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Maunakea Spectroscopic Explorer (MSE): systems engineering management for a massively multiplexed spectroscopic survey facility

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Maunakea Spectroscopic Explorer

ABSTRACT

MSE is an upgrade of the existing 3.6-m Canada France Hawaii Telescope to an 11.25-m segmented primary mirror with a 1.5 square degrees field-of-view at the telescope's prime focus. MSE will be massively multiplexed, observing 4,332 astronomical targets in every pointing. There are several subsystems needed to accomplish this. At MSE's prime focus, a hexapod supports and positions several subsystems, including a wide field corrector barrel, a field derotator, guide and phasing cameras and a system of fiber optics with their individual piezo-actuated positioners. The fiber optics transmit light to two banks of low/moderate and high resolution spectrographs in optical to near-infrared wavelengths, several meters away. An array of primary mirror segments and several spectrographs are supported by the telescope structure as well.

All of these subsystems are being designed and built by various partners and contributors around the world. Integration and compliance to requirements will require careful planning. To ensure this is successful, MSE has developed a plan for consistently flowing and tracking the many requirements from the Observatory Requirements into its subsystems. This involves reviewing subsystem design requirements that were developed in the conceptual design phase and updating them based on recent changes in the Observatory Requirements. Also, internal interfaces have been identified and will be closely controlled to ensure consistency throughout the project. This also involves consideration of several other topics related to requirements development and maintenance through the lifecycle of the project.

We present an overview of the systems engineering management plans that will ensure consistency and traceability of requirements to science cases and stakeholder needs, as well as anticipating the verification process in the future work.

Keywords: spectroscopic facility, survey facility, multiplex, fibre, fiber, spectrograph, Systems Engineering, requirement, interface

1. INTRODUCTION

The Maunakea Spectroscopic Explorer (MSE) is a next-generation massively multiplexed ground-based spectroscopic survey facility. MSE is designed to enable truly transformative science, being completely dedicated to large-scale multi-object spectroscopic surveys, each studying thousands to millions of astrophysical objects. MSE will use an 11.25 m aperture telescope to feed 4,332 fibers over a 1.5 square degree field of view and has the capability to observe at a range of spectral resolutions, from R~3,000 to R~40,000, with all spectral resolutions available at all times across the entire field. The MSE project completed a Conceptual Design Review of the facility in 2018 [1]; the Conceptual Design of the facility is shown in Figure 1. With these capabilities, MSE will collect more than 10 million fiber-hours of 10m-class spectroscopic observations every year and is designed to excel at precision studies of large samples of faint astrophysical targets.

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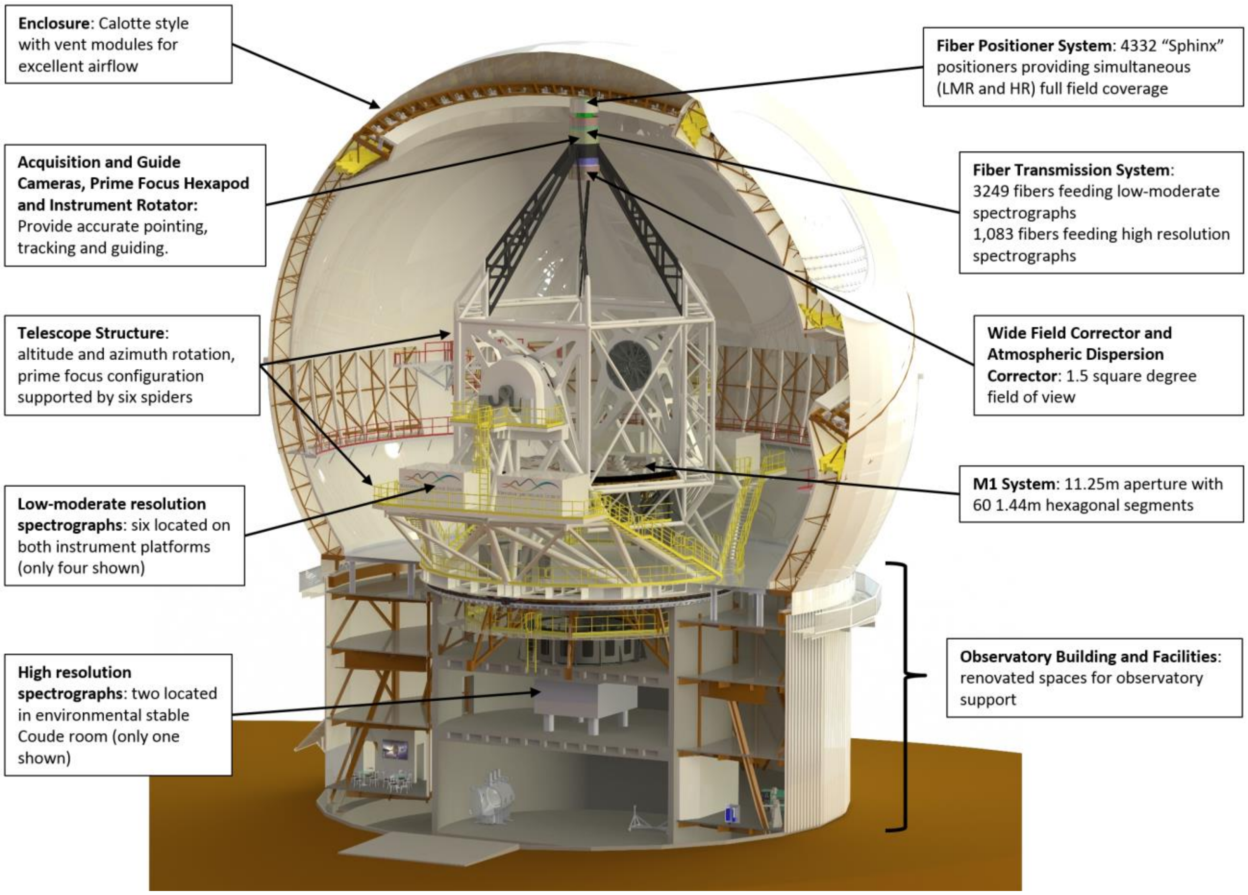

Figure 1. MSE Observatory architecture as described by the 2018 Conceptual Design [1].

The scientific impact of MSE will be made possible and attainable by upgrading the existing Canada-France-Hawaii Telescope (CFHT) infrastructure on the Maunakea summit, Hawaii. CFHT is located at a world-class astronomical site with excellent free-atmosphere seeing (0.4 arcseconds median seeing at 500 nm). The Mauna Kea Science Reserve Comprehensive Management Plan (Ku'iwalu 2009) for the Astronomy Precinct explicitly recognizes CFHT as one of the sites that can be redeveloped. In order to minimize environmental and cultural impacts to the site, and also to minimize cost, MSE will replace CFHT with an 11.25 m aperture telescope while retaining the current summit facility footprint. MSE will greatly benefit by building on the technical and cultural experience of CFHT throughout the development of the project.

MSE is designed to take advantage of the excellent site characteristics of Maunakea, which allows for an extremely sensitive, wide-field, and massively multiplexed facility (see Table 1). The MSE Conceptual Design positions 4,332 input fibers at MSE's prime focus, packed into a hexagonal array. The fibers are precisely positioned to submillimeter accuracy in order to maximize the amount of light injected from science targets into the input fibers, which collect and transmit light to banks of spectrographs tens of meters away. One bank of spectrographs receives light from 3,249 fibers from the focal surface and may be used in either low resolution (R~2500) or moderate resolution (R~6000) mode, covering the optical to near-infrared wavelength range of 0.36–1.8 microns. Concurrently, the other bank of spectrographs receives light from 1,083 fibers from the focal surface and is dedicated to collecting the high resolution spectra in three targeted optical wavelength windows within the wavelength range of 0.36–0.5 microns at R~40,000 and 0.5–0.9 microns at R~20,000. All resolution modes have simultaneous full field coverage, and the massive multiplexing results in the ability to collect many thousands of spectra per hour and over a million spectra per month, all of which will be made available to the MSE user community. Moreover, an upgrade path to add an Integral Field Unit (IFU) system has been incorporated into the design as a second-generation capability for MSE.

Table 1. The detailed science capabilities of MSE.

Site characteristics				
Observatory latitude	19.9 degrees			
Accessible Sky	30,000 square degrees (airmass < 1.55 i.e., $\delta > -30$ degrees)			
Median image quality	0.37 arcsec (free atmosphere, zenith, 500 nm)			
Average length of night	10.2 hours			
Historical weather losses (average)	2.2 hours / night			
Observing efficiency (on-sky, on-target)	80%			
Expected on-target science observing hours	2336 hours / year			
Expected on-target fiber-hours	10,112,544 fiber-hours / year (total): 7,589,664 (LR & MR) / 2,529,888 (HR)			
Telescope architecture				
Structure, focus	Altitude-azimuth, Prime			
M1 aperture	80.8 m^2			
Science field of view	1.52 square degrees			
Spectrograph system	6 x LMR spectrographs (4 channels/spectrogrpah, all identical, each channel seperately switchable to provide LR and MR modes 2 x HR spectrographs (3 channels/spectrograph), both identical, to provide high resolution mode All spectrographs always available with full multiplexing Deployable IFU system using LR /MR spectrograph system available as second generation capability			
Fiber positioning system				
Multiplexing	4,329 (total): 3,249 (LR & MR) / 1,083 (HR)			
Fiber size	1 arcsec (LR & MR) / 0.8 arcsec (HR)			
Positioner patrol radius	90.3 arcsecs			
Positioner accuracy	0.06 arcsec rms			
Positioner closest approach	Two fibers can approach with 7 arcsecs of each other (three fibers can be placed within 9.9 arcsec diameter circle)			
Repositioning time	< 120 seconds			
Typical allocation efficiency	> 80 % (assuming source density approximately matched to fiber density)			
Low resolution (LR) spectroscopy				
Wavelength range	$360 \leqq \lambda \leqq 560$ nm	$540 \leqq \lambda \leqq 740$ nm	$715 \leqq \lambda \leqq 985$ nm	$960 \leqq \lambda \leqq 1320$ nm
Spectral resolution ***(approx. at center of band)***	2,550	3,650	3,600	3,600
Sensitivity requirement ***(pt. source, 1hr, zenith, median seeing, monochromatic magnitude)***	m = 24.0 SNR/res. elem. = 2, $\lambda > 400$ nm SNR/res. elem. = 1, $\lambda \leqq 400$ nm	m = 24.0 SNR/resolution element = 2	m = 24.0 SNR/resolution element = 2	m = 24.0 SNR/resolution element = 2
Moderate resolution (MR) spectroscopy				
Wavelength range	$391 \leqq \lambda \leqq 510$ nm	$576 \leqq \lambda \leqq 700$ nm	$737 \leqq \lambda \leqq 900$ nm	$1457 \leqq \lambda \leqq 1780$ nm
Spectral resolution ***(approx. at center of band)***	4,400	6,200	6,100	6,000
Sensitivity requirement ***(pt. source, 1hr, zenith, median seeing, monochromatic magnitude)***	m = 23.5 SNR/res. elem. = 2, $\lambda > 400$ nm SNR/res. elem. = 1, $\lambda \leqq 400$ nm	m = 23.5 SNR/resolution element = 2	m = 23.5 SNR/resolution element = 2	m = 24.0 SNR/resolution element = 2
High resolution (HR) spectroscopy				
Wavelength range	$360 \leqq \lambda \leqq 460$ nm	$440 \leqq \lambda \leqq 620$ nm	$600 \leqq \lambda \leqq 900$ nm	
Wavelength band	$\lambda / 30$ [baseline: 401 - 415 nm]	$\lambda / 30$ [baseline: 472 - 488.5 nm]	$\lambda / 15$ [baseline: 626.5 - 672 nm]	
Spectral resolution ***(approx. at center of band)***	40,000	40,000	20,000	
Sensitivity requirement ***(pt. source, 1hr, zenith, median seeing, monochromatic magnitude)***	m = 20.0 SNR/resolution element = 10, $\lambda > 400$ nm SNR/resolution element = 5, $\lambda \leqq 400$ nm	m = 20.0 SNR/resolution element = 10	m = 24.0 SNR/resolution element = 10	
Science calibration				
Sky subtraction accuracy	0.5% requirement (0.1% goal)			
Velocity precision	100 m/s (HR, SNR/resolution element = 30)			
Relative spectrophotometric accuracy	3% (LR, SNR/resolution element = 30)			

Aside from the physical infrastructure, MSE's success is enabled by efficiently scheduled and executed surveys, by the quality of the data collected, and by MSE's ability to make the science products available to survey teams in a timely and efficient manner. MSE will devote 80% of available time to executing large, homogeneous surveys which will typically require several years to complete. More focused programs, which require smaller amounts of observing time and typically lead to more rapid publications, will occupy the remaining 20% of observing time. Proposals for both types of programs will be solicited from the MSE user community at regular intervals. MSE is operated solely in a queue-based mode, requiring sophisticated scheduling software. Data will be made available to the survey team immediately, and to the larger MSE community on a short timescale.

Since 2018, MSE participants have increased from six national institutions in Australia, Canada, China, France, India and Hawaii to ten, with Texas A&M University and Kyung Hee University (South Korean) joined as participants and US NSF's NOIRLab and UK university consortium (Cambridge, Durham, Oxford, University College London) led by the Astronomy Technology Centre in Edinburgh join as observers. Each institution contributes to MSE, usually by providing their expertise in the design and construction of various parts of the telescope. This is discussed in detail in described in [2]. In addition, several vendors will provide key subsystems or components.

The complexity of the organization requires significant effort and leadership from MSE's Project Office (PO) which is now preparing for the Preliminary Design Phase of the project. The overall scope, schedule and budget are the responsibility of the Project Manager. Systems Engineering activity at MSE focuses on controlling the technical scope of the project and ensuring that science capabilities in the Figure 1 and stakeholder needs are realized. This is the main goal of the Systems Engineering effort at the MSE Project Office.

2. BACKGROUND AND CONTEXT

2.1 Early Requirements Development

We describe here MSE's process for identifying and composing subsystem requirements before and during the Conceptual Design Phase (CoDP) of the project.

- As is common on ground based astronomy projects, logical decomposition of requirements based on a preliminary architecture of the project began very early (compared to other types of projects) because a pre-concept was necessary during the proposal phase of the project. For example, the observatory architecture was decomposed to spectrographs and fiber positioning and transmission systems very early on.
- For subsystems, identification of requirements was started in the CoDP. Each subsystem was given a "strawman" design and proposed a set of subsystem requirements based on known science needs, rather than decomposing science requirements into their component parts. *This included work by the most critical subsystems but necessarily resulted in a preliminary and incomplete set of subsystem requirements.*
- The PO reviewed and updated the sets subsystem of requirements and folded them into an overall proposed set of Observatory Requirements and bottoms-up performance budgets.
- At the end of the CoDP, the bottoms-up performance budgets were compared to science requirements. This resulted in identifying critical and difficult to meet requirements at both the system and subsystem level. We previously presented our systems engineering methodology [3] which resulted in science requirements flowing through system performance budgets into an Observatory Requirements Document.

2.2 Current Status

After CoDP, work began to identify the full set of requirements for the system and subsystems. The PO performed a functional analysis of the overall observatory, decomposing the functions as far as the level of subsystems. This has resulted in a comprehensive set of functional flow block diagrams that illustrate all of the functions the observatory must do (the top level only is provided in Figure 3). This work also resulted in a slightly revised Product Breakdown Structure (Figure 4).

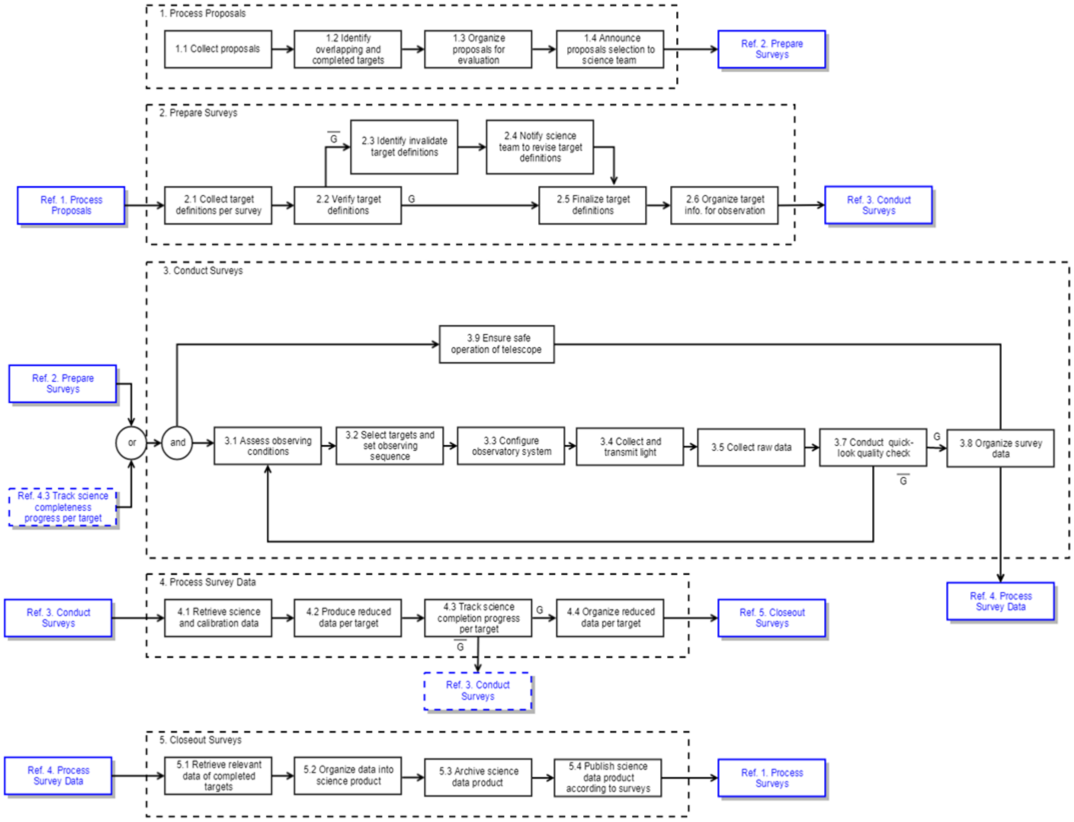

Figure 2. MSE top level functional flow block diagram

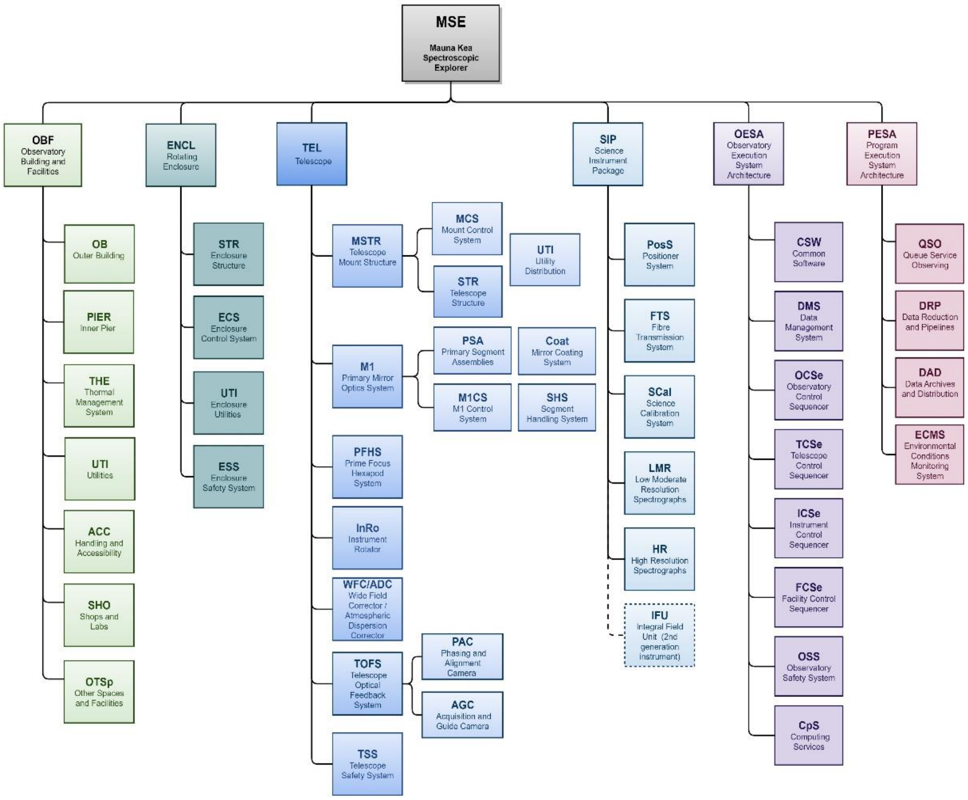

Figure 3. MSE product breakdown structure

2.3 Requirements Hierarchy and Defining Documents

Given the technical solutions proposed in the CoDP, some science requirements could not be met or were risky in terms of cost, schedule and technical feasibility. For this reason, the feasibility and science justification for many of the proposed requirements have been reviewed and amended. Recent work in the MSE PO has included consulting with the science working groups to refine and update the science requirements. This has resulted in a pending revision to the SRD to respond to the science working groups' needs.

Recently, the PO also began a critical piece of work, the process of capturing stakeholders' needs and overall operational concepts more formally in a Concept of Operations Document (ConOps). This provides traceability for system level requirements in MSE and ultimately flow down to subsystem requirements.

A description of the current set of MSE's five system-defining documents is presented here for context.

Concept of Operations Document (ConOps) –describes the stakeholders' and owners' intention and needs for MSE. This includes high level operational objectives that describe what the observatory is expected to do.

Science Requirements Document (SRD) –quantifies the science goals and observational requirements1 of MSE, which are described in the Detailed Science Case (DSC). The SRD includes Science Reference Observations and formally stated Science Requirements.

The ConOps and SRD complement each other, with the ConOps describing 'what' needs to be done and the SRD describing 'how' (and 'how well') it should be done.

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[1] Science requirements are defined as the capabilities that the MSE system must have in order to make the measurements necessary to successfully carry out the programs described by the SROs.

Operations Concept Document (OCD) –describes in detail how MSE will be operated to meet operational objectives and SRD specifications. The OCD includes a high-level summary of Observatory behaviours and operator interactions.

Observatory Architecture Document (OAD) -prescribes the top-level architecture of MSE that realizes the science requirements and stakeholders' needs. The OAD defines high level observatory requirements for defined modes of operation and decomposes the system into its subsystems, their interactions and performance budgets.

Observatory Requirements Document (ORD) –fully describes the top-level requirements for MSE in engineering terms. The ORD synthesizes all of the other defining documents into a set of requirements for the reference of all of the subsystems in the observatory. The ORD is intended to be a stand-alone governing document for requirements for the entire MSE observatory and high level requirements for its subsystems (Level 2). As such, all subsystems will refer to the ORD for developing requirements and will not directly reference those documents, though they may be used as a reference to clarify or better understand the intent of requirements in the ORD.

The flow of requirements from science and stakeholders to the ORD and ultimately to the subsystems is shown hierarchically in Figure 4, which also shows the many contributing and supporting documents that are a part of the Systems Engineering approach in the MSE PO.

Both the SRD and ConOps are decomposed, flowed down or otherwise interpreted to a set of Observatory Requirements that fully describe MSE.

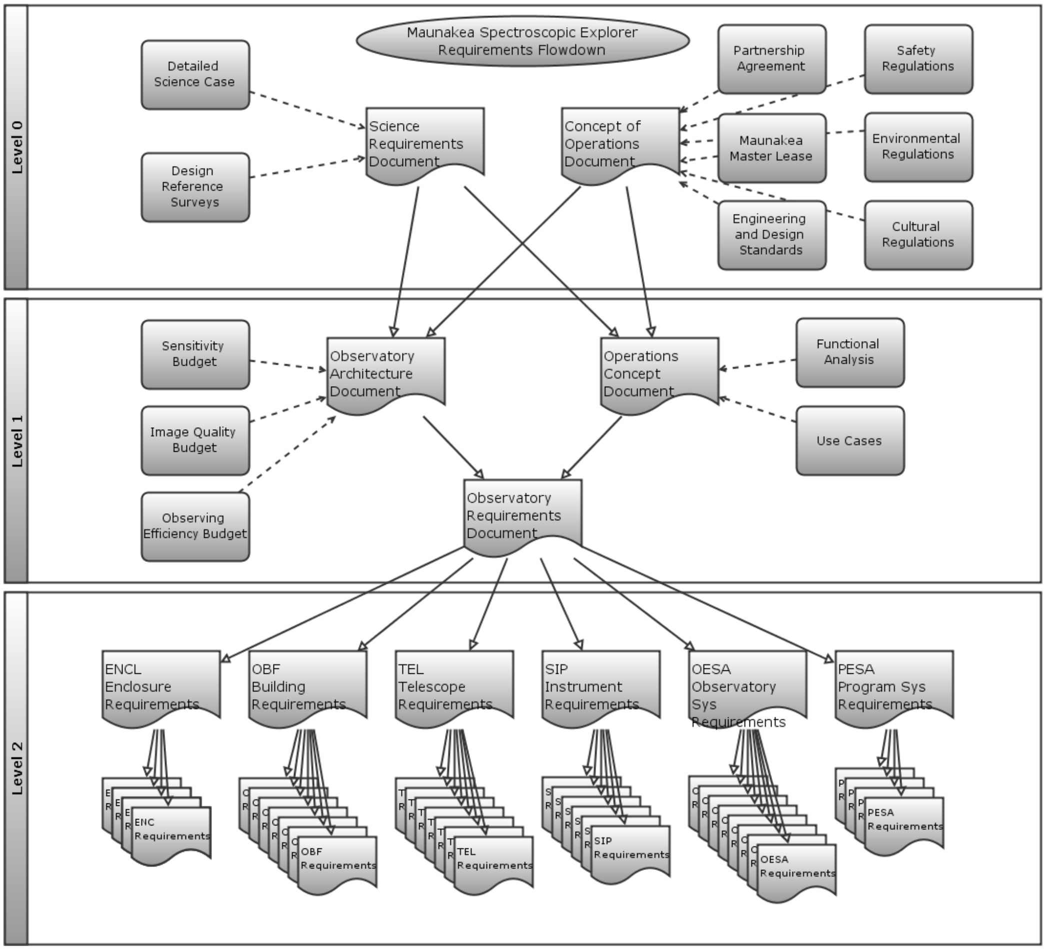


Figure 4. MSE Requirements flowdown and document structure.

The latest revisions of these documents, in preparation for the beginning of the Preliminary Design Phase of MSE, are expected to be released in the first half of 2021.

3. SYSTEMS ENGINEERING PLAN

MSE has developed a plan for ensuring the observatory meets scientist and other stakeholder' needs and includes many activities that are applied at both the system and subsystem levels. All of the activities listed below are sometimes considered by different organizations to be Systems Engineering activities, however these activities have significant overlap with Project Management (PM) and Engineering (PE) activities. In the MSE project, these roles are defined based on the skills and availability of the staff. All are discussed here due to their relevance for maintaining the technical scope of MSE through the lifecycle of the project. This is expected to be captured in a formal Systems Engineering Management Plan (SEMP) in the first half of 2021.

The bulk of this paper focusses on the details for planning for b) through e), since they encompass most of MSE's recent SE activity. The remaining activities are discussed briefly; either they are covered in related papers and documents or a plan for them is not yet comprehensive. In the latter case, current thinking is discussed along with future work.

a) System Design and Analysis
b) Requirements Definition: identification, decomposition
c) Technical Budgets
d) Requirements Management: traceability, processes, tools
e) Interfaces
f) Risk Management
g) Configuration and Change Control
h) Quality Management
i) Verification

Since the system level aspects have been covered in previous papers, each section of this paper begins with only a brief description of context and/or the system level plans and then goes on to describe the plan for subsystem activity.

4. SYSTEM DESIGN AND ANALYSIS

System design and analysis activities include aspects of the system design that cross over several functional areas, subsystems or organizations. The PO is responsible for defining and performing trade studies, developing and maintaining performance budgets and resource-related budgets as well as the end-to-end optical design. For example, trade studies were performed, resulting in the choice to go with a Calotte enclosure and the Altitude-Azimuth focus telescope configuration (described in the [1]). Performance budgets (such as for image quality, throughput) that help the interpretation of Science Requirements to Observatory Requirements and resource-related budgets (such as for mass, power distribution) are examples of system design and analysis that is undertaken by the PO. The resulting requirements and decisions are captured within the SE requirements document structure and configuration management system.

For subsystems, design and analysis are the responsibility of the designers, with support and oversight from the Project Engineer and in response to subsystem requirements. Subsystems define their architecture, perform trade studies and design their systems with guidance, support and oversight of the PO.

One example of current work is a result of the consultation with the science team and subsequent updates to the science requirements. This has prompted design iterations with some of MSE's subsystems and in fact the consultation with the science team and the subsystem design teams has been iterative and collaborative in nature. Both spectrograph subsystems present their recent design studies for Low-Moderate Resolutions Spectrograph and High Resolution Spectrographs are presented in [4] and [5], respectively.

In general, at MSE, this work is will be undertaken by a combination of systems engineers and project engineers. The parallel work of planning for the budget and schedule of this are the responsibility of the PM and therefore is not discussed here.

5. REQUIREMENTS DEFINITION

The requirements definition process includes identifying and developing requirements, decomposing them into their subsystem and component levels until the requirements are independently testable.

The existing system functional analyses will be decomposed to the subsystems and functional flow block diagrams will be created that identify what each subsystem needs to do. Subsystem functional requirements will then be written and checked against the existing set of subsystem requirements, if they were created in CoDP. The functional requirements, then, are further elaborated by performance requirement (specifying how well the system needs to perform) and other non-functional requirements. Again, these will be checked against existing requirements. Performance requirements are identified using a combination of this examination of the functional requirements and then checked to see that they have a parent the ORD and/or in the system technical budgets. Technical budgets are discussed in a later section of this document. This work will culminate with written in subsystem Design Requirements Documents (DRD), one for each subsystem.

Requirements are linked and traced from one level to another in order to analyze the system with the goal of identifying missing requirements and scope creep. This will be the responsibility of the PO. This will be managed in a DOORS NG database so that changes at one level can be traced to other levels of the system. The traceability and management aspects of this are discussed in a later section of this paper.

6. TECHNICAL BUDGETS

Technical budgets represent the break down and allocated of higher level requirements to individual subsystems. Performance budgets relating to science requirements, for example for sensitivity, fiber injection efficiency, image quality, etc. and their relative interactions (Figure 5) were discussed in [2]. These are being updated as discussed to reflect updates to the SRD and ConOps.

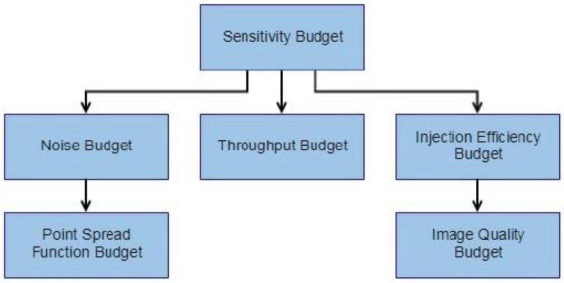
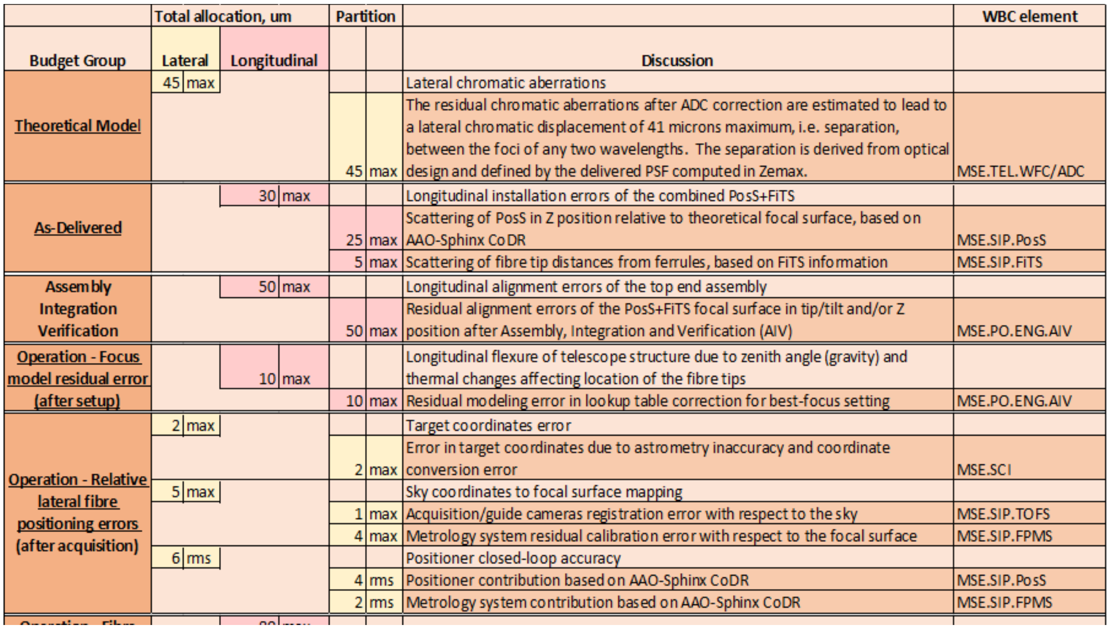


Figure 5. MSE performance budget hierarchy

In the decomposition from system level requirements to the subsystems, each of these budgets has allocated line items that correspond to specific requirements that must be written for the subsystems. For example, in the portion of the Injection Efficiency budget shown in Figure 6, it can be seen that specific subsystems listed in the “WBC element” column refer to subsystems of MSE.

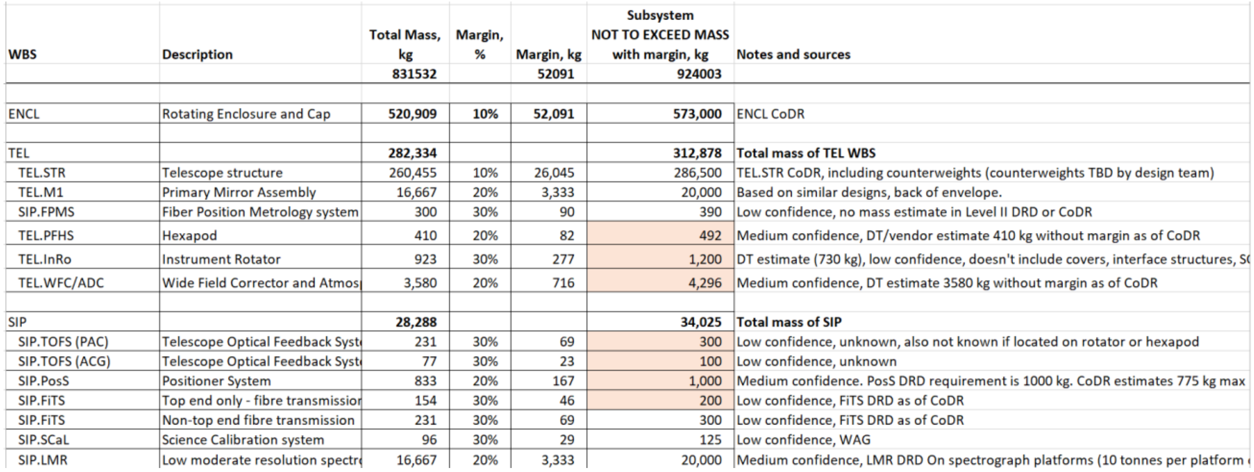


	Total allocation, um				Partition			WBC element
Budget Group	Lateral		Longitudinal				Discussion	
Theoretical Model	45	max					Lateral chromatic aberrations	
					45	max	The residual chromatic aberrations after ADC correction are estimated to lead to a lateral chromatic displacement of 41 microns maximum, i.e. separation, between the foci of any two wavelengths. The separation is derived from optical design and defined by the delivered PSF computed in Zemax.	MSE.TEL.WFC/ADC
As-Delivered			30	max			Longitudinal installation errors of the combined PosS+FiTS	
					25	max	Scattering of PosS in Z position relative to theoretical focal surface, based on AAO-Sphinx CoDR	MSE.SIP.PosS
					5	max	Scattering of fibre tip distances from ferrules, based on FiTS information	MSE.SIP.FiTS
Assembly Integration Verification			50	max			Longitudinal alignment errors of the top end assembly	
					50	max	Residual alignment errors of the PosS+FiTS focal surface in tip/tilt and/or Z position after Assembly, Integration and Verification (AIV)	MSE.PO.ENG.AIV
Operation - Focus model residual error (after setup)			10	max			Longitudinal flexure of telescope structure due to zenith angle (gravity) and thermal changes affecting location of the fibre tips	
					10	max	Residual modeling error in lookup table correction for best-focus setting	MSE.PO.ENG.AIV
Operation - Relative lateral fibre positioning errors (after acquisition)	2	max					Target coordinates error	
					2	max	Error in target coordinates due to astrometry inaccuracy and coordinate conversion error	MSE.SCI
	5	max					Sky coordinates to focal surface mapping	
					1	max	Acquisition/guide cameras registration error with respect to the sky	MSE.SIP.TOFS
					4	max	Metrology system residual calibration error with respect to the focal surface	MSE.SIP.FPMS
	6	rms					Positioner closed-loop accuracy	
					4	rms	Positioner contribution based on AAO-Sphinx CoDR	MSE.SIP.PosS
					2	rms	Metrology system contribution based on AAO-Sphinx CoDR	MSE.SIP.FPMS

Figure 6. MSE example performance budget (injection effieciency)

In practice, the line items in the Injection Efficiency Budget are written in a way that applies directly to subsystems, in engineering units. In some other budgets, such as for Image Quality, units must be converted into practical engineering units via analysis and other methods when the requirement is written in the subsystem Design Requirements Document.

Resource allocation budgets are a further way of decomposing system level requirements. Resource budgets refer to such budgets as mass/centre of mass, distribution of electrical power, vibration generation and heat generation. Similar to the performance budgets, system level available resources and constraints are divided and allocated to subsystems. An illustration of the not-to-exceed mass budget, including margin held back by the project office, is shown in Figure 7.

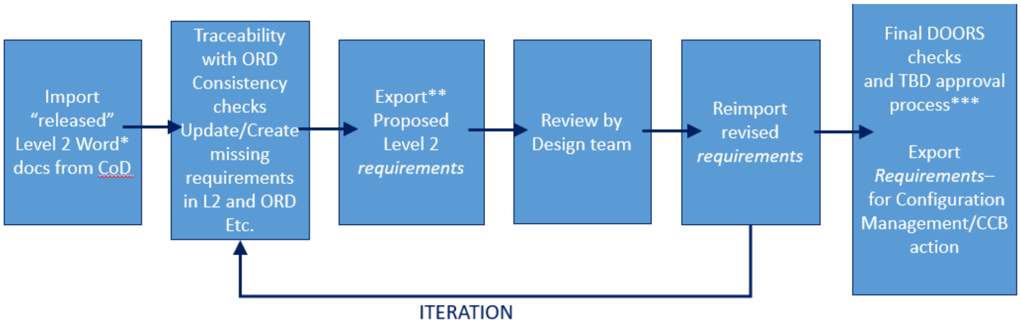


WBS	Description	Total Mass, kg	Margin, %	Margin, kg	Subsystem NOT TO EXCEED MASS with margin, kg	Notes and sources
		831532		52091	924003	
ENCL	Rotating Enclosure and Cap	**520,909**	**10%**	**52,091**	**573,000**	ENCL CoDR
TEL		**282,334**			**312,878**	**Total mass of TEL WBS**
TEL.STR	Telescope structure	260,455	10%	26,045	286,500	TEL.STR CoDR, including counterweights (counterweights TBD by design team)
TEL.M1	Primary Mirror Assembly	16,667	20%	3,333	20,000	Based on similar designs, back of envelope.
SIP.FPMS	Fiber Position Metrology system	300	30%	90	390	Low confidence, no mass estimate in Level II DRD or CoDR
TEL.PFHS	Hexapod	410	20%	82	492	Medium confidence, DT/vendor estimate 410 kg without margin as of CoDR
TEL.InRo	Instrument Rotator	923	30%	277	1,200	DT estimate (730 kg), low confidence, doesn't include covers, interface structures, S
TEL.WFC/ADC	Wide Field Corrector and Atmos	3,580	20%	716	4,296	Medium confidence, DT estimate 3580 kg without margin as of CoDR
SIP		**28,288**			**34,025**	**Total mass of SIP**
SIP.TOFS (PAC)	Telescope Optical Feedback Syst	231	30%	69	300	Low confidence, unknown, also not known if located on rotator or hexapod
SIP.TOFS (ACG)	Telescope Optical Feedback Syst	77	30%	23	100	Low confidence, unknown
SIP.PosS	Positioner System	833	20%	167	1,000	Medium confidence. PosS DRD requirement is 1000 kg. CoDR estimates 775 kg max
SIP.FiTS	Top end only - fibre transmissior	154	30%	46	200	Low confidence, FiTS DRD as of CoDR
SIP.FiTS	Non-top end fibre transmission	231	30%	69	300	Low confidence, FiTS DRD as of CoDR
SIP.SCaL	Science Calibration system	96	30%	29	125	Low confidence, WAG
SIP.LMR	Low moderate resolution spectr	16,667	20%	3,333	20,000	Medium confidence, LMR DRD On spectrograph platforms (10 tonnes per platform

Figure 7. MSE "not-to-exceed" mass budget

7. REQUIREMENTS MANAGEMENT

Once requirements are decomposed and flowed down to subsystem requirements, via logical decomposition and functional analysis or via budget allocations, MSE will manage change and trace the source of subsystem requirements by linking "parent" and "children" requirements. This will be done using the DOORS NG database [6]. The process of importing, tracing/linking, iterating change with design teams and the final approval process is shown in Figure 8.



* Could be Word docs converted to Excel before import. **not all subsystems have something to import**
** First iteration should be at PDP Kick-off

Figure 8. MSE database management process

To provide consistency through the project, subsystems will provide their first requirements draft in a document template that can be imported into the DOORS NG database. This template will start with a Word document, based on an MSE-specific document template that is imported into the DOORS NG database. The document template includes the contents shown in Figure 9, which is tailored to the function-based systems engineering process previously described.

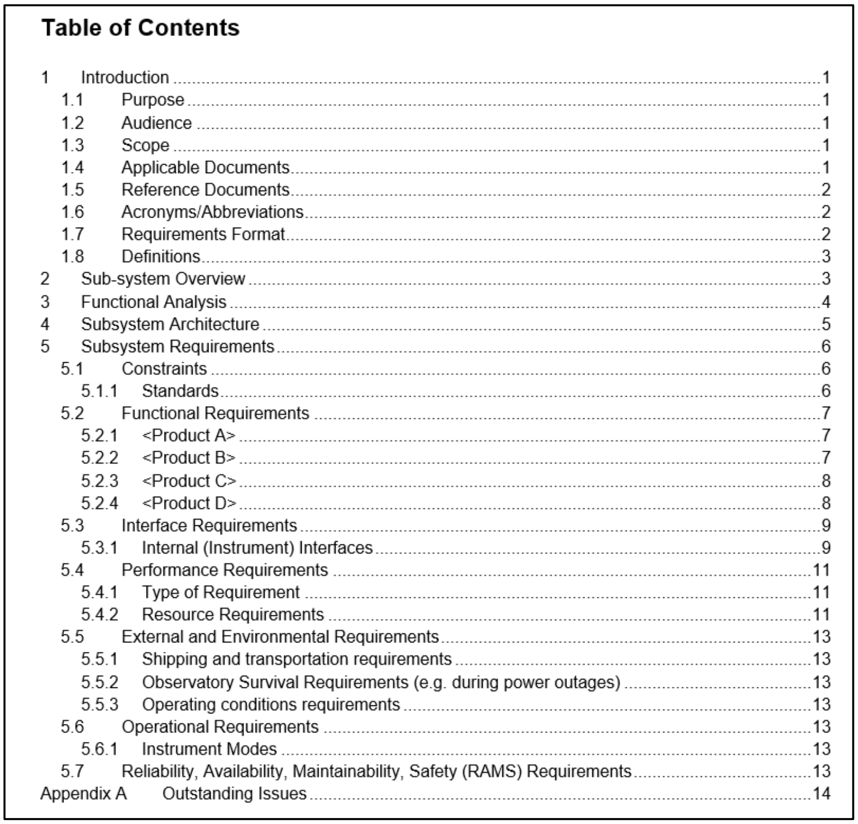


Table of Contents

1 Introduction 1
  1.1 Purpose 1
  1.2 Audience 1
  1.3 Scope 1
  1.4 Applicable Documents 1
  1.5 Reference Documents 2
  1.6 Acronyms/Abbreviations 2
  1.7 Requirements Format 2
  1.8 Definitions 3
2 Sub-system Overview 3
3 Functional Analysis 4
4 Subsystem Architecture 5
5 Subsystem Requirements 6
  5.1 Constraints 6
    5.1.1 Standards 6
  5.2 Functional Requirements 7
    5.2.1 <Product A> 7
    5.2.2 <Product B> 7
    5.2.3 <Product C> 8
    5.2.4 <Product D> 8
  5.3 Interface Requirements 9
    5.3.1 Internal (Instrument) Interfaces 9
  5.4 Performance Requirements 11
    5.4.1 Type of Requirement 11
    5.4.2 Resource Requirements 11
  5.5 External and Environmental Requirements 13
    5.5.1 Shipping and transportation requirements 13
    5.5.2 Observatory Survival Requirements (e.g. during power outages) 13
    5.5.3 Operating conditions requirements 13
  5.6 Operational Requirements 13
    5.6.1 Instrument Modes 13
  5.7 Reliability, Availability, Maintainability, Safety (RAMS) Requirements 13
Appendix A Outstanding Issues 14

Figure 9. MSE design requirements document template

Every requirement in the subsystem DRD will include the following information:

- REQ ID – a unique numerical identifier for every requirement in the format MSE-SUBSYSTEM-#NUM
- REQ TITLE – a brief title describing the requirement
- REQ STATEMENT – a formal, binding, "shall" statement, written in precise language
- RATIONALE – informal information about the origin of the requirement and/or clarifying information
- VERIFICATION METHOD – initially, a general term that describes the expected verifications method (e.g. inspection, test, analysis)

Once imported into DOORS NG, the PO will want several other fields for tracking purposes. This will include:

- VERIFICATION PHASE – the phase in which the requirement will be verified
- VERIFICATION STATUS
- REQ STATUS – status of the requirement within the Change Control and Configuration Management System
- APPLICABILITY – for decomposition and flowdown purposes
- COMPLIANCE STATUS -tracking of expected compliance at certain design phases

Note that more verification fields may be added at any time, depending on the Verification Plans as they are developed.

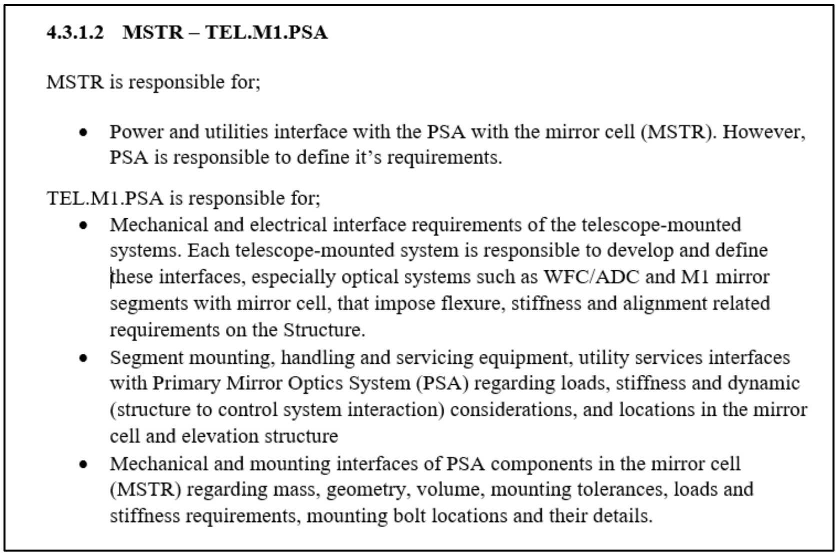
Note also that DOORS NG provides the ability to export the requirements as documents for the purpose of gaining signatures and approvals within the Configuration Management Process at periodic intervals during the lifecycle of the project.

Once the requirements are imported to DOORS NG, and the linking and traceability analysis are complete as discussed in a previous section, then proposed changes to any given requirement can flag what their impact both up and down the traceability chains. This will be especially important during the Verification and Test activities of the project.

8. INTERFACE MANAGEMENT

As discussed previously in this paper, the product architecture was developed using functional analysis with all subsystems of MSE being defined. This included identifying the interfaces between subsystems. An Interface Definition Document (IDD) defines all of the known subsystem boundaries and types of interfaces and assigns responsibility to one subsystem or another.

For example, the interface between the Telescope Mount Structure (TEL.MSTR) and Primary Mirror Segment Assemblies (TEL.M1.PSA) Figure 10 shows responsibility and type of interface for the mirror segment being supported by the telescope structure and includes mechanical supports and dynamic interactions, power and utilities.



4.3.1.2 MSTR – TEL.M1.PSA

MSTR is responsible for;

- Power and utilities interface with the PSA with the mirror cell (MSTR). However, PSA is responsible to define it's requirements.

TEL.M1.PSA is responsible for;

- Mechanical and electrical interface requirements of the telescope-mounted systems. Each telescope-mounted system is responsible to develop and define these interfaces, especially optical systems such as WFC/ADC and M1 mirror segments with mirror cell, that impose flexure, stiffness and alignment related requirements on the Structure.
- Segment mounting, handling and servicing equipment, utility services interfaces with Primary Mirror Optics System (PSA) regarding loads, stiffness and dynamic (structure to control system interaction) considerations, and locations in the mirror cell and elevation structure
- Mechanical and mounting interfaces of PSA components in the mirror cell (MSTR) regarding mass, geometry, volume, mounting tolerances, loads and stiffness requirements, mounting bolt locations and their details.

Figure 10. MSE example interface description

During the Preliminary Design Phase of the project, the subsystem designers will be responsible for developing Interface Control Documents (ICDs) based on the IDD, one for each identified interface.

To ensure consistency, MSE has an ICD document template which includes placeholder sections to describe:

- Location of all interfaces in the context of the observatory, with respect to the observatory coordinate system
- Optical Interfaces
- Mechanical interfaces
- Access and Handling interfaces
- Communication, Software and Control Interfaces
- Services and Utilities Interfaces
- Safety Interfaces

Interface definitions are expected to be refined over time as the subsystem develops detailed functional analysis for their subsystems and refine their designs. This activity will be coordinated and tracked by the PO. During the Preliminary Design Phase, both parties will participate in drafting and developing the interfaces. This may involve one or many iterations between the design teams with agreement being reached before the Preliminary Design Phase comes to an end. In further phases of the project, changes and developments will be tracked under a Change Control Board Process (see later section of this paper).

Progress for the large number subsystem interfaces will be tracked on an ongoing basis by the PO's Project Engineers, with the oversight of the Systems Engineer. One preliminary tool for tracking this work is a typical N^2 diagram Figure 10 which is used as a quick reference for defining and tracking all interfaces that exist.

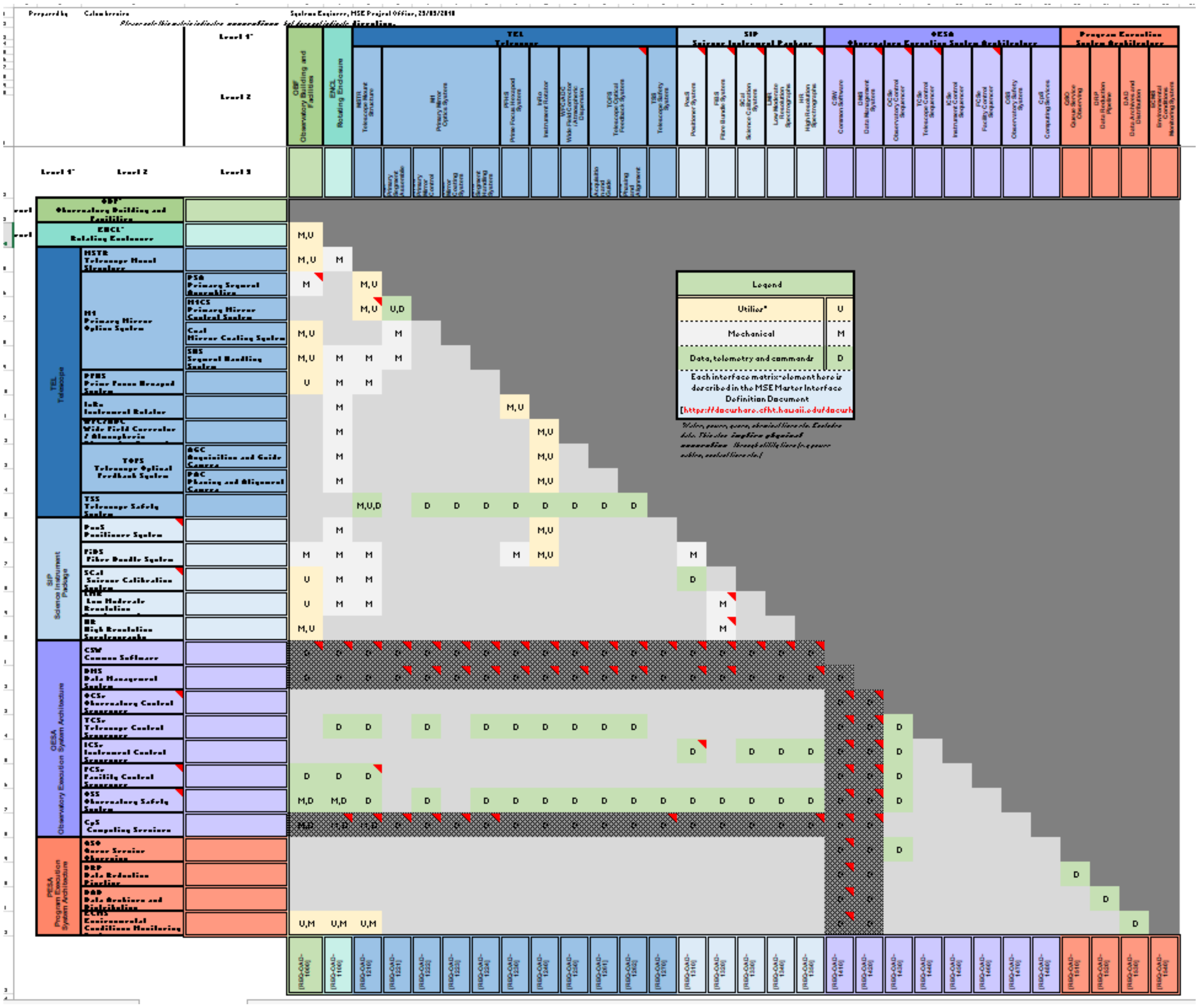


Figure 11. MSE N-squared interface diagram

9. RISK MANAGEMENT

MSE maintains a risk register for the project at a system-wide level. This was completed to a conceptual level of detail and will be further developed in future work.

Each subsystem will be asked to provide a subsystem risk register and these will be rolled up to an overall risk mitigation strategy. The risk register is the responsibility of the PM and therefore is not discussed here.

10. CONFIGURATION MANAGEMENT AND CHANGE CONTROL

MSE maintains the baseline configuration of the observatory and makes it available to the entire project team and stakeholders through the full project lifecycle. This is the responsibility of the Project Manager in MSE and is described in detail in [7] and so is only touched on briefly here.

MSE captures the baseline design in a document archive. To make the baseline design easy to find, a Configuration Index Document (CID) lists the individual documents and items that describe the design, along with the status of their most recent revisions. The documents and tools discussed in this paper, such as the five so-called defining documents, the subsystem Design Requirement Documents and Interface Control Documents are listed in the CID. In addition, the CID also lists design descriptions documents, analysis reports and models (such as CAD or Zemax models) that together make up the configuration of the observatory.

Changes can be needed to DRDs, ICDs and many other documents. These are managed via a Change Control Board with appropriate levels of approval for any and all changes to the baseline of the observatory. Subsystems are responsible for proposing changes to the baseline at appropriate times, and following the change control procedures as defined.

11. QUALITY MANAGEMENT

Quality Management includes a defined set of policies, procedures, tools and training to ensure that quality is maintained. As well, during development phases, MSE will verify that Quality Assurance procedures are followed and that deliverables meet quality standards. For the Preliminary Design Phase, the PO will be defining the Quality Management System and producing the tools and resources needed for subsystems to follow consistently. Subsystems will then show how they will adhere to the Quality Management System over the lifecycle of the project. MSE will define standardized process and document templates and tools to maintain consistency across the project. This is future work for the PO.

12. VERIFICATION AND TEST

Verification of requirements is a cornerstone of Systems Engineering and the MSE PO will write a verification plan to verify the system as a whole. Individual subsystems will be asked to create subsystem specific verification and test plans for their components and subsystems based on a standardized process and document templates and tools to maintain consistency across the project.

During the Preliminary Design Phase, subsystem designers will update their Design Requirements Documents with guidance from the PO. During this process, each requirement will have a generic verification method described. Generic verifications methods are limited to:

- analysis (use of mathematical modeling and analytical techniques to predict the compliance of a design to its requirements based on calculated data or data derived from lower system structure end product validations),
- inspection (visual examination of a realized end product to validate physical design features or specific manufacturer identification), or
- test (use of a realized end product to obtain detailed data to validate performance or to provide sufficient information to validate performance through further analysis).

Subsystems will then be asked to identify at what stage each verification will happen. In future project phases, the verification method and stage will be one input to the subsystem verification plans which will then include the details of types of test, inspection or analysis are necessary and when in the overall project schedule they will need to occur.

When verification activity is ongoing, the PO will oversee requirements verification activities and sign-off on results, track open verification issues and develop a plan to address those issues. The planning for this is future work.

13. CONCLUSION

The current Systems Engineering effort at MSE is focused on development of the observatory system by primarily understanding its scientific needs and then define an accurate set of system and subsystem requirements. The Project Office continues to decompose and allocate these system level requirements into subsystem requirements and is using tools and processes that will help ensure consistent application in the areas of System Design and Analysis, Requirements Definition and Decomposition, Technical Budgeting, Requirements and Interface Management, Configuration Management and Change Control, Quality Management and Verification and Test Procedures. The status of planning for these activities varies depending on topic but is appropriate considering MSE has not yet entered Preliminary Design Phase of project.

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