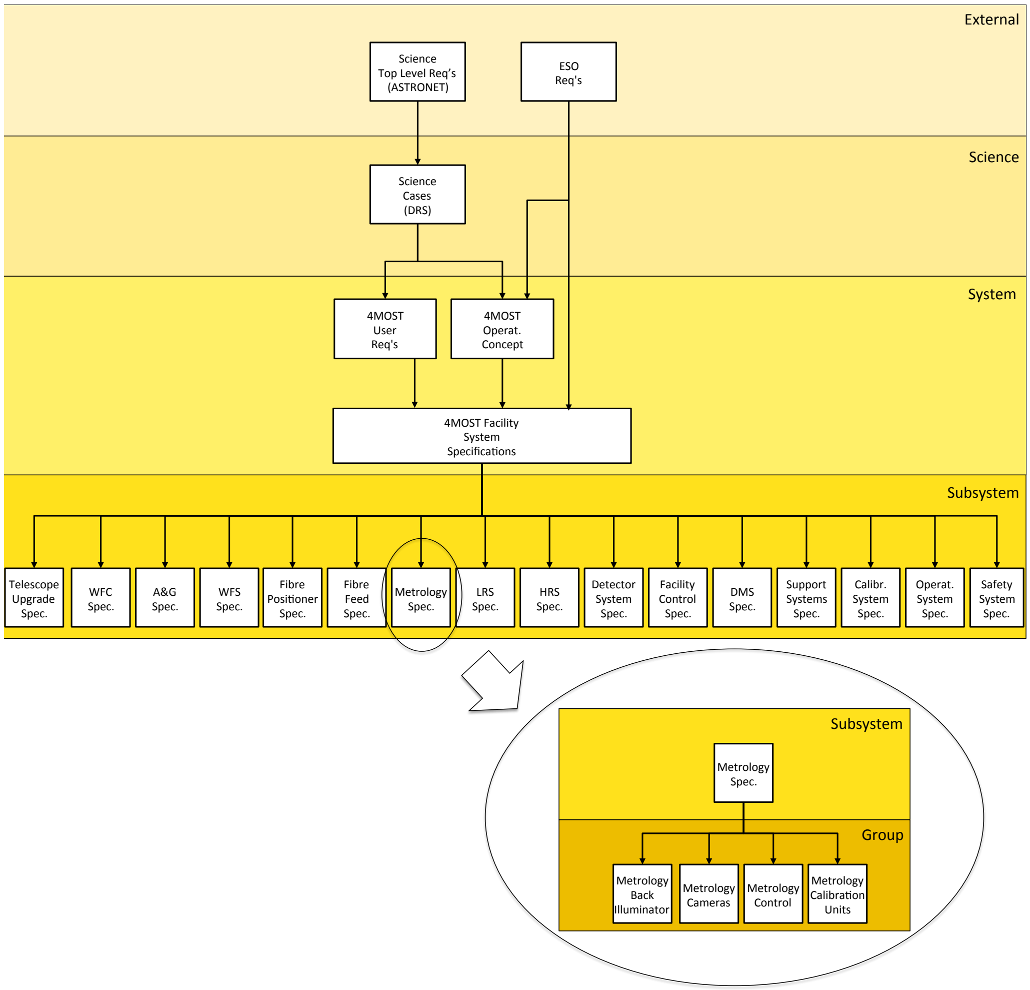

Figure 4. 4MOST Requirements Hierarchy

2.2.1 Requirements Hierarchy

4MOST requirements are organized into three main hierarchical levels. See Figure 4

Science Requirements Science requirements reflect the needs of the system core-science cases, so called Design Reference Survey (DRS). Although they are mostly driven by complementing and enhancing the science cases of three key all-sky, space-based observatories of prime European interest (i.e. Gaia, eROSITA and Euclid), 4MOST's capabilities will allow to perform additional surveys. For a defined set of requirements, each DRS provides its needed values (e.g. abundance measurement accuracy, line coverage, etc.)

System Requirements System requirements are gathered in three main documents:

- 4MOST User Requirements Document lists the top level facility requirements derived from the prime science requirements.
- 4MOST Operations Concept describes the operational concept and defines the requirements that support the science and technical operations of the facility. The Operations Concept describes how 4MOST is to be used to achieve the science requirements.

- 4MOST System Facility Requirements Specification defines the product to be developed, states the requirements the designed system must fulfill, and specifies the main requirements the subsystems must comply with. The system facility requirements are derived from the user requirements, the operational concept and additionally from the applicable ESO requirements.

Although all of them reside at the same level, there is a hierarchy to these documents that determines their precedence and the flow-down from one of them to the other.

Subsystems Requirements Below system requirements documents, there is another layer of requirement documents used to define subsystems requirements. Subsystem requirements are derived from system requirements. In some cases, due to the complexity of the subsystems, they are broken down further into different groups, which requirements are gathered in the subsystem requirements documents.

In this way, a science requirement specifying the needed abundance measurement accuracy is translated into a user requirement that defines the signal to noise ratio to be achieved. The signal to noise user requirement is in turn flown-down to the system requirement specification. At this level, it is analysed and broken down into throughput and noise requirements that are allocated to the contributing subsystems.[3]

2.2.2 Requirements Traceability

When dealing with different levels of requirements, documenting the relationship between them is essential. DOORS is the requirements management tool used in 4MOST by systems engineering. It allows to save in a single database the project requirements from science to subsystem requirements and helps us to manage the links between requirements on different levels. Requirements traceability is essential to:

- guarantee completeness of system and subsystem requirements. DOORS will be very useful to detect orphan requirements (i.e. requirements without a "parent" requirement). The presence of orphan requirements may in some cases be correct, but it may also indicate that the requirements documentation is incomplete and a requirement needs to be defined or modified on the upper level.
- plan requirement verification procedures. Traceability information may help to establish that sufficient verification activities are being done at subsystem level and that system-level verification can be limited to simply reviewing and analyzing the results of the subsystems verification process.
- analyze the impact of changes to high-level requirements. Traceability may be used to assess and understand the effects of changes in system requirements on subsystems.

2.3 Interfaces Management

The management and control of interfaces is crucial to successful projects. Interface management defines the processes and methodology that allow the project to control the development of the system when efforts are divided among several partners and to describe and maintain compliance among the different components that are physically or logically joined together to perform a function.[4]

The existence of an interface between two 4MOST subsystems is captured in a N-squared Diagram. Figure 5 shows the 4MOST N-squared Diagram. Each non-blank entry of the matrix indicates an interface between two subsystems. The details of this interface are documented in one ICD (Interface Control Document). Each ICD is organized in several sections that describe optical, mechanical, utility, electronic, software, human, and safety interfaces.

	External	Telescope upgrade	Wide Field Corrector	Wavefront Sensors	Acquisition and Guiding	Fibre Positioner	Fibre Feed	Metrology	Low Resolution Spectrograph	High Resolution Spectrograph	Detectors	Facility Control System	Data Management System	Calibration System	Operations System	Support Systems	Safety System
External																	
Telescope upgrade																	
Wide Field Corrector		1															
Wavefront Sensors		2	14														
Acquisition and Guiding		3															
Fibre Positioner		4															
Fibre Feed		5				23											
Metrology		6		17	20	24											
Low Resolution Spectrograph		7					28	32									
High Resolution Spectrograph		8					29	33									
Detectors		9							37	42							
Facility Control System		10	15	18	21	25		34	38	43	47						
Data Management System												49					
Calibration System		11							39	44		50					
Operations System												51	54				
Support Systems		12	16	19	22	26	30	35	40	45	48	52	55	56			
Safety System		13				27	31	36	41	46		53		57		58	

Figure 5. 4MOST N-squared Diagram. The numbers in the cells correspond to the interface IDs

3. SYSTEMS ENGINEERING IN THE CONCEPTUAL DESIGN PHASE

3.1 Conceptual Design Phase

The Conceptual Design phase was aimed at investigating and developing a good understanding of the required system, and defining the very general type of solution that will be pursued, for the system and the subsystems. This phase was also fundamental to identify the questions and risks that may arise during the next phases of the project.

During this phase, the systems engineering activities focused on determining the basic systems engineering processes, defining the system level requirements and the design architecture. System requirements were flowed down from the user requirements and allocated to functions and related performances, at system and subsystem level, ensuring that traceability information was recorded. System engineering efforts have been also dedicated to establish, and document, the preliminary interfaces between the system and the external entities and between the different subsystems within the system. In the frame of the systems engineering activities, different system architectures and operation concepts were elaborated and compared against the identified needs, in order to assess the technical, economic and schedule feasibility of the different proposals. Additionally, trade-off studies were performed and the optimal designs were down-selected.

At the end of the Conceptual Design phase, 4MOST proposed an operations concept and a system architecture, with specific technical solutions and verification approaches, all of them to be further elaborated during the Preliminary Design Phase. ESO reviewed and evaluated them during the Conceptual Design Review and positively recommended 4MOST for study and construction phase.

3.1.1 Concept Optimization Phase

The Conceptual Design Phase was just the first step of the project life cycle. Currently, before entering into the formal Preliminary Design Phase, 4MOST is going through a Optimisation Phase in which some of the concept proposed at the CoDR (i.e. spectrographs' design, metrology concept and detector selection) are been further developed in order to maximise the cost-performance ratio, considering the financial constrains, and mitigate the identified risks.

3.2 High Level Requirements Documentation

In order to collect all the requirement generated during the Conceptual Design Phase, a set of Top Level Specifications was developed. Figure 6 summarizes the documentation prepared and the relationship between the different documents.

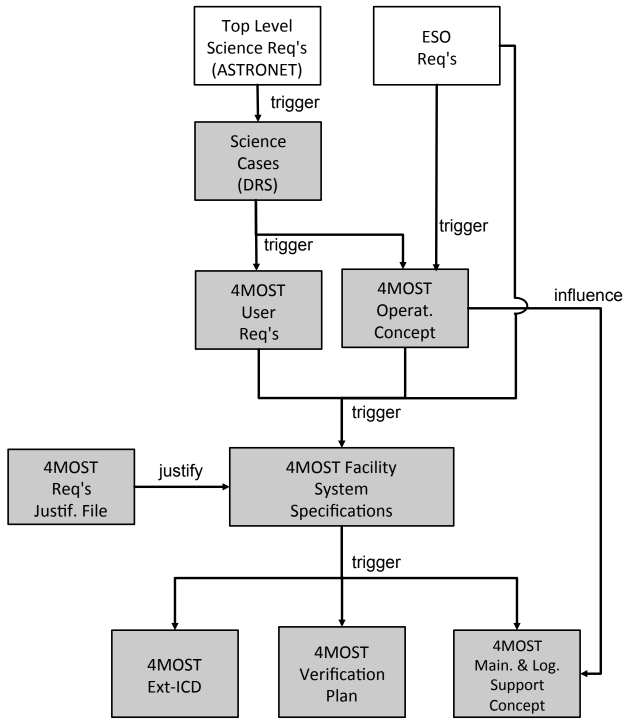

Figure 6. 4MOST Top Level Requirement Documentation. Documents external to 4MOST are showed in white

Everything started with the Science Top Level requirements identified in the ASTRONET infrastructure roadmap.[5] To address these top level requirements, 4MOST defined a set of design reference surveys. They reflect the Science Requirements that triggered the 4MOST User Requirements. The User Requirements, together with ESO applicable requirements and the 4MOST Operational Concept, that describes the desired system characteristics from an operational perspective, motivated the 4MOST Facility System Specification. This document, that establishes the different requirements for the facility without any system architecture assumption, triggered in turn the content of documents such as the 4MOST External ICD, the 4MOST Verification Plan and the Maintenance and Logistic Support Concept. The same structure is adopted at subsystem level. Subsystems specifications are expected to define architecture dependent requirements, that will trigger ICDs, verification plans and maintenance and logistic support concepts at subsystem level. The last document within this group was the 4MOST Requirements Justification File, a bridge document that includes the rationale of each of the requirements in the System Specifications.

3.3 Trade-offs

3.3.1 Telescope selection

In the frame of the Conceptual Design Phase and the Concept Optimization Phase, several trade-off studies have been performed. One of the trade studies carried out, and probably, the one with the biggest impact in the overall design of the facility was the study aimed to analyze the implications of mounting the instrument on either the VISTA telescope or the NTT. The conclusions obtained by the Consortium were provided to ESO who, with the necessary information, selected the most appropriate location.

The agreement reached by the Consortium, regarding the most appropriate location for the Facility, was the result of evaluating and comparing VISTA and NTT in terms of: science capabilities, technical feasibility, associated costs and schedule.

With regard to the telescopes science capabilities, VISTA is able to collect photons more efficiently, due mainly to its larger collecting area and larger field of view capability. This significantly improves data quality for most of the science cases for a given exposure time.

In terms of technical feasibility and operational challenges, the installation of 4MOST at the NTT implied that a set of the instrument subsystems, including fiber positioner, support structures and cable wraps, would need to be located above M1. The limited accessibility to this area would entail a series of risks associated to the installation, commissioning and maintenance of the subsystems located there. To that one should add the telescope modifications that would be needed to install 4MOST at the NTT (e.g. a new secondary mirror would be required to obtain a larger field of view).

No significant cost differences were found between the two options. The NTT hardware itself was estimated cheaper than VISTA's, however the labor associated to the former was estimated to be more expensive, due to additional components needed. Similarly, the differences between the schedules proposed for both implementations (including design, development, integration and commissioning) were not considered decisive.

Although it was concluded that 4MOST was technically feasible to implement on both NTT and VISTA, the Consortium expressed its preference[6] for VISTA because, for the same cost, it would provides better science performance at a lower technical risk.

3.3.2 Spectrographs trade-off

One of the conclusions of the Conceptual Design Review was the need to review the proposed spectrograph's designs, and explore new options if necessary, i.e. to come out with an alternative design that maximizes the cost-effectiveness ratio, all of which needed to considering the economical constrains. For that reason, a trade-off study between the proposed and newly considered spectrographs was set as one of the principal activities to be developed during the Concept Optimization Phase.

One of the major cost drivers for the 2-arm spectrographs designs presented at the Conceptual Design Review was the selection of the 3kx8k pixel detector format (a mosaic of 2x3kx3k pixel for each camera for the low resolution spectrograph and a single 3kx8k for each of the high resolution spectrograph cameras) and their associated large, complex and therefore expensive optics. In order to reduce the cost it was posed the option of investigating a 3-arm design with smaller and more symmetric detectors, i.e. 4kx4k and 6kx6k pixel devices.

Currently the latest updates on the new designs are being reviewed. The proposals will be evaluated and compared. The optimal option will be chosen based on criteria such as feasibility, performance, cost, maintainability, risk and compliance with ESO interfaces and maintenance approach. The final conclusions, together with the trade study performed, will be properly documented at the end of the third term of 2014, when the results of the Concept Optimization Phase will be submitted to ESO.

4. WHAT COMES NEXT?

4.1 Preliminary Design Phase

Concerning Systems Engineering, the main aim of this phase, that will start at the end of 2014, is threefold:

- review and update the requirement that were defined in the Conceptual Design Phase,
- investigate and refine the technology options identified during the Conceptual Design Phase in order to confirm the operations concept and the technical solutions for the system, and establish a preliminary design of the facility and,
- develop the subsystems requirements, based on the Conceptual Design architectural system solution.

Prior to the start of the Preliminary Design phase, the subsystem functional, physical and cost budget will be review and updated as necessary. From this point onwards they will be formal managed and be under strict change control. Additional "trade-off" studies will be performed early in this phase in order to select the optimal system architecture and detailed technical solution(s) for this concept. Reliability and safety assessments will be conducted to verify that reliability and safety requirements are likely to be met and the risk evaluation will be updated, including the reviewed mitigation options.

During this phase, the detailed verification program will be determined, using as starting point the verification plan elaborated during the Conceptual Design phase. In the same way, the interfaces between the different subsystems, will be further detailed, taking as base the ICD generated during the previous phase. In order to coordinate, guide and manage the different activities at system and subsystems level the systems engineering management plan will be refined and implemented by the project. To be able to control the changes and maintain the integrity of the system baseline, a change control procedure will be defined and implemented. At the end of this phase, i.e. at PDR, the capability of the selected design solution to meet all specified requirements according to the schedule, the budget, the target cost, and the organization requirements will be evaluated.

4.1.1 Instrument Numerical Model: TOAD

The 4MOST instrument numerical model[7] (TOAD) was initiated during the Conceptual Design Phase. Its software architecture was decided and some of its key functions are already available. It will be heavily developed during the Preliminary Design Phase and at the end of this phase it is expected that it can provide a major part of its functionality. It will simulate the optical performance of the instrument from the top of the atmosphere to the detector, hence its name (TOAD stands for **T**op **O**f **A**tmosphere to **D**etector). The implementation of such a tool is necessary for a complex system such a s 4MOST, and will be a great benefit to the systems engineering activities.

TOAD will support trade off studies to be performed during the Preliminary Design Phase and will help in early identification of system level problems. It will assist us in better comprehending the behavior of the system as a whole, allowing us to foresee the impact of a design change on the performance of the instrument. Part of the function of TOAD is the generation of FITS files, containing detector images, that in early stages will be used to verify functionality and interfaces of the 4MOST Data Management System.

For systems engineering it is fundamental to understand the performance of each element in the system and the interactions among these elements. TOAD will be a powerful tool in accomplishing this aim.

5. CONCLUSIONS

Within this paper the system engineering concept adopted by 4MOST has been presented. 4MOST is a project that has relied, since the beginning, on a system engineering approach to achieve the scientific, technical and financial goals of the project. The workload associated to the design, development and implementation of the facility has been distributed among a consortium, whose members complement each other with their experience and expertise.

During the Conceptual Design Phase, the importance of defining good requirements, and maintaining the trace of their flow-down from the top level to the subsystem level has been highlighted. Preliminary 4MOST external interfaces, as well as interfaces between the different subsystems, have been identified, and an interface management approach has been adopted. Additionally, diverse trade-off studies have been performed and their results incorporated into the initial system solution, to be further developed during the Preliminary Design phase.

A proper implementation of a system engineering approach can provide enormous benefits to the design and construction of 4MOST, and we have just taken the first step in the right direction.

ACKNOWLEDGMENTS

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