THIRTY METER TELESCOPE

OBSERVATORY ARCHITECTURE DOCUMENT

TMT.SEN.DRD.05.002.CCR20

March 27, 2009

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1. INTRODUCTION

1.1 INTRODUCTION

This is the TMT Observatory Architecture Document (OAD). It is one of the three systems engineering level requirement documents, the others being the Operations Concept Document (OCD), and the Observatory Requirements Document (ORD).

The three documents are the project's response to the science requirements encapsulated in the Science Requirements Document (SRD). The requirements in these documents flow down to requirements for the observatory subsystems.

As necessary, concepts and requirements respond to the TMT Science Requirements Document (SRD), and flow down from the Operations Concept Document (OCD), and the Observatory Requirements Document (ORD).

As necessary, new requirements implied by the current document flow down into the Level 2 Subsystem Requirements Documents.

The requirements in this document are numbered in the form [REQ-X-Y-Z], where the placeholders X, Y and Z denote the level of the requirement, the document the requirement is associated with, and a unique number for the requirement. This numbering scheme allows for unambiguous reference to requirements.

1.2 PURPOSE

The Observatory Architecture Document (OAD) defines the architecture for the observatory, including system wide implementation details, and the subsystem decomposition. It partitions function and performance requirements among the subsystems, as necessary to ensure the integrated systems level performance of the observatory.

It does not contain requirements that define the overall performance of the observatory as viewed in the context of the top level Science Requirements Document (SRD). These high level requirements are contained in the OCD and the ORD.

1.3 SCOPE

This document contains high-level site specific requirements in the following areas:

- Observatory Subsystem Decomposition
- Reliability and Availability Budgets
- Image Size Error Budget for Seeing Limited Operations
- Wavefront Error Budget for Adaptive Optics Operations
- Pointing Error Budget
- Pupil Shift Budget
- Other Performance Budgets
- Telescope
- Instrumentation
- Services

- Facilities
- Servicing and Maintenance
- Safety
- Observatory Control Architecture
- Observatory Software Architecture
- Coordinate Systems

1.4 ASSUMPTIONS

All geometric dimensions contained within this document are specified at the expected sub-system temperature during observing conditions, e.g. the telescope structure, optics and enclosure are at the ambient observing temperature, instruments are at their expected steady state operating temperatures.

1.5 APPLICABLE DOCUMENTS

AD1 – Science-Based Requirements Document (TMT.PSC.DRD.05.001)

AD2 – Observatory Requirements Document (TMT.SEN.DRD.05.001)

AD3 – Operations Concept Document (TMT.OPS.MGT.07.002)

AD4 – TMT Acronym List (TMT.SEN.COR.06.018)

AD5 – International Building Code, International Code Council
(http://www.iccsafe.org/e/catalog.html)

AD6 - ICC Electrical Code, International Code Council
(http://www.iccsafe.org/e/catalog.html)

AD7 - International Mechanical Code, International Code Council
(http://www.iccsafe.org/e/catalog.html)

AD8 - International Plumbing Code, International Code Council
(http://www.iccsafe.org/e/catalog.html)

AD9 - International Fire Code, International Code Council
(http://www.iccsafe.org/e/catalog.html)

AD10 - Civil Engineering Standard ASCE 7-98 “Minimum Design Loads for Buildings and Other Structures”
(http://www.pubs.asce.org/)

AD11 – Part 1910 Occupational Safety and Health Standards
(http://www.osha.gov/pls/oshaweb/owastand.display_standard_group?p_toc_level=1&p_part_number=1910)

AD12 – MIL-STD-461E: “Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment”
(http://www.emclab.umr.edu/pdf/M461E.pdf)

AD13 - MIL-STD-810F: “Department of Defense Test Method Standard for Environmental Engineering Considerations and Laboratory Tests”
(http://www.weibull.com/mil_std/mil_std_810f.pdf)

AD14 - American Institute of Steel construction Load and Resistance Factor Design, http://www.aisc.org/

1.6 REFERENCE DOCUMENTS

RD1 - TMT WBS Dictionary (TMT.SEN.SPE.05.005)

RD2 – TMT Observatory Reliability and Availability Budget, TMT.SEN.TEC.07.005

RD3 – TMT Image Size and Wavefront Error Budgets volumes 1, 2, and 3 (TMT.OPT.TEC.07.001, TMT.OPT.TEC.07.002, TMT.OPT.TEC.07.003)

RD4 – B. J. Seo et al. *Analysis of Normalized Point Source Sensitivity as a performance metric for the Thirty Meter Telescope*, Proceedings of the SPIE, vol.7017, 2008

RD5 – Pupil Stability Error Budget, (TMT.SEN.CCD.07.001)

RD6 – M. S. Bessel, Annu. Rev. Astron. Astrophys. 43, pp293-336, 2005

RD7 - Gemini Observatory and S. D. Lord, NASA Technical Memorandum 103957, 1992

RD8– Relationship between the Science Productivity Metric and normalized Point Source Sensitivity metric, **TMT.SEN.TEC.08.030.DRF03**

RD9- K. Vogiatzis and G. Z. Angeli, *Monte Carlo simulation framework for TMT*, TMT.SEN.JOU.08.002.DRF03

RD10 Impact of Observatory Wavefront Errors upon DM Stroke Requirements for NFIRAOS TMT.AOS.TEC.08.028.DRF01

1.7 CHANGE RECORD

Revision	Date	Section	Modifications
CCR20	March 27 2009		• Updates as per Level 1 DRD Change History Document, TMT.SEN.TEC.07.038.REL05
CCR19	January 28' 2009		• Updates as per Level 1 DRD Change History Document, TMT.SEN.TEC.07.038.REL04
CCR18	September 4, 2008		• Updates as per Level 1 DRD Change History Document, TMT.SEN.TEC.07.038.REL03
CCR 17	March 19, 2008		• Updates as per Level 1 DRD Change History Document, TMT.SEN.TEC.07.038.REL02
CCR 16	November 14, 2007		• Updates as per Level 1 DRD Change History Document, TMT.SEN.TEC.07.038.REL01
CCR 15	October 19, 2007		• Updates as per systems engineering watch list document TMT.SEN.TEC.07.025.REL14

CCR 14	August 14, 2007	3.4.3	• Change to REQ-1-OAD-0595
		4.1.2	• Added REQ-1-OAD-1080, 1085
		4.1.3.3	• Change to REQ-1-OAD-1310
		4.1.3.7.1	• Modification to discussion point after REQ-1-OAD-1385.
		4.1.3.7.5	• Update to REQ-1-OAD-1460
			• Added REQ-1-OAD-1461, 1467, 1472, 1473, 1482
		4.1.3.7.7	• Addition of REQ-1-OAD-1492
		4.1.3.7.12	• Added REQ-1-OAD-1580, 1585, 1590
		4.1.5.1	• Added REQ-1-OAD-1692, 1694
		4.1.5.2	• Updated Figure 6 (Primary Mirror Layout)
		4.1.6.1	• Deleted REQ-1-OAD-1810, 1815
		4.2.2	• Change to REQ-1-OAD-2760
		4.2.4	• Change to REQ-1-OAD-2940
		4.3.2.1	• Added REQ-1-OAD-4705, 4710
		4.4.1.4	• Added REQ-1-OAD-5257, 5258
		4.5.1	• Update of Crane System requirements, Requirements REQ-1-OAD-6200 through 6275.
		4.6.4.1	• Added REQ-1-OAD-7230, 7235
CCR13	May 25, 2007		• *Updates as per proposed errata and updates as documented in TMT.SEN.TEC.07.025.DRF05, including:*
		4.1.2.5	▪ Add Cable Wrap requirements.
		4.1.2.7.2	▪ Update Table 8 to include WIRC and planned 1st decade instrument positions on NFIRAOS.
		4.1.2.7.2	▪ Update OAD requirement [REQ-1-OAD-1415] to include WIRC
		4.1.2.7.1	▪ Update of equation in [REQ-1-OAD-1385]

DRF12	May 12, 2007	2.1.2 3.7 4.1.2. 4.1.4 4.1.5 4.1.6 4.1.7 4.4.1.2 5.1.4.2 General	• *Renamed M2 Optics System and M3 Optics system to M2 System and M3 System* • *Added Other Performance Budgets Section* • *Additions and modifications to Telescope Structure Section* • *Additions and modifications to M1 Optics System Section* • *Additions and modifications to M2 System Section* • *Additions and modifications to M3 System Section* • *Additions and modifications to M1CS Section* • *Additions and modifications to Enclosure Geometry Section* • *Additions and modifications to Active Optics Actuators Section* • *Document renumbering and editing*
DRF11	May 7, 2007	1.5 3.6 4.1.1 4.1.3 4.1.4.2 4.1.5 4.1.7 4.1.8	• *Updated References* • *Updated pupil alignment budget* • *Updated pupil obscuration figure* • *Added mirror coating requirements* • *Added requirement for pupil obscuration due to segment gaps.* • *Updated M2 optical requirements* • *Added M1CS Section* • *Updated APS section*
DRF10	May 1, 2007	Numerous changes	***Update after April 24th and 25th review***
DRF09	April, 2007		***Complete reorganization and rewrite***

1.8 ABBREVIATIONS

The abbreviations used in this document are listed in the project acronym list [AD4]

2. SYSTEM DEFINITION

2.1 OBSERVATORY SYSTEM DECOMPOSITION

2.1.1 System Decomposition

The TMT System decomposition identifies WBS [RD1] elements that are not just tasks, but also deliverable subsystems of the observatory. The list of subsystems below is comprehensive, i.e. the aggregate of these subsystems will form the complete observatory.

[REQ-1-OAD-0100] The TMT System shall be decomposed into subsystems as shown in Table 1 .

Table 1 TMT System Decomposition

System	Related WBS Element(s)
Enclosure (ENC)	TMT.FAC.ENC
Summit Facilities (SUM)	TMT.FAC.INF.SUM
Road (ROAD)	TMT.FAC.INF.ROAD
Support Facilities (SUPP)	TMT.FAC.INF.SUPP
Observatory Headquarters (HQ)	TMT.FAC.INF.HQ
Site Construction Camp (CAMP)	TMT.FAC.INF.CAMP
Observatory Safety System (OSS)	TMT.FAC.OSS
Telescope Structure (STR)	TMT.TEL.STR
M1 Optics System (M1)	TMT.TEL.OPT.M1
M2 System (M2)	TMT.TEL.OPT.M2
M3 System (M3)	TMT.TEL.OPT.M3
Optical Cleaning Systems (CLN)	TMT.TEL.OPT.CLN
Optical Coating System (COAT)	TMT.TEL.OPT.COAT
Test Instruments (TINS)	TMT.TEL.OPT.TINS
Optics Handling Equipment (HNDL)	TMT.TEL.OPT.HNDL
Alignment and Phasing System (APS)	TMT.TEL.CONT.APS
Telescope Control System (TCS)	TMT.TEL.CONT.TCS
Mount Control System (MCS)	TMT.TEL.CONT.MCS
M1 Control System (M1CS)	TMT.TEL.CONT.M1CS
Test Instrument Control (TINC)	TMT.TEL.CONT.TINC
Telescope Safety System (TSS)	TMT.TEL.CONT.TSS
Engineering Sensors (ESEN)	TMT.TEL.CONT.ESEN
Power, Lighting, and Grounding (PL&G)	TMT.TEL.CONT.POWR
Narrow Field Near Infrared On-Axis AO System (NFIRAOS)	TMT.INS.AO.NFIRAOS TMT.INS.AO.COMP.PCVWFS.NFIRAOS, TMT.INS.AO.COMP.RTC.NFIRAOS, TMT.INS.AO.COMP.WC.NFIRAOS
NFIRAOS Science Calibration Unit (NSCU)	TMT.INS.INST.NSCU
Laser Guide Star Facility (LGSF)	TMT.INS.AO.LGSF,

	TMT.INS.AO.COMP.SLASR
Adaptive Optics Executive Software (AOESW)	TMT.INS.AO.AOESW
InfraRed Imaging Spectrometer (IRIS)	TMT.INS.INST.IRIS TMT.INS.AO.COMP.IRWFS.IRIS
Wide Field Optical Spectrometer (WFOS)	TMT.INS.INST.WFOS
IRMS/MOSFIRE (IRMS)	TMT.INS.INST.IRMS TMT.INS.AO.COMP.IRWFS.IRMS
Communications and Information Systems (CIS)	TMT.DEOPS.CIS
Data Management System (DMS)	TMT.DEOPS.OSW.DMS
Executive Software (ESW)	TMT.DEOPS.OSW.ESW
Science Operations Support Systems (SOSS)	TMT.DEOPS.OSW.SOSS
Data Processing System (DPS)	TMT.DEOPS.OSW.DPS
Site Conditions Monitoring System (SCMS)	TMT.DEOPS.SCMS

2.1.2 System decomposition element descriptions

2.1.2.1 *Enclosure (ENC)*

[REQ-1-OAD-0125] The Enclosure system decomposition element is defined as follows:

Associated WBS element(s): TMT.FAC.ENC

The TMT Enclosure System is a dome structure housing the telescope. The three principal enclosure subsystems are the rotating base, cap and shutter. The base and cap are a part of a continuous spherical shell split by a plane (cap / base interface plane) inclined at a 32.5° relative to a horizontal reference plane (half of the maximum zenith angle). Combined rotation of the rotating base and cap provides a range of required azimuth and zenith angles. The shutter is a rotating structure enabling opening and closing of the aperture.

Main components of the rotating base include rib and tie framework, exterior structural skin and two ring girders stiffening the base edges. The rotating base incorporates ventilation doors and supporting structure responsible for providing adequate aerodynamic ventilation during observation. Other rotating base components include cap/base walkway and non-structural insulation panels. The rotating base rotates in the azimuth direction. The cap incorporates an aperture opening and is constructed in a similar manner as the rotating base. Cap rotates about an axis perpendicular to cap/base interface plane. The shutter structure is located inside the cap and consists of an open framework of steel tubing supporting an aluminium plug structure. The shutter rotates about the same axis as the cap. The system incorporates a set of external aperture flaps designed to provide enhanced wind protection of the M2.

Enclosure mounted cranes and hoists enable service and handling of large components inside the enclosure. The enclosure incorporates components to provide adequate safety for the observatory personnel and visitors. The enclosure also includes the M2 servicing platform and lighting.

2.1.2.2 *Summit Facilities (SUM)*

[REQ-1-OAD-0128] The Summit Facilities system decomposition element is defined as follows:

Associated WBS element(s): TMT.FAC.INF.SUM

The summit facilities are the infrastructure located adjacent to, or nearby, the enclosure and telescope that are required to operate TMT. The summit facilities include a Primary Summit Facility that contains the control room; computer room; conference room; office space; space for hydrostatic bearing equipment; an electrical equipment room; rooms for mirror stripping, recoating, and storage; engineering and mechanical shops; a safety equipment room, and spaces for support services such as restrooms and janitor's closets. The primary facility also includes overhead and monorail cranes that are mounted to the building structure, and mechanical and electrical equipment integral to the primary facility.

The summit facilities also include a Summit Utility Building that houses equipment that generate heat or are sources of vibration. This building is located on the summit, but is physically separated from the enclosure and telescope to minimize the affect of any heat plumes from the equipment and to minimize the transmission of vibrations to the telescope. Equipment located in this building are the main electrical transformers and switchgear, chillers, compressors, pumps and cryogenic equipment. Some mechanical equipment may be located in the Primary Facility depending on the site selected.

The summit facilities also include the Enclosure Fixed Base. This is the lower portion of the enclosure and includes the active air conditioning system for maintaining the enclosure interior air temperature near the nighttime air temperature, utility tunnel to the cable wrap at the telescope pier, provisions for power, signal, chilled water and other utilities required to operate the telescope, rotating enclosure, and the fixed base itself. It includes lighting, the first stage of elevators to the Nasmyth areas. Not included is the rotating enclosure. The interface between the fixed enclosure base and the rotating enclosure is at the enclosure azimuth track.

The telescope pier is included as part of the Enclosure Fixed Base foundation work. The interface between the telescope and the telescope pier is at the telescope azimuth track, with the cable wrap included as part of the telescope. The walkways and stairs around the pier are not included.

2.1.2.3 Road (ROAD)

[REQ-1-OAD-0131] The Road system decomposition element is defined as follows:

Associated WBS element(s): TMT.FAC.INF.ROAD

This is the access road between an existing public road and the Support Facilities and between the Support Facilities and the summit. This road will be an improved gravel road with a width that allows two vehicles to meet or pass without either vehicle having to pull off the road, has a surface and alignment to permit reasonable driving speeds, allows for future paving of the surface, and has curves with sufficiently large radii so that large trucks may easily negotiate the curves. The first kilometer of the road, starting from the summit will be paved with asphalt. Other methods of paving will be used near the telescope and enclosure to minimize emission of heat from the paving.

2.1.2.4 Support Facilities (SUPP)

[REQ-1-OAD-0134] The Support Facilities system decomposition element is defined as follows:

Associated WBS element(s): TMT.FAC.INF.SUPP

The Support Facilities are the infrastructure that provide services to the observatory that need to be located near the telescope and enclosure, but do not need to be located on the summit. These facilities include offices, conferences rooms, lecture hall, mechanical shop, engineering laboratory, shipping and receiving, emergency vehicle garage, safety equipment room, and administrative areas. Also included are electrical generation equipment, electrical distribution equipment, mechanical equipment facilities, electrical shop, welding shop, and warehouse. Chillers, water storage, fuel storage and other equipment that can be located outside will be located in a utility yard. An area for open-air storage and lay down is included.

Dining facilities that include a dining hall, kitchen, and food storage areas are included with the Support Facilities. Also included are accommodations consisting of single-occupancy motel-style bedrooms with private bathrooms, along with supporting facilities. For a high-elevation site, the dining and support facilities may be located away from the base of the mountain and at an elevation below 3,000 meters.

2.1.2.5 *Observatory Headquarters (HQ)*

[REQ-1-OAD-0137] The Observatory Headquarters system decomposition element is defined as follows:

Associated WBS element(s): TMT.FAC.INF.HQ

The Observatory Headquarters house the main administrative functions of the observatory. In the case of a remote site for the telescope, or site that is not near a major metropolitan area, the headquarters will be located in a metropolitan area, and will be the normal work location for many of the science, engineering and technical staff.

The Observatory Headquarters will be rented space, and as such, is not a deliverable for construction.

2.1.2.6 *Site Construction Camp (CAMP)*

[REQ-1-OAD-0140] The Site Construction Camp decomposition element is defined as follows:

Associated WBS element(s): TMT.FAC.INF.CAMP

The Site Construction Camp will provide the full boarding and lodging needs of contractors and TMT personnel during the construction phase of TMT, and will remain in operating condition to serve as overflow capacity after the construction is complete. The Site Construction Camp will utilize a modular approach, such as modified containers, prefabricated units, or similar construction that will allow rapid installation of this facility on site. This facility is required at the remote sites because of excessive commuting time to nearby towns, and to minimize the impact on the environment from individual contractors erecting separate camps.

2.1.2.7 *Observatory Safety System (OSS)*

[REQ-1-OAD-0143] The Observatory Safety System system decomposition element is defined as follows:

Associated WBS element(s): TMT.FAC.OSS

The Observatory Safety System is the top level binding between the interlock and emergency stop (E-stop) subsystems of other observatory system decomposition elements, including the telescope, enclosure, plant facilities, laser and instrumentation systems. The OSS includes the wiring and hardware to interconnect all observatory interlock and emergency stop (E-Stop) systems. The OSS also includes hardware and software to monitor and identify the location of E-stop and interlock trigger events.

The OSS does not include earthquake stops, over-travel or over-speed monitoring, fire suppression systems or emergency lighting. These are the responsibility of the individual subsystems.

2.1.2.8 Telescope Structure (STR)

[REQ-1-OAD-0146] The Telescope Structure system decomposition element is defined as follows:

Associated WBS element(s): TMT.TEL.STR

The Telescope Structure System contains the azimuth track; azimuth and elevation structures that support the telescope-mounted optics and instrumentation; mount control system hardware that enables the telescope to operate over the azimuth and zenith angle range with integrated safety features; crane system for mirror segment handling; alignment fixtures and special tools to support assembly and maintenance; temperature control system; and utility services distribution system.

The main structural components are the azimuth central structure, Nasmyth platforms, mirror cell, elevation structure lower and upper tubes, elevation journals, and the support structures for instruments and LGSF. The mount control system hardware is the hydrostatic bearings including their oil supply system, drive motor system, encoder system, brake system, limit switch and hard stop system, cable tray and cable wrap system for the azimuth and elevation motions. Additional safety features include an elevation structure counterbalance system using a combination of static ballasts and active counterweights; locking system with pins to hold an unbalanced elevation structure at predetermined zenith angles during operation; and walkways, stairs, handrails and elevators for safe and convenient access and servicing throughout the telescope structure and around the telescope pier. The utility services distribution system provides services such as coolant, compressed air, cryogen, power, data and communication to the telescope structure system components and telescope-mounted systems. These services are passed through the cable wraps and delivered to the required locations on the telescope structure. The coolant distribution system is an integral part of the temperature control strategy; in addition, the temperature control system also includes passive and active components to minimize mirror seeing and temperature gradient across the telescope structure.

Not included in the telescope structure system are the telescope pier, or the mechanical plant that supplies power, coolant, compressed air, cabling for power, control and monitoring, lighting, and mount control electronics and cryogens. These items are in the Summit Facilities.

2.1.2.9 M1 Optics System (M1)

[REQ-1-OAD-0149] The M1 Optics system decomposition element is defined as follows:

Associated WBS element(s): TMT.TEL.OPT.M1

The M1 Optics System is the primary mirror of the telescope. It comprises the Primary Mirror Segment Assemblies, which include the polished segments, the, segment support assemblies, the warping harnesses, the adjustable attachment points (to the mirror cell), the lifting jacks used to raise a segment to allow removal, and the spare segments. The segment support assemblies include the segment warping harnesses and their actuators. The M1 Optics System does not include segment cabling, position actuators, edge sensors, control electronics and the corresponding power and coolant distribution systems; these are part of the primary mirror control system (M1CS).

2.1.2.10 M2 System (M2)

[REQ-1-OAD-0152] The M2 system decomposition element is defined as follows:

Associated WBS element(s): TMT.TEL.OPT.M2

The M2 System is the telescope secondary mirror assembly. It includes the M2 Cell (weldment with axial and lateral mirror supports), the polished secondary mirror, the M2 hexapod positioner, the mirror shape control actuators and sensors, the M2 control system and electronics, and the interfaces to the telescope structure including required cables and hoses.

2.1.2.11 M3 System (M3)

[REQ-1-OAD-0155] The M3 system decomposition element is defined as follows:

Associated WBS element(s): TMT.TEL.OPT.M3

The M3 System is the telescope tertiary mirror assembly. It includes the M3 Cell (weldment with axial and lateral supports), the polished tertiary mirror, the M3 positioner, the mirror shape control actuators and sensors, the M3 cable wrap, the M3 control system and electronics, and the interfaces to the telescope structure including required cables and hoses.

2.1.2.12 Optical Cleaning Systems (CLN)

[REQ-1-OAD-0158] The Optical Cleaning system decomposition element is defined as follows:

Associated WBS element(s): TMT.TEL.OPT.CLN

The Optical Cleaning Systems include the CO_2 snow cleaning and liquid cleaning equipment, nozzles, hoses and fixtures for the M1, M2 and M3, while they are on the telescope. It also includes the special attachments that are required to interface the cleaning equipment to the telescope and dome cranes. It does not include the cleaning equipment required for mirror coating, which is included in Optical Coating Systems.

2.1.2.13 Optical Coating System (COAT)

[REQ-1-OAD-0161] The Optical Coating system decomposition element is defined as follows:

Associated WBS element(s): TMT.TEL.OPT.COAT

The Optical Coating system includes the coating chamber with its associated equipment (vacuum pumps, magnetrons, etc.), the equipment used to remove the old reflective coating and wash and dry the mirror, coating laboratory instruments, and fixtures used to support the mirrors during washing and in the coating chamber. It does not include the mirror handling equipment, which is included in Optics Handling Equipment. It also does not include the coating laboratory facility equipment (air compressors, cranes, sinks, drains & sumps or fume hoods) or the utilities for the coating chamber, which are included in Summit Facilities.

2.1.2.14 Test Instruments (TINS)

[REQ-1-OAD-0164] The Test Instruments system decomposition element is defined as follows:

Associated WBS element(s): TMT.TEL.OPT.TINS

The Optical Test Instruments include the prime focus camera with all of its supports, cables, controls, and interfaces and the global metrology system (GMS), which consists of three mounted surveying instruments in insulated, light-tight enclosures, along with the associated controls and cabling.

2.1.2.15 Optics Handling Equipment (HNDL)

[REQ-1-OAD-0167] The Optics Handling system decomposition element is defined as follows:

Associated WBS element(s): TMT.TEL.OPT.HNDL

The Optical Handling Equipment is used to install, remove and transport the optical assemblies of the telescope. It includes all of the lifting and handling fixtures/ frames and transportation carts for M1, M2 and M3 along with the associated lifting accessories, including HydraSets, slings, and connecting hardware. For the M2 and M3, separate lifting fixtures are required for the entire assembly and for the mirror alone. The Optical Handling Equipment also includes the storage racks for the spare segments. It does not include the cranes, which are included in the Telescope Structure. It does not include the crane attachments required for in-situ optics cleaning, which are included in the Optical Cleaning Systems. It does not include the segment jacks, which are included in the M1 Optics System.

2.1.2.16 Alignment and Phasing System (APS)

[REQ-1-OAD-0170] The Alignment and Phasing system decomposition element is defined as follows:

Associated WBS element(s): TMT.TEL.CONT.APS

The Alignment and Phasing System (APS) is responsible for the alignment of the rigid body and surface figure degrees of freedom for the M1, M2 and M3. As part of the alignment process APS will have the capability to phase the 492 M1 segments. APS will use starlight to measure the wavefront errors and then will determine the appropriate corrections to align the optics.

The APS will align the telescope at various elevation angles and then from the set points for the M1, M2 and M3 control systems, lookup tables will be generated to correct for gravity-induced deformations. In a similar fashion, data will be collected at various temperatures over time and lookup tables will be built as a function of temperature as well. APS is not responsible for the generation of the LUTs.

APS includes all the necessary hardware, software, and interfaces (to the TCS; and M1, M2, and M3 control systems) required to accomplish the alignment tasks defined above.

APS will have an acquisition camera with a 1 to 2 arcminute field of view which can be used for telescope pointing, acquisition, and tracking tests. APS will also provide a port where an On-Board Instrument WaveFront Sensor (OIWFS) can be placed in order to test its performance and to validate the active optics control algorithms.

APS will provide an expert user GUI.

2.1.2.17 Telescope Control System (TCS)

[REQ-1-OAD-0173] The Telescope Control system decomposition element is defined as follows:

Associated WBS element(s): TMT.TEL.CONT.TCS

The TCS is responsible for the coordination and control of the various subsystems that comprise the telescope system. The TCS primarily consists of software and the associated off the shelf computer hardware necessary to perform the following functions.

The TCS consists of a Sequencer and Status/Alarm Monitor, a Pointing Kernel, a Corrections Module, and several adaptors. The Sequencer and the Status/Alarm Monitor controls and coordinates the telescope systems based on commands received from the Observatory Control System (OCS) and expert user interfaces. The TCS Sequencer and Status/Alarm Monitor provides high level control of the mount, M1, M2, M3, and the enclosure (cap, base, shutter, vents). The enclosure vents will be controllable individually or via pre-set configurations; the design will provide the hooks enabling future automated control of vent configurations based on environmental conditions

The TCS pointing kernel converts target positions (right ascension and declination) into pointing and tracking demands in the appropriate coordinate system for use by the telescope mount; instrument and AO WFS probes, atmospheric dispersion correctors, rotators; and the enclosure cap and base.

In seeing limited operation the correction module receives and processes focus, tip/tilt, coma and low order radial corrections from an OIWFS that have been reconstructed and rotated into telescope mount, M1, and M2 coordinates. In diffraction limited mode (AO) the corrections are based on an offload of the time averaged position of the AO tip/tilt stage and the DM; up to 100 modes can be offloaded in this configuration. The corrections module also processes data from the Global Metrology System for use by the M1, M2 and M3 systems. The corrections module is also responsible for the creation and management of the M1, M2, and M3 rigid body and shape LUTs.

The TCS contains adaptors to handle differences between vendor and commercially supplied software systems and the core observatory software systems. There will be adaptors for the M2, M3, Enclosure, and Engineering Sensor systems.

The TCS includes an expert user GUI.

2.1.2.18 Mount Control System (MCS)

[REQ-1-OAD-0176] The Mount Control system decomposition element is defined as follows:

Associated WBS element(s): TMT.TEL.CONT.MCS

The MCS provides local servo control of the mount azimuth and elevation axis. The MCS closes a position loop around telescope mounted motors and encoders. The MCS receives pointing and tracking commands from the TCS. Via the TCS the MCS can utilize tip/tilt feedback as measured by an OIWFS or offloaded by the AO system to close a real time optical position loop (guiding). The MCS supports pointing and acquisition, open loop tracking, closed loop tracking (guiding), offsetting, and nodding processes.

The MCS includes insulated and cooled drive cabinets, commutating drive amplifiers, associated switchgear, cables, and input/output devices required to interface with the telescope mounted motors, encoders, limit switches; and the Telescope Safety System.

The MCS contains a servo controller which includes the software and computer hardware required to close a digital control loop around the telescope drives and encoders and interface with the TCS.

Telescope motors and encoders are not part of the TCS; they are included as part of the telescope structure.

The MCS includes an expert user GUI.

2.1.2.19 M1 Control System (M1CS)

[REQ-1-OAD-0179] The M1 Control system decomposition element is defined as follows:

Associated WBS element(s): TMT.TEL.CONT.M1CS

The M1 Control System (M1CS) is responsible for maintaining the overall shape of the segmented M1 mirror despite structural deformations caused by temperature and gravity and disturbances from wind and vibrations (observatory generated and seismic). The M1 set-points are determined from measurements made with the APS.

The M1CS is a distributed control system that includes actuators for 492 segments, sensors for 574 segments (includes sensors for spare segments), electronics mounted and distributed on the telescope mirror cell, telescope and segment mounted cabling, telescope mounted power supplies, a communications bus, control software, and associated computer processing hardware.

The design and packaging of the electronics mounted on the mirror cell will limit the amount of heat released into the local environment. Chilled liquid cooling will be provided to the electronics through the telescope structure.

Installation and calibration equipment required to mount the sensors to the segments is included. Test sets will be provided to enable quick and efficient lab bench testing of PCBs, actuators, and sensors.

The M1CS software will include comprehensive diagnostic capability and an expert user GUI.

2.1.2.20 Test Instrument Control (TINC)

[REQ-1-OAD-0182] The Test Instrument Control system decomposition element is defined as follows:

Associated WBS element(s): TMT.TEL.CONT.TINC

Test Instrument Control includes all electronics and software required to integrate and utilize the Prime Focus Camera (PFC) and the Global Metrology System (GMS). The PFC will be used to verify that the initial 120 segments have been installed correctly and to conduct early pointing and tracking tests. The TINC will provide the electronic, software, and user interfaces to support these measurements and tests. Use of the PFC is not expected past the installation of the first 120 segments.

During operations the GMS will be used to measure the relative positions of the M1, M2, M3 and instruments. This data will be used to update the rigid body LUTs for M2 and M3 as well as the mount pointing model. GMS measurements would take place at the beginning of the night and as part of the science object acquisition process. The TINC will provide the electronics and software required to interface the GMS with the Telescope Control System. It will be possible to utilize GMS measurements in manual and fully automated modes.

The GMS will include an expert user GUI.

2.1.2.21 Telescope Safety System (TSS)

[REQ-1-OAD-0185] The Telescope Safety system decomposition element is defined as follows:

Associated WBS element(s): TMT.TEL.CONT.TSS

The TSS provides for personnel and telescope equipment safety. The TSS will be a stand alone system, based on a Programmable Logic Controller (PLC), and will provide safety via hard wired interlocks and the issuance of audible and software alarms. The TSS will interface with the observatory wide emergency stop (E-stop) system as well as other observatory safety systems. The TSS will be designed as a component of a comprehensive global observatory safety system (See OSS system decomposition element).

Examples of the conditions that the TSS will monitor include telescope over speeds, telescope travel limits, drive motor over currents, dome crane stowed, segment crane stowed, TCS watchdog, cable wrap failure, telescope out of balance, etc.

The TSS will include and expert user GUI.

2.1.2.22 Engineering Sensors (ESEN)

[REQ-1-OAD-0188] The Engineering Sensor system decomposition element is defined as follows:

Associated WBS element(s): TMT.TEL.CONT.ESEN

The ESEN system will provide an array of temperature, wind speed, acceleration, and seismic sensors mounted on and around the telescope. The ESEN system will include the sensors, data acquisition hardware, cables, and software necessary to make the data available on a real time basis via the Observatory Data Management System.

The ESEN system will include an expert user GUI.

2.1.2.23 Power, Lighting, and Grounding (PL&G)

[REQ-1-OAD-0191] The Power, Lighting and Grounding system decomposition element is defined as follows:

Associated WBS element(s): TMT.TEL.CONT.POWR

The PL&G system will distribute dedicated and general purpose AC power throughout the telescope structure. Both clean and dirty power will be distributed. Dedicated primary power will be made available, at a minimum for the following systems; Instruments and AO systems, Telescope Drives, Laser Room, Cable Wraps, Laser Launch Telescope, M1, M2, and the M3 systems; and the Beam Transfer Optics. General utility power will be made available via industry standard keyed and color coded power outlets. Single and Three Phase power will be available; voltages and frequency characteristics are dependent on the site location.

Spot and emergency lighting will be available on the mirror cell, Nasmyth platforms, and walkways.

Clean, dirty, and safety grounds will be distributed on the telescope for use by all telescope mounted equipment. Dedicated isolated grounds will be utilized for sensitive equipment.

2.1.2.24 Narrow Field Near Infrared On-Axis AO System (NFIRAOS)

[REQ-1-OAD-0194] The NFIRAOS system decomposition element is defined as follows:

Associated WBS element(s): TMT.INS.AO.NFIRAOS,
TMT.INS.AO.COMP.PCVWFS.NFIRAOS, TMT.INS.AO.COMP.RTC.NFIRAOS,
TMT.INS.AO.COMP.WC.NFIRAOS

NFIRAOS is a Laser Guide Star, Multi-conjugate Adaptive Optics System (LGS MCAO) system intended to provide atmospheric turbulence compensation in the near IR over a 2’ FOV for up to 3 instruments working in the near IR. Near-diffraction-limited performance is provided over the central 10-30” FOV. NFIRAOS includes several optical tables, 6 LGS WFS, 1 NGS WFS, 1 TWFS, 1 acquisition camera, 2 DMs and a tip/tilt platform (TTP), a source simulator (for natural objects and laser beacons) and all associated entrance windows, beamsplitters, fore-optics, opto-mechanical devices, cooling, electronics and computing systems. It also includes test equipment, which is composed of a high-resolution wavefront sensor, a turbulence generator and miscellaneous fixtures. Instrument rotators, cable wraps, Science ADCs, on-instrument TTF WFSs, rotating lip seals and windows at NFIRAOS exit ports are included in the NFIRAOS-fed instruments and not in NFIRAOS. Also excluded are instrument wavelength and flat field calibration sources.

2.1.2.25 NFIRAOS Science Calibration Unit (NSCU)

[REQ-1-OAD-0195] The NSCU system decomposition element is defined as follows:

Associated WBS element(s): TMT.INS.INST.NSCU

The NFIRAOS Science Calibration Unit (NSCU) provides daytime and nighttime calibrations to NFIRAOS-fed science instruments. Four main sets of calibrations are provided by the NSCU: (1) uniform (flat) illumination for pixel-to-pixel sensitivity corrections, (2) wavelength scale mapping, (3) point-spread-function mapping and (4) characterization of the on-instrument wavefront sensor pointing model. The NSCU consists of two optical systems: an integrating sphere fed by a set of lamps and a patrolling light source mounted on a X-Y-Z stage. The NSCU also includes a rotating pupil mask to simulate the illumination of the telescope onto NFIRAOS, its client instruments and their wavefront sensors. The NSCU is mounted at the front of NFIRAOS.

2.1.2.26 Laser Guide Star Facility (LGSF)

[REQ-1-OAD-0197] The LGSF system decomposition element is defined as follows:

Associated WBS element(s): TMT.INS.AO.LGSF, TMT.INS.AO.COMP.SLASR

The LGSF is responsible for generating the artificial laser guide stars required by the TMT LGS AO systems. The LGSF uses multiple 589 nm lasers to generate and project LGS asterisms of up to 9 guide stars from a laser launch telescope (LLT) located behind the TMT secondary mirror. The LGSF is composed of 3 main subsystems: (i) the laser system (which includes the lasers and the Laser Service Enclosure), (ii) the Beam Transfer Optics and the Laser Launch Telescope System and (iii) the Laser Safety System.

2.1.2.27 Adaptive Optics Executive Software (AOESW)

REQ-1-OAD-0200] The AOESW system decomposition element is defined as follows:

The Adaptive Optics Executive Software is composed of three main software sub-systems: (i) the AO Sequencer, necessary to coordinate all of the AO subsystems and to sequence their AO internal tasks, (ii) the Reconstructor Parameter Generator, necessary to generate the AO reconstruction parameters of the AO system, (iii) and the PSF Reconstructor, dedicated to post-processing the AO PSF. The AO Sequencer of the AOESW controls the actions of the Laser Guide Star Facility (LGSF) and NFIRAOS. The AO Sequencer also controls the wavefront sensors of the NFIRAOS instruments and the wavefront sensing components of the seeing limited instruments. The AO Sequencer does not control the instruments themselves (i.e. IRIS, WFOS, etc.)

2.1.2.28 InfraRed Imaging Spectrometer (IRIS)

[REQ-1-OAD-0203] The IRIS system decomposition element is defined as follows:

Associated WBS element(s): TMT.INS.INST.IRIS, TMT.INS.AO.COMP.IRWFS.IRIS

IRIS is an integral field spectrograph and imager operating at near-infrared wavelengths, fed AO compensated images by NFIRAOS. IRIS includes the entire instrument hardware, including the atmospheric dispersion compensation system, integral field spectrograph, imager, detectors, rotator interface bearing with NFIRAOS, and the NGS wavefront sensor mechanisms, as well as instrument software and control electronics. It includes the NGS wavefront sensor detectors and associated electronics (TMT.INS.AO.COMP.IRWFS.IRIS) and WFS control system. The system also includes dedicated optical test equipment, handling jigs and fixtures, and shipping crates. The deliverable software includes basic data reduction software to ensure a) real time assessment of data quality, b) removal of observatory signatures (eg, mosaic, bias subtraction, bad pixel mask, flat field) and c) reconstruction of data cube for integral field spectroscopy.

2.1.2.29 Wide Field Optical Spectrometer (WFOS)

[REQ-1-OAD-0206] The WFOS system decomposition element is defined as follows:

Associated WBS element(s): TMT.INS.INST.WFOS

WFOS is a wide field, seeing limited multi-object spectrometer and imager. WFOS includes the entire instrument hardware, including the structure and hydrostatic bearings, atmospheric dispersion compensators, calibration unit, ngs wavefront sensors and mini-RTC, focal plane mechanisms, collimators and cameras, and the associated drive electronics and computers, and the control software. WFOS will be delivered with a set of gratings, a set of wide and narrow band filters, and mask frames. A mask making system and mask design software is also a deliverable. The system also includes acquisition and calibration systems, dedicated optical test equipment, handling jigs and fixtures, and shipping crates. WFOS will be upgradeable to a GLAO system, but does not include any of the components such as the lgs wavefront sensors. The deliverable software includes basic data reduction software to ensure a) real time assessment of data quality, b) removal of observatory signatures (eg, mosaic, bias subtraction, bad pixel mask, flat field), and c) reconstruction of data cube for integral field spectroscopy if and IFU mode is implemented.

2.1.2.30 Infrared Multiple Object Spectrograph (IRMS)

[REQ-1-OAD-0209] The IRMS system decomposition element is defined as follows:

Associated WBS element(s): TMT.INS.INST.IRMS, TMT.INS.AO.COMP.IRWFS.IRMS

IRMS is a multislit NIR spectrograph and imager, fed by NFIRAOS. It is a clone of the Keck MOSFIRE instrument that includes a reconfigurable slit unit and NIR spectrograph. IRMS includes all the instrument hardware and software including the rotator bearing interface to NFIRAOS and the NGS WFS mechanisms. It includes the NGS WFS detectors and associated electronics (TMT.INS.AO.COMP.IRWFS.IRMS), and the WFS control system. The system also includes dedicated optical test equipment, handling jigs and fixtures, and shipping crates. The deliverable software includes basic data reduction software to ensure a) real time assessment of data quality, b) removal of observatory signatures (eg, mosaic, bias subtraction, bad pixel mask, flat field).

2.1.2.31 Communications and Information Systems (CIS)

[REQ-1-OAD-0212] The CIS system decomposition element is defined as follows:

Associated WBS element(s): TMT.DEOPS.CIS

Communications and Information Systems (CIS) encompass the IT hardware, software, and cabling necessary to implement the generalized communications backbones and establish connection to Internet. CIS also includes the implementation of a time bus system consisting of a central GPS receiver (with antenna) and a cable-based distribution system out to various patch panels.

2.1.2.32 Data Management System (DMS)

[REQ-1-OAD-0215] The DMS system decomposition element is defined as follows:

Associated WBS element(s): TMT.DEOPS.OSW.DMS

The Data Management System (DMS) provides the mechanisms and interfaces needed to capture, time-stamp, describe, store, and (in some cases) archive all scientific and technical information flowing through the TMT system. It includes the on-site hardware systems needed to store this information securely. The DMS does not include subsystems for data processing - these are found in the Data Processing System.

2.1.2.33 Executive Software (ESW)

[REQ-1-OAD-0218] The ESW system decomposition element is defined as follows:

Associated WBS element(s): TMT.DEOPS.OSW.ESW

The Executive Software (ESW) subsystem enables synchronized operation of all TMT subsystems. The Observatory Control System (OCS) contains the master system sequencer. Other ESW deliverables include interfaces for system operators and observers as well as monitors of system status and overall environmental monitoring. This subsystem enables classical observing for on-site and remote observers.

2.1.2.34 Science Operations Support Systems (SOSS)

[REQ-1-OAD-0221] The SOSS decomposition element is defined as follows:

Associated WBS element(s): TMT.DEOPS.OSW.SOSS

Science Operations Support Systems (SOSS) are a tightly coupled set of applications to manage high-level science operations workflow from proposal preparation through observation execution to data delivery. SOSS includes tools to support: (1) proposal preparation, handling, review, and time allocation; (2) observation preparation, handling, review, and queuing; (3) observation scheduling; (4) observation execution and problem resolution; and (5) data delivery. This system enables queue observing and end-to-end science operations.

2.1.2.35 Data Processing System (DPS)

[REQ-1-OAD-0224] The DPS system decomposition element is defined as follows:

Associated WBS element(s): TMT.DEOPS.OSW.DPS

The Data Processing System (DPS) enables the removal of atmospheric and instrument signatures from data produced by TMT science instruments. It also enables a quick-look and long-term trending data quality assurance process. The DPS has three main components: data processing modules (“recipes”), a library for building recipes and infrastructure for automating data processing workflows. This subsystem enables the creation of observatory-based pipelines for data quality assurance and science data product production.

2.1.2.36 Site Conditions Monitoring System (SCMS)

[REQ-1-OAD-0227] The SCMS system decomposition element is defined as follows:

Associated WBS element(s): TMT.DEOPS.SC

The Site Conditions Monitoring System (i.e. "the weather stations") has two or more stations on the TMT site with sensors to measure such parameters as temperature, wind speed, wind direction, free-air seeing, etc. SCMS data are captured and stored in the observatory database. They are displayed in near-real-time to the TMT system operators via their high-level environmental conditions. They are also available to the TMT community at large via a Web interface.

3. PERFORMANCE ALLOCATION AND SYSTEM BUDGETS

3.1 RELIABILITY AND AVAILABILITY BUDGETS

A detailed discussion of the TMT Observatory Reliability and Availability Budget is given in [RD2].

The maximum unscheduled technical downtime top level value of 3% flows down from the OCD [AD3].

[REQ-1-OAD-0300] The allowable downtime budgets for the observatory subsystems are given in Table 2 (These values are preliminary, and subject to change).

Table 2 Observatory Downtime Allocation

Requirement Number	Budgeted Science Availability 97.00%	Top Down				
		Downtime Allocation				
		3.00%	Level			
	System	1	2	3	4	5
[REQ-1-OAD-0310]	Enclosure	0.17%				
[REQ-1-OAD-0312]	Summit Facilities	0.02%				
	Support Facilities	N/A				
	Observatory Headquarters	N/A				
	Site Construction Camp	N/A				
[REQ-1-OAD-0314]	Telescope Structure	0.02%				
[REQ-1-OAD-0316]	Telescope Optics	0.13%				
[REQ-1-OAD-0318]	M1 Optics System		0.03%			
[REQ-1-OAD-0320]	M2 Optics System		0.05%			
[REQ-1-OAD-0322]	M3 Optics System		0.05%			
	Optical Cleaning Systems	N/A				
	Optical Coating System	N/A				
	Test Instruments	N/A				
	Optics Handling Equipment	N/A				
[REQ-1-OAD-0324]	Telescope Control System (TCS)	0.81%				
[REQ-1-OAD-0326]	Mount Control System		0.08%			
[REQ-1-OAD-0328]	M1 Control System (M1CS)		0.73%			
[REQ-1-OAD-0330]	Sensors			0.17%		
[REQ-1-OAD-0332]	Actuators			0.48%		
[REQ-1-OAD-0334]	Control & misc			0.08%		
[REQ-1-OAD-0336]	Alignment and Phasing System (APS)	0.17%				
	Test Instrument Control (TINC)	N/A				
[REQ-1-OAD-0338]	Telescope Safety, Sensors, Power	0.08%				
[REQ-1-OAD-0340]	Telescope Safety System (TSS)		0.02%			
[REQ-1-OAD-0342]	Engineering Sensors (ESEN)		0.05%			
[REQ-1-OAD-0344]	Power, Lighting, and Grounding (PL&G)		0.02%			
[REQ-1-OAD-0346]	AO Downtime (cf SRD 1%)	1.00%				
[REQ-1-OAD-0348]	NFIRAOS Narrow Field Near Infrared AO		0.4%			
[REQ-1-OAD-0350]	Laser Guide Star Facility (LGSF)		0.5%			
[REQ-1-OAD-0352]	Laser System			0.26%		
[REQ-1-OAD-0353]	Lasers				0.25%	
[REQ-1-OAD-0354]	Individual Lasers					0.85%
[REQ-1-OAD-0355]	Laser Service Enclosure				0.01%	
[REQ-1-OAD-0356]	BTO / LLT			0.23%		
[REQ-1-OAD-0357]	Laser Safety System			0.01%		
[REQ-1-OAD-0358]	AO Executive Software		0.1%			
[REQ-1-OAD-0360]	Instrument Downtime (cf OAD discussions 0.5%)	0.50%				
[REQ-1-OAD-0361]	NSCU		0.025%			
[REQ-1-OAD-0362]	InfraRed Imaging Spectrometer		0.475%			
[REQ-1-OAD-0364]	IRMS/MOSFIRE		0.475%			
[REQ-1-OAD-0366]	Wide Field Optical Spectrometer		0.500%			
[REQ-1-OAD-0368]	Observation Execution Software	0.15%				
[REQ-1-OAD-0370]	Data Management System		0.05%			
[REQ-1-OAD-0372]	Executive Software		0.10%			
	Science Operations Support Systems	N/A				
	Data Processing System	N/A				

3.2 HEAT DISSIPATION BUDGETS

This section will specify the allowable heat leakage to the environment from the observatory subsystems. These allowances are currently TBD.

3.3 IMAGE SIZE ERROR BUDGET FOR SEEING LIMITED OPERATIONS

3.3.1 On-Axis Budget

Discussion: The following error budget provides image jitter and image blur allocations for on-axis images delivered to any instrument location with the telescope pointing to a 30 degree zenith angle, not including the effects of the instrument. Also not included are the effects of image rotators and atmospheric dispersion compensators, as these functions are allocated to the instrument.

Image jitter is the change in image position during an observation. For this document, it is characterized by the corresponding normalized Point Source Sensitivity (PSS$_N$*) value.*

Image blur is the size of the image of a point object at a given time instant. For this document, it is characterized by the corresponding normalized Point Source Sensitivity value.

The balance of the image size error budget defined in this document was advised by [RD3].

Discussion: The normalized Point Source Sensitivity is defined as the square integral of the Point Spread Function of a given observation, normalized to the same integral for the perfect observatory, assuming the same observation:

$$PSS_N = \frac{\iint_{\infty} \left|PSF_{obs+atm}\right|^2 d\alpha}{\iint_{\infty} \left|PSF_{atm}\right|^2 d\alpha}$$

A more detailed discussion of PSS is in [RD4]

Discussion: The error categories of the budget are explained below as Notes to Table 3.

T-A ***Thermal Seeing*** *includes dome and mirror seeing.*

Dome seeing is defined as the optical effect of non-isothermal air turbulence inside the enclosure and in front of the observing opening.

While it is thought of as the adverse effect of the enclosure, for a well designed enclosure dome seeing can be smaller than the atmospheric ground layer seeing it replaces.

Mirror seeing is defined as the adverse optical effect of the air-glass boundary layer at the front surface of the primary mirror due to thermal gradients and heat transfer between the air and the mirror.

M1-A ***Segment Residual Figure Error*** *is quasi-static image degradation due to the non-perfect shape of the M1 segments after correction by the segment warping harnesses. Prior to warping harness correction, the segment surface errors include the (i) residual polishing errors, (ii) uncertainty in the optics shop acceptance testing, (iii) low order passive support errors due to SSA* *manufacturing and installation errors, (iv) effects of the temperature change between optics shop testing and observatory operating temperature, (v) effects of segment warping from coating stress, (vi) virtual segment shape errors due to segment installation and alignment errors (in-plane translation and rotation) . All of these figure errors are partially compensated by the warping harnesses, with the following residuals: (i) fitting errors of the warping harness, including introduced higher order deformations (ii) APS errors in measuring the segment surface, including sensor noise, atmospheric residual, sampling and estimating problems, (iii) warping harness noise (repeatability), and (iv) other potential control loop errors.*

M1-B ***Segment Thermal Distortion*** *accounts for changing segment shape errors due to differences in temperature and temperature distribution between the time of the segment shape measurement used to set the warping harnesses and the actual observation. It includes the combined temperature-induced interaction between the glass and Segment Support System (SSA). Segment-to-segment variations in the mean glass coefficient of thermal expansion (CTE), and CTE gradients are also included.*

M1-C ***Segment Support Print Through*** *includes high order surface distortions associated with the axial and lateral segment support structure, At the 30 degree telescope zenith angle, the segment distortions are in relation to the local segment zenith angles and vary throughout the array due to the curvature of M1. These errors change with telescope zenith angle and account for (i) fabrication and installation tolerances and (ii) the effect of glass weight...*

M1-D ***Segment Drift Errors*** *capture all the errors associated with (i) uncertainties of the system state at segment shape measurements (LUT generation), (ii) system state drift between measurement and observation, and (iii) potential numerical (fitting) issues. An example for the first type is our insufficient knowledge of the actual static wind pressure distribution above M1. An example for the second type is M1 edge sensor drift. An example for the third type is extrapolation error between LUTs. It does not include errors separately addressed in M1-A, M1-B, M1-E, and M1-F.*

M1-E ***Segment In-Plane Displacement*** *addresses the virtual segment shape errors due to rigid body segment in-plane translation and rotation (clocking) tangential to the theoretical primary mirror surface that occur subsequent to the most recent warping harness correction. These displacements can be the results of, (i) gravitational effects that change with zenith angle, and (ii) thermal deformations of the mirror cell and SSA.*

M1-F ***Segment Out-of-Plane Displacement*** *accounts for the optical effects of quasi-static segment rigid body misalignment perpendicular to the theoretical primary mirror surface, in other words segment tip/tilt/piston. These errors are the results of (i) APS measurement and estimation errors, both correlated (atmospheric residual) and uncorrelated (optical sensor noise), (ii) edge sensor calibration and linearity errors, (iii) static wind pressure, and (iv) other potential control loop errors. It's worth to note that this error category may contain global M1 shape errors, besides the local segment to segment displacements. It is also understood that with closed aO loops (OIWFS loops) the measurement and estimation error is a combination of APS and OIWFS related errors.*

M1-G ***Segment Dynamic Displacement Residuals*** *account for the optical effects of segment rigid body misalignment (segment tip/tilt/piston) due to (i) the control residuals of wind buffeting, equipment and microseismic vibrations, as well as (ii)* *edge sensor and segment actuator dynamic noise, and (iii) other potential control loop errors, like A matrix uncertainty.*

M2-A ***M2 Residual Figure Error*** *accounts for image degradation due to the non-perfect shape of M2 after correction by its active optics system. Prior to active optics correction, M2 surface errors include the (i) residual polishing errors, (ii) uncertainty in the optics shop acceptance testing, (iii) effects of the temperature change between optics shop testing and observatory operation, (iv) low order passive support errors due to manufacturing and installation errors, and (v) effects of mirror warping from coating stress. These figure errors are partially compensated by the active optics system, with the following residuals: (i) fitting errors of M2 aO actuators, (ii) shape measurement and estimation errors, either by APS or an off-telescope calibration system, and (iii) M2 aO actuator and sensor noise (repeatability).*

M2-B ***M2 Thermal Distortion*** *accounts for M2 shape errors due to temperature and temperature distribution differences between the time of shape calibration (LUT generation) and the actual observation. It includes the combined effect of glass and support system deformations. The effect of glass CTE variations is also included.*

M2-C ***M2 Shape Drift Errors*** *capture all the errors associated with (i) uncertainties of the system state at M2 shape measurements (LUT generation), (ii) system state drift between measurement and observation, and (iii) potential numerical (fitting) issues. An example for the first type is our insufficient knowledge of the actual static wind pressure distribution above M2. An example for the second type is sensor drift. An example for the third type is extrapolation error between LUTs. It does not include errors separately addressed in M2-A, M2-B, and M2-E.*

M2-D ***M2 Support Print Through*** *includes high order surface distortions associated with the axial and lateral glass support structure, which change with telescope zenith angle. It accounts for (i) finite fabrication and installation tolerances as well as for (ii) the effect of glass weight.*

M2-E ***M2 Dynamic Shape Residual*** *include (i) the control residuals of wind buffeting, equipment and microseismic vibrations, as well as (ii) local M2 shape sensor and actuator noise.*

M3-A ***M3 Residual FIgure Error*** *accounts for image degradation due to the non-perfect shape of M3 after correction by its active optics system. Prior to active optics correction, M3 surface errors include the (i) residual polishing errors, (ii) uncertainty in the optics shop acceptance testing, (iii) effects of the temperature change between optics shop testing and observatory operation, (iv) low order passive support errors due to manufacturing and installation errors, and (v) effects of mirror warping from coating stress. These figure errors are partially compensated by the active optics system, with the following residuals: (i) fitting errors of M3 aO actuators, (ii) shape measurement and estimation errors, either by APS or an off-telescope calibration system, and (iii) M3 aO actuator noise (repeatability).*

M3-B ***M3 Thermal Distortion*** *accounts for M3 shape errors due to temperature and temperature distribution differences between the time of shape calibration (LUT generation) and the actual observation. It includes the combined effect of glass and support system deformations. The effect of glass CTE variations is also included.*

M3-C ***M3 Shape Drift Errors*** *captures all the errors associated with (i) uncertainties of the system state at M3 shape measurements (LUT generation), (ii) system state*

	drift between measurement and observation, and (iii) potential numerical (fitting) issues. An example for the first type is our insufficient knowledge of actual static wind pressure distribution above M3. An example for the second type is sensor drift. An example for the third type is extrapolation error between LUTs. It does not include errors separately addressed in M3-A, M3-B, and M3-E.
M3-D	***M3 Support Print Through*** *includes high order surface distortions associated with the axial and lateral glass support structure, which change with telescope zenith angle. It accounts for (i) finite fabrication and installation tolerances as well as for (ii) the effect of glass weight.*
M3-E	***M3 Dynamic Shape Residual*** *include (i) the control residuals of wind buffeting, equipment and microseismic vibrations, as well as (ii) local M3 shape sensor and actuator noise.*
SB-A	***APS Alignment Error*** *accounts for the less than perfect rigid body alignment of M1 (as a whole), M2, and M3 due to APS measurement and estimation errors, resulting in quasi-static image blur. While telescope misalignment is the result of various M1, M2, and M3 rigid body displacements, the optical effects of these displacements are not necessarily separable or even need to be separated.*
SB-B	***Alignment Drift Errors*** *capture all the small errors associated with (i) uncertainties of the system state at alignment measurements (LUT generation), (ii) system state drift between measurement and observation, and (iii) potential numerical (fitting) issues. An example for the first type is our insufficient knowledge of static wind pressure distribution on the telescope. An example for the second type is sensor drift. An example for the third type is extrapolation error between LUTs.*
IJ-A	***Image Jitter (Control Noise)*** *is a collection of image jitter due to dynamic errors of the local loops controlling the rigid body positions of the mirrors. This term includes (i) tip/tilt noise of the guide sensor (OIWFS), and (ii) local sensor and actuator dynamic noise. The budget breaks down the errors into the degrees of freedom having noticeable effect on image jitter. While the position of M1 (as a whole) is defined against the sky (pointing), M2, M3, and the instruments are positioned relative to M1.*
IB-A	***Dynamic Image Blur (Control Noise)*** *is the image blur corresponding to dynamic errors of the local loops controlling the rigid body positions of the mirrors. This term includes (i) tip/tilt noise of the guide sensor (OIWFS), and (ii) local sensor and actuator dynamic noise. The budget breaks down the errors into the degrees of freedom having noticeable effect on image blur. While the position of M1 (as a whole) is defined against the sky (pointing), M2, M3, and the instruments are positioned relative to M1.*
W-A	***Wind Jitter Residual*** *accounts for all optical surface rigid body motions due to wind buffeting that result in image jitter. The effect of segment rigid body motion is not contained here, only the motion of M1 as a whole. As both the mount control system and the guiding system reduce this wind induced image motion, this error category includes the dynamic residual only (formerly addressed as uncontrolled frequencies).*
W-B	***Wind Blur Residual*** *accounts for all optical surface rigid body motions due to wind buffeting that result in image blur. The effect of segment rigid body motion is not contained here, only the motion of M1 as a whole. As both the mount control system and the guiding system reduce this wind induced image blur, this error category includes the dynamic residual only (formerly addressed as uncontrolled frequencies).*

V-A ***Vibration Jitter Residual*** *accounts for all optical surface rigid body motions due to equipment induced and microseismic vibrations that result in image jitter. The effect of segment rigid body motion is not contained here, only the motion of M1 as a whole. As both the mount control system and the guiding system reduce this image motion, this error category includes the dynamic residual only (formerly addressed as uncontrolled frequencies).*

V-B ***Vibration Blur Residual*** *accounts for all optical surface rigid body motions due to equipment induced and microseismic vibrations that result in image blur. The effect of segment rigid body motion is not contained here, only the motion of M1 as a whole. As both the mount control system and the guiding system reduce this image blur, this error category includes the dynamic residual only (formerly addressed as uncontrolled frequencies).*

Discussion: Observatory performance is a function of the actual environmental and operational conditions and parameters. The PSS image quality error budget is defined under the following conditions [RDXX]:

- *The optical wavelength is 0.5 μm*
- *Image quality is defined on-axis, i.e. at the center of the focal surface*
- *Telescope is pointing to 30° zenith distance (approx. median operating condition)*
- *The atmospheric Fried parameter is 20cm in zenith direction (approx. median seeing for 60 meters above ground at the TMT baseline site, Armazones)*
- The temperature difference between calibration (LUT generation) and observation is 2 C° (median environmental condition at Armazones, assuming ~2 week APS calibration intervals)

Table 3 PSS Image Quality Error Budget

Requirement #	Description	Error allocation				Notes
[REQ-1-OAD-0400]	System (up to the Nasmyth Focus)	0.8500				
[REQ-1-OAD-0402]	Thermal (mirror and dome) seeing		0.9750			T-A
[REQ-1-OAD-0404]	Optical surface shapes		0.8987			
[REQ-1-OAD-0406]	M1 shape			0.9215		
[REQ-1-OAD-0408]	Segment residual figure error				0.9650	M1-A
[REQ-1-OAD-0410]	Segment thermal distortion				0.9980	M1-B
[REQ-1-OAD-0412]	Segment support print through				0.9762	M1-C
[REQ-1-OAD-0414]	Segment drift errors				0.9999	M1-D
[REQ-1-OAD-0416]	Segment in-plane displacement				0.9998	M1-E
[REQ-1-OAD-0418]	Segment out-of-plane residual				0.9910	M1-F
[REQ-1-OAD-0420]	Segment dynamic displacement residual				0.9894	M1-G
[REQ-1-OAD-0422]	M2 shape			0.9873		
[REQ-1-OAD-0424]	M2 residual figure error				0.9900	M2-A
[REQ-1-OAD-0426]	M2 thermal distortion				0.9984	M2-B
[REQ-1-OAD-0428]	M2 shape drift errors				0.9999	M2-C
[REQ-1-OAD-0430]	M2 support print through				0.9991	M2-D
[REQ-1-OAD-0432]	M2 dynamic shape residual				0.9998	M2-E
[REQ-1-OAD-0434]	M3 shape			0.9879		
[REQ-1-OAD-0436]	M3 residual figure error				0.9900	M3-A
[REQ-1-OAD-0438]	M3 thermal distortion				0.9991	M3-B
[REQ-1-OAD-0440]	M3 shape drift errors				0.9999	M3-C
[REQ-1-OAD-0442]	M3 support print through				0.9991	M3-D
[REQ-1-OAD-0444]	M3 dynamic shape residual				0.9998	M3-E
[REQ-1-OAD-0446]	Optical alignment		0.9849			
[REQ-1-OAD-0448]	Quasi-static blur			0.9949		
[REQ-1-OAD-0450]	APS alignment error				0.9950	SB-A
[REQ-1-OAD-0452]	Alignment drift errors				0.9999	SB-B
[REQ-1-OAD-0454]	Image jitter (control noise)			0.9947		IJ-A
[REQ-1-OAD-0456]	M1 jitter (relative to the sky)				0.9970	
[REQ-1-OAD-0458]	M2 tilt jitter (relative to M1)				0.9989	
[REQ-1-OAD-0460]	M2 decenter jitter (relative to M1)				0.9989	
[REQ-1-OAD-0462]	M3 tilt jitter (relative to M1)				0.9999	
[REQ-1-OAD-0464]	M3 piston jitter (relative to M1)				1.0000	
[REQ-1-OAD-0468]	Dynamic image blur (control noise)			0.9996		IB-A
[REQ-1-OAD-0470]	M2 tilt blur (relative to M1)				1.0000	
[REQ-1-OAD-0472]	M2 decenter blur (relative to M1)				0.9997	
[REQ-1-OAD-0474]	M2 piston blur (relative to M1)				1.0000	
[REQ-1-OAD-0476]	M3 piston blur (relative to M1)				1.0000	
[REQ-1-OAD-0480]	Wind residual			0.9982		
[REQ-1-OAD-0482]	Wind jitter residual				0.9986	W-A
[REQ-1-OAD-0484]	Wind blur residual				0.9996	W-B
[REQ-1-OAD-0486]	Vibration (equipment and microseismic residual)			0.9974		
[REQ-1-OAD-0488]	Vibration jitter residual				0.9979	V-A
[REQ-1-OAD-0490]	Vibration blur residual				0.9995	V-B

3.3.2 Off-Axis Budget

[REQ-1-OAD-0500] The seeing limited PSS_N at the Nasmyth focus is allowed to degrade with increasing telescope field angle. At the edge of the 20 arcminute diameter field, at 0.5μm wavelength and r_0 = 20cm in zenith direction, the allowed normalized PSS_N is 0.5339.

Discussion: The image blur of an R-C optical design increases with field angle due to field dependent astigmatism inherent to the design. The corresponding PSS_N value of a perfect telescope is a function of the field angle resulting in a PSS_N of 0.6612 at 10 arcmin (λ=0.5μm, r_0 = 20cm).

When the optical design error is combined with the on-axis error allocation, the resultant error is a PSS_N of 0.5620 at the edge of the FOV. An additional 5% decrease is budgeted in the form of field dependent errors that are due to both the linear functions of the field angle, and field rotation image motion. This additional allowance is leading to a total PSS_N of 0.5339 at 10 arcmin.

3.3.3 Elevation Angle Dependence of the Budget

[REQ-1-OAD-0525] The error budget allocations shall not depend on telescope zenith angle between 0° and 65°.

Discussion: The normalized Point Source Sensitivity metric is normalized to the actual atmospheric seeing. Correspondingly, it accounts for atmospheric conditions, including seeing degradation due to increasing zenith angle.

3.4 WAVEFRONT ERROR BUDGET FOR ADAPTIVE OPTICS OPERATIONS

3.4.1 Facility AO System (NFIRAOS) Error Budget

Discussion: The RMS wavefront error budgets define the allocations at the center of the corrected field. The higher order wavefront error requirements specified for the telescope, instrument, dome, and mirror seeing are to be computed as the fitting and servo lag errors for an idealized (linear, noise free, well calibrated) AO system with a -3dB error rejection bandwidth of 30 Hz and order 60 x 60 wavefront compensation. Any additional wavefront errors due to AO component imperfections should be treated as part of the "Implementation" error term. Table 4 therefore imposes requirements upon both the Facility AO system and the other observatory subsystems introducing these disturbances.

Table 4 NFIRAOS RMS wavefront error budget (60 x 60 actuators, on axis) in nm

REQ-1-OAD-0550	Delivered Wavefront	187			
REQ-1-OAD-0552	First-order turbulence compensation		124		
REQ-1-OAD-0530	LGS control loop			124	
REQ-1-OAD-0531	DM fitting error				72
REQ-1-OAD-0532	DM projection error				50
REQ-1-OAD-0533	LGS WFS aliasing				34
REQ-1-OAD-0534	Tomography error				65
REQ-1-OAD-0535	Servo lag				21
REQ-1-OAD-0536	LGS WFS noise				43
REQ-1-OAD-0554	Opto-mechanical implementation		79		
REQ-1-OAD-0538	Telescope pupil misregistration			12	
REQ-1-OAD-0556	Telescope and observatory OPD			49	
REQ-1-OAD-0558	M1 static shape				30
REQ-1-OAD-0560	M2 & M3 static shape				11
REQ-1-OAD-0562	TMT pupil function				28
REQ-1-OAD-0540	Segment dynamic misalignment				14
REQ-1-OAD-0566	Dome seeing				16
REQ-1-OAD-0568	Mirror seeing				14
REQ-1-OAD-0541	NFIRAOS			53	
REQ-1-OAD-0564	Residual Instrument			30	
REQ-1-OAD-0542	AO components errors & higher order effects		97		
REQ-1-OAD-0543	DM effects			51	
REQ-1-OAD-0544	LGS WFS & Na layer			48	
REQ-1-OAD-0549	LGS WFS non-linearity			25	
REQ-1-OAD-0545	Control algorithm			62	
REQ-1-OAD-0569	Simulation undersampling		26		
REQ-1-OAD-0570	Tip / Tilt WFE at 50% sky coverage		45		
REQ-1-OAD-0546	Residual telescope windshake			17	
REQ-1-OAD-0572	Residual telescope vibration			10	
REQ-1-OAD-0574	Atmospheric servo lag			14	
REQ-1-OAD-0576	Atmospheric tilt anisoplanatism			8	
REQ-1-OAD-0578	NGS WFS noise			13	
REQ-1-OAD-0579	Physical optics			35	
REQ-1-OAD-0547	NGS controlled plate scale modes at 50% sky coverage		16		
REQ-1-OAD-0548	Contingency		30		

3.4.2 Off-Axis Budget

[REQ-1-OAD-0585] The AO system shall correct all off-axis field dependent astigmatism, hence there is no additional error budget allocation for off-axis image quality degradation due to the optical design.

Discussion: As the AO system assumed to correct the field dependent astigmatism inherent to the optical design, there is no additional field dependent error allowed in near diffraction limited observations.

3.4.3 Elevation Angle Dependence of the Budget

[REQ-1-OAD-0595] The residual telescope error budget [REQ-1-OAD-0556] is allowed to degrade the same way as the atmospheric seeing does, i.e. $W_{RMS} \propto \sqrt{\sec z}$ [AD1].

Discussion: For Kolmogorov turbulence, the RMS wavefront error W_{RMS} *of atmospheric seeing is proportional to* $\sqrt{\sec z}$ *.*

Discussion: Based on simulation, from 0 to 65 degrees zenith angle the RMS wavefront error shall increase by a factor of 1.54, resulting in 38.5 nm for a 128 x 128 deformable mirror and 69 nm for a 60 x 60 one.

3.4.4 Wavefront Corrector Stroke Allocation

[REQ-1-OAD-0610] The higher-order wavefront errors induced by telescope aberrations, instrument aberrations, and dome/mirror seeing must be correctable to the error budget allocations listed in section 3.4.1 above using a total wavefront correction of no more than 2 microns RMS. The budgeted optical path difference allocation between these sources is as follows:

Table 5 OPD budget for the correction of Observatory wavefront error source

REQ-1-OAD-0612	Overall Observatory	2μm		
REQ-1-OAD-0614	Local Seeing		1.414	
REQ-1-OAD-0616	Mirror Seeing			1.000
REQ-1-OAD-0618	Dome Seeing			1.000
REQ-1-OAD-0620	Telescope		0.379	
REQ-1-OAD-0622	Static			0.346
REQ-1-OAD-0624	Dynamic			0.154
REQ-1-OAD-0626	NFIRAOS		0.247	
REQ-1-OAD-0628	Common Path			0.175
REQ-1-OAD-0630	Non-Common Path			0.175
REQ-1-OAD-0632	Instrument Aberrations		0.150	
REQ-1-OAD-0634	Contingency		1.348	

Discussion: The tip/tilt/piston removed RMS OPD due to atmospheric turbulence is about 1.5 [2.1] microns for an r_0 of 15 [10] cm and a 30 meter outer scale. Each NFIRAOS DM will provide a total stroke +/- 10 microns of wavefront correction. Treating all wavefront error sources as normally distributed, zero-mean random numbers, we find that the additional wavefront error due to DM saturation is about 6 [24] nm RMS if the observatory wavefront errors are no larger than 2 um RMS. See RD 10

3.5 POINTING ERROR BUDGET

Discussion: Pointing is the operation when the telescope initially settles a given sky point on the center of its focal surface. Pointing error is the distance on the sky between the actual sky point settled on and the intended (theoretical) sky point.

The pointing error budget allocates repeatability errors to the alignment tolerances of the various optical elements. Although the pointing accuracy of the telescope is an absolute measure, it is achieved by intermittent calibration of the pointing system, i.e. building a pointing model. Consequently, the pointing accuracy depends only on the repeatability of the calibration settings and measurements. For this error budget, repeatability is measured as the standard deviation (1 σ) of the pointing on the sky, in arcsec.

[REQ-1-OAD-0650] Pointing error shall be measured on a single calibration camera.

Discussion: Instruments and AO systems in different positions on the Nasmyth platform may experience slightly different pointing errors, depending on the stability and accuracy of the relative positioning of the instrument and calibration camera. (Considering the plate scale of the telescope, a random, 0.5 mm RMS instrument positioning error would result in 0.23 arcsec pointing error. Added in quadrature, it would increase the pointing error with 26 mas.)

Telescope pointing error budget in arcsec:

The pointing error is defined in two dimensions, i.e. we assume statistically independent azimuth and elevation errors.

Table 6 Pointing Error Budget

Telescope		1.00
[REQ-1-OAD-0660]	Residual astrometry	0.2
[REQ-1-OAD-0663]	Mount (encoder)	0.5
[REQ-1-OAD-0666]	Mount/M1 (alignment of elevation/azimuth axes, M1 tip/tilt)	0.5
[REQ-1-OAD-0669]	M2 alignment (relative to M1)	0.6
[REQ-1-OAD-0672]	M3 alignment (relative to M1)	0.4
[REQ-1-OAD-0675]	Pointing camera location (relative to M1)	0.2

3.6 PUPIL SHIFT BUDGET

Discussion: The system pupil shift is defined as the lateral shift of the first primary mirror (entrance pupil) image in the instrument. Further possible pupil shifts introduced by the misalignment of the instrument are not considered here. The pupil budget is based on [RD5]

Table 7 Pupil Shift Budget in RMS, assuming a Gaussian distribution with RMS = 1 sigma.

Requirement Number	**Component**	**Pupil Shift RMS (% of pupil diameter)**
[REQ-1-OAD-0700]	Observatory	0.1
[REQ-1-OAD-0703]	Mount Pointing	0.000
[REQ-1-OAD-0706]	M1 Stability	0.001
[REQ-1-OAD-0709]	M2 Stability	0.026
[REQ-1-OAD-0712]	M3 Stability	0.060
[REQ-1-OAD-0715]	Instrument Stability	0.074

3.7 MASS BUDGET

Table 8 Telescope Mass Budget

Subsystem Decompostion		Mass (not to exceed)				Center of Gravity							Mass moment of Inertia about CofG (max)				Reference	Requirement
Abbreviation	Description	Elevation (tonnes)	Azimuth (tonnes)	Sub-total (tonnes)	Subsystem Total (tonnes)	Coordinate System	Location X (m)	Tol X (m)	Location Y (m)	Tol X (m)	Location Z (m)	Tol X (m)	Alignment of axes	Ix (kg x m^2)	Iy (kg x m^2)	Iz (kg x m^2)		
STR	Telescope Structure				1435.0												TMT.STR.TEC.07.010.REL01	[REQ-1-OAD-0740]
	Elev. Structure	835.0		835.0		ECRS	TBD	± TBD	TBD	± TBD	TBD	± TBD	ECRS	TBD	TBD	TBD		
	Az. Structure		600.0	600.0		ACRS		± TBD		± TBD		± TBD	ACRS	TBD	TBD	TBD		
M1S	M1 System	120.0		120.0	120.0	ECRS	0.000	± TBD	0.000	± TBD	-2.800	± TBD		TBD	TBD	TBD	TMT.OPT.TEC.07.031.DRF01	[REQ-1-OAD-0742]
M2S	M2 System	6.3		6.3	6.3	ECRS		± TBD		± TBD		± TBD		TBD	TBD	TBD	TMT.OPT.TEC.07.034.DRF01	[REQ-1-OAD-0744]
M3S	M3 System	10.5		10.5	10.5	ECRS		± TBD		± TBD		± TBD		TBD	TBD	TBD	TMT.OPT.TEC.07.035.DRF01	[REQ-1-OAD-0746]
TINS	Test Instruments	0.4		0.4	0.4		0.000	± TBD	0.100	± TBD	12.500	± TBD		TBD	TBD	TBD	TMT.OPT.TEC.07.032.DRF01	[REQ-1-OAD-0748]
APS	Alignment and Phasing System				5.4												TMT.INS.TEC.07.004.DRF01	[REQ-1-OAD-0750]
	Instrument (early light)		5.0	5.0		ACRS	-21.160	± TBD	-1.200	± TBD	19.500	± TBD	Local**	3000	5000	8000		
	Instrument (first decade)		same mass			ACRS	-20.531	± TBD	-5.119	± TBD	19.500	± TBD	Local**	3000	5000	8000		
	Electronics + misc Nasmyth		0.4	0.4				± TBD		± TBD		± TBD		TBD	TBD	TBD		
MCS	Mount Control System		2.5	2.5	2.5			± TBD		± TBD		± TBD		TBD	TBD	TBD	TMT.CTR.TEC.07.024.REL01	[REQ-1-OAD-0752]
M1CS	M1 Control System	22.0		22.0	22.0			± TBD		± TBD		± TBD		TBD	TBD	TBD	TMT.CTR.TEC.07.024.REL01	[REQ-1-OAD-0754]
TINC	Test Instrument Controls				0.1			± TBD		± TBD		± TBD		TBD	TBD	TBD	TMT.CTR.TEC.07.024.REL01	[REQ-1-OAD-0756]
TSS	Telescope Safety System				0.1			± TBD		± TBD		± TBD		TBD	TBD	TBD	TMT.CTR.TEC.07.024.REL01	[REQ-1-OAD-0758]
ESEN	Engineering Sensors	1.5		1.5	1.5			± TBD		± TBD		± TBD		TBD	TBD	TBD	TMT.CTR.TEC.07.024.REL01	[REQ-1-OAD-0760]
POWR	Power, Lighting and Grounding	1.0		1.0	1.0			± TBD		± TBD		± TBD		TBD	TBD	TBD	TMT.CTR.TEC.07.024.REL01	[REQ-1-OAD-0762]
NFIRAOS	NFIRAOS				30.0												TMT.AOS.TEC.07.039.DRF01	[REQ-1-OAD-0764]
	Instrument		28.5	28.5		ACRS	-20.900	± TBD	3.200	± TBD	19.100	± TBD		TBD	TBD	TBD		
	Electronics + misc Nasmyth		1.5	1.5				± TBD		± TBD		± TBD		TBD	TBD	TBD		
LGSF	Laser guide star facility				36.0												TMT.AOS.CDD.06.035.REL03	[REQ-1-OAD-0766]
	LGSF LSE		34.0	34.0				± TBD		± TBD		± TBD		TBD	TBD	TBD		
	LGSF BTO Optical Path	0.5 (TBC)	0.5 (TBC)	1.0 (TBC)				± TBD		± TBD		± TBD		TBD	TBD	TBD		
	LGSF Top End	1.0		1.0		ECRS	0.040	±0.434	-0.207	±0.426	26.245	± 0.354		TBD	TBD	TBD	TMT.AOS.CDD.08.001.REL09	
IRIS	IRIS				5.8												TMT.INS.TEC.07.004.DRF01	[REQ-1-OAD-0768]
	Instrument		5.0	5.0		ACRS	-19.338	± TBD	3.108	± TBD	15.817	± TBD	Local*	6300	6300	2500		
	Electronics + misc Nasmyth		0.8	0.8				± TBD		± TBD		± TBD		TBD	TBD	TBD		
IRMS	IRMS				2.3												TMT.INS.TEC.07.004.DRF01	[REQ-1-OAD-0770]
	Instrument + elec		2.3	2.3		ACRS	-18.986	± TBD	6.764	± TBD	19.491	± TBD		TBD	TBD	TBD		
MIRES	MIRES + MIRAO				5.6												TMT.INS.TEC.07.004.DRF01	[REQ-1-OAD-0772]
	Instrument (MIRAO)		2.0	2.0		ACRS	-19.722	± TBD	-8.371	± TBD	20.000	± TBD	Local**	1088	2160	1635		
	Instrument (MIRES)		2.8	2.8		ACRS	-19.031	± TBD	-8.078	± TBD	17.000	± TBD	Local*	3763	3763	788		
	Electronics + misc Nasmyth		0.8	0.8				± TBD		± TBD		± TBD		TBD	TBD	TBD		
PFI	PFI				5.8												TMT.INS.TEC.07.004.DRF01	[REQ-1-OAD-0774]
	Instrument		5.0	5.0		ACRS	-21.674	± TBD	-1.599	± TBD	19.898	± TBD	Local**	6000	13000	15000		
	Electronics + misc Nasmyth		0.8	0.8				± TBD		± TBD		± TBD		TBD	TBD	TBD		
NIRES-B	NIRES				5.8												TMT.INS.TEC.07.004.DRF01	[REQ-1-OAD-0776]
	Instrument		5.0	5.0				± TBD		± TBD		± TBD		TBD	TBD	TBD		
	Electronics + misc Nasmyth		0.8	0.8				± TBD		± TBD		± TBD		TBD	TBD	TBD		
NIRES-R	NIRES				5.8													[REQ-1-OAD-0777]
	Instrument		5.0	5.0				± TBD		± TBD		± TBD		TBD	TBD	TBD		
	Electronics + misc Nasmyth		0.8	0.8				± TBD		± TBD		± TBD		TBD	TBD	TBD		
WIRC	WIRC				4.8												TMT.INS.TEC.07.004.DRF01	[REQ-1-OAD-0778]
	Instrument		4.0	4.0				± TBD		± TBD		± TBD		TBD	TBD	TBD		
	Electronics + misc Nasmyth		0.8	0.8				± TBD		± TBD		± TBD		TBD	TBD	TBD		
WFOS	WFOS				33.0												TMT.INS.TEC.07.004.DRF01	[REQ-1-OAD-0780]
	Instrument		32.0	32.0		ACRS	22.650	± TBD	0.000	± TBD	19.500	± TBD	Local*	463040	463040	196000		
	Electronics + misc Nasmyth		1.0	1.0				± TBD		± TBD		± TBD		TBD	TBD	TBD		
HROS	HROS				38.0												TMT.INS.TEC.07.004.DRF01	[REQ-1-OAD-0782]
	Instrument		37.0	37.0		ACRS	21.000	± TBD	9.000	± TBD	14.500	± TBD	Local**	422417	357667	681417		
	Electronics + misc Nasmyth		1.0	1.0				± TBD		± TBD		± TBD		TBD	TBD	TBD		
IRMOS	IRMOS				15.1												TMT.INS.TEC.07.004.DRF01	[REQ-1-OAD-0784]
	Instrument		13.0	13.0		ACRS	17.854	± TBD	-6.498	± TBD	16.550	± TBD	Local*	50711	50711	260000		
	Electronics + misc Nasmyth		2.1	2.1				± TBD		± TBD		± TBD		TBD	TBD	TBD		
NSCU			2.0	2.0	2.0	ACRS	-17.718	± TBD	1.706	± TBD	19.500	± TBD						
Misc. Nasmyth	Misc. Nasmyth				20.0												TMT.INS.TEC.07.004.DRF01	[REQ-1-OAD-0786]
	+X Side		10.0	10.0				± TBD		± TBD		± TBD		TBD	TBD	TBD		
	-X Side		10.0	10.0				± TBD		± TBD		± TBD		TBD	TBD	TBD		
	Mass Sums	**998.2**	**816.4**	**1814.6**														

*Local	For instruments with cylindrical volumes, the local axis is defined with z parallel with optical axis
**Local Axis	For instruments with volumes defined as a box, the local axis is defined with x parallel to depth, y parallel to width and z parallel to height,

3.8 OTHER PERFORMANCE BUDGETS

3.8.1 M1CS Actuator Range of Travel Budget

Discussion: The range of travel of the M1CS position actuators is budgeted to accommodate the factors listed in Table 9.

Table 9 M1CS Actuator Range of Travel Budget

Requirement Number	**Component**	**Actuator Travel Allowance**
[REQ-1-OAD-0800]	Gravity deflection of Telescope Elevation Structure and M1 Optics System	1.80 mm
[REQ-1-OAD-0802]	Thermal deflection of Telescope Elevation Structure and M1 Optics System	0.42 mm
[REQ-1-OAD-0804]	M1 Subcell installation errors	0.20 mm
[REQ-1-OAD-0806]	Added range for actuator diagnostics	0.25 mm
	Margin	2.33 mm
[REQ-1-OAD-0808]	Total required M1CS Actuator travel	5.00 mm

4. SYSTEM SPECIFICATION

4.1 TELESCOPE

4.1.1 Optical Design

Discussion: The optical design flows from requirements in the ORD, and is documented in [reference Ritchey Chrétien baseline design].

[REQ-1-OAD-1000] The telescope optical design shall be a Ritchey Chrétien (R-C) configuration. See Figure 1.

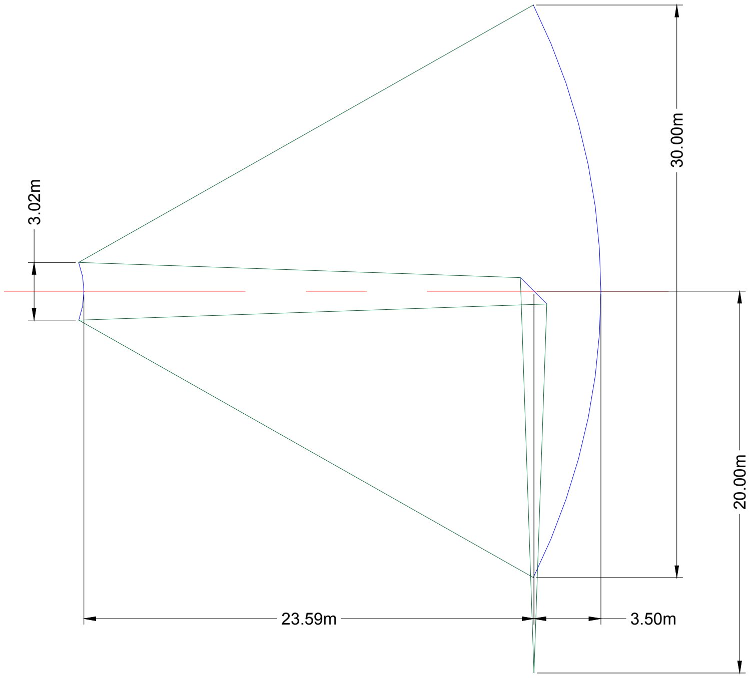


Figure 1 Optical Configuration of the telescope

[REQ-1-OAD-1005] The entrance pupil of the system shall be the primary mirror.

[REQ-1-OAD-1010] The system shall have a flat tertiary mirror, located in front of the primary mirror, to steer the telescope beam to Nasmyth foci.

[REQ-1-OAD-1015] The back focal distance of the system shall be 16.5 m.

Discussion: The BFD is defined as the distance or back relief from the primary mirror vertex to focus in the absence of the tertiary mirror.

[REQ-1-OAD-1020] The system shall provide Nasmyth focus in the horizontal plane containing the elevation axis, along a 20 meter radius circle around the origin of the Elevation Coordinate System (ECRS) for light collection or further light processing.

Discussion: This results in the elevation axis being 3.5 m in front of the primary mirror vertex.

[REQ-1-OAD-1025] Stray light control shall be provided downstream of the telescope optics, in the instrument designs.

[REQ-1-OAD-1030] The pupil obscuration pattern of the telescope shall be as shown in Figure 2.(TBR)

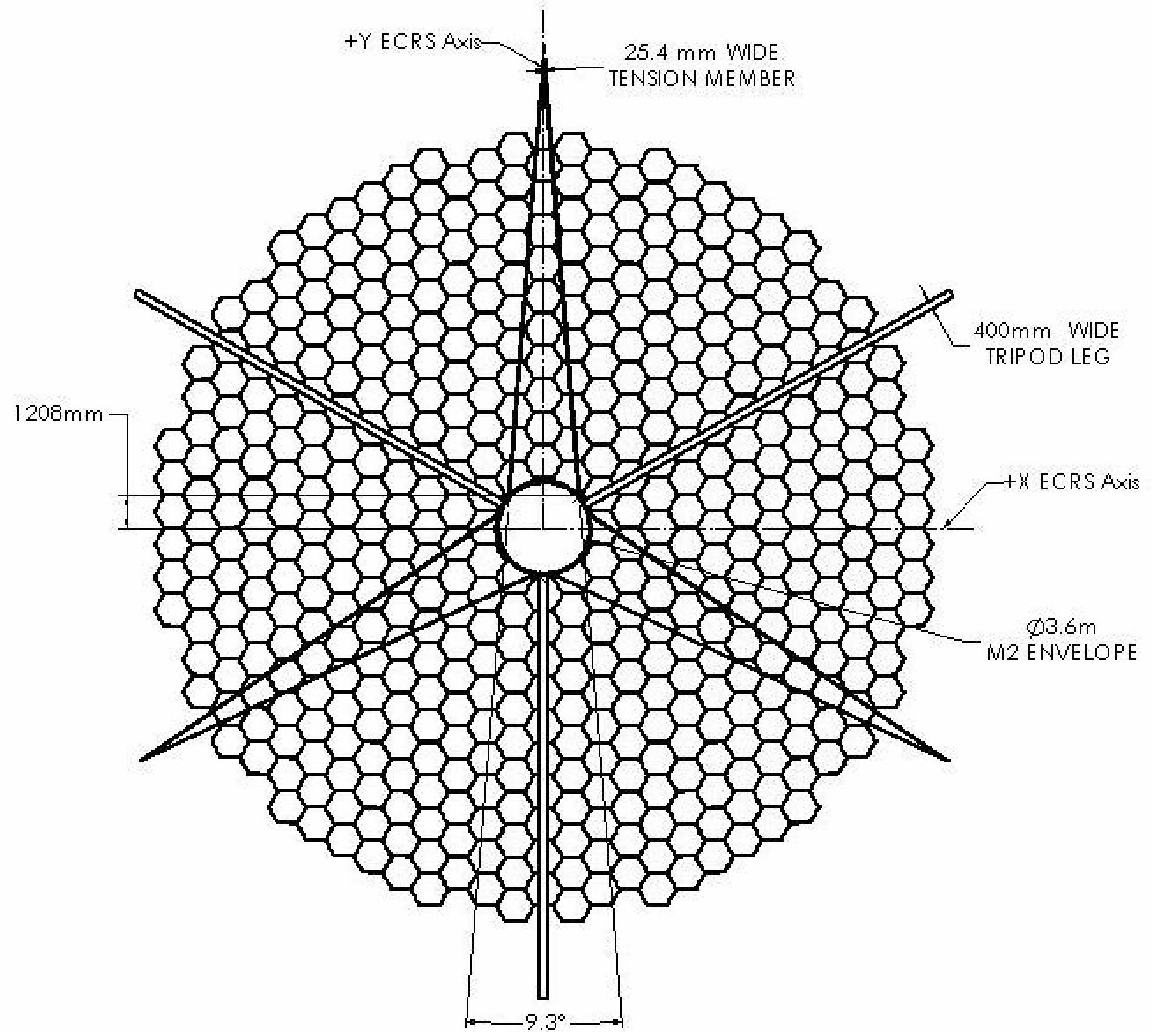


Figure 2 Pupil obscuration pattern

Requirement #	***Parameter***	***Value***
[REQ-1-OAD-1050]	Final focal length and plate scale	450 m and 0.458366 arcsec/mm
[REQ-1-OAD-1052]	Primary mirror vertex radius of curvature	+60.000000 m
[REQ-1-OAD-1054]	Primary mirror conic constant	- 1.00095348
[REQ-1-OAD-1056]	Primary to secondary mirror separation	27.0937500 m
[REQ-1-OAD-1058]	Secondary mirror vertex radius of curvature	- 6.22767857 m
[REQ-1-OAD-1060]	Secondary mirror conic constant	- 1.31822813
[REQ-1-OAD-1062]	Tertiary mirror focal length	Infinity (flat)
[REQ-1-OAD-1064]	Medial Field curvature (concave towards the sky)	3.00923
[REQ-1-OAD-1066]	Unobstructed field of view delivered to foci	20 arcmin
[REQ-1-OAD-1068]	Unvignetted field of view (FOV) based on clear apertures of M2 and M3.	15 arcmin

Table 10 Summary of the optical design

Discussion: positive surface radius of curvature, and field curvature, are concave towards the incoming light to the surface. In the TMT RC design, the M1 is concave towards the sky, M2 is convex towards M1, M3 is flat and the focal plane is concave towards the M3 mirror.

4.1.2 Aerothermal Considerations

[REQ-1-OAD-1080] The maximum transverse cross sectional area of the telescope, when considered from any direction perpendicular to the telescope optical axis and above a plane perpendicular to the optical axis and 14.4m above the telescope elevation axis, shall be less than 44 m^2. The allocation to LGSF, M2S and Telescope Structure is shown in Table 11 below:

Table 11 Maximum Allowable Cross Sectional Area of Telescope Top End

Requirement Number	Sub-System	Maximum Transverse cross sectional area (m^2)
REQ-1-OAD-1090	M2S	4.0
REQ-1-OAD-1092	LGSF Top End	4.0
REQ-1-OAD-1094	LGSF Beam Transfer Tube	6.0
REQ-1-OAD-1096	Telescope Structure	30.0

Discussion: Modeling suggests that only the transverse forces (orthogonal to optical axis) have significant performance effects. It is assumed that the design of the components listed in the table above will give consideration to reducing aerodynamic drag, and that the resulting coefficient of drag will be 1.6 or less. If possible, components should be oriented so that the smallest cross sectional area is presented to wind in the 'Y' direction.

4.1.3 Telescope Structure

4.1.3.1 General

[REQ-1-OAD-1200] The telescope structure shall provide support for the telescope optics and their associated systems, instruments and adaptive optics systems, and provide services and auxiliary systems as additionally specified in this document.

Discussion: Adaptive optics systems include the laser guide star facilities.

[REQ-1-OAD-1205] The telescope mount axes shall allow movement in altitude and azimuth.

Discussion: the telescope pointing is primarily defined by its rotation around the local vertical (azimuth) and its angle relative to the local vertical (elevation).

[REQ-1-OAD-1210] The telescope shall be able to maintain zenith pointing position for prolonged time periods.

[REQ-1-OAD-1215] The telescope shall be able to maintain horizon pointing position for indefinite time period.

[REQ-1-OAD-1220] The telescope shall be able to point to the range of zenith angles from -1° to 90°.

[REQ-1-OAD-1225] The telescope mount axes shall intersect at a single point.

[REQ-1-OAD-1230] The telescope elevation axis shall be above the primary mirror.

[REQ-1-OAD-1235] The intersection of the elevation and azimuth axes shall be coincident with the center of the enclosure radius.

[REQ-1-OAD-1240] The observatory floor shall be at the level of the external grade.

[REQ-1-OAD-1245] No point on the telescope, including equipment on the Nasmyth platforms and behind the secondary mirror, shall be more than 28.5 meters from the origin of the ECRS.

[REQ-1-OAD-1250] The Laser Guide Star Facility (LGSF) components shall be supported on the Telescope Elevation Structure (the LGSF Top End and part of the LGSF Beam Transfer Optics Optical Path) and on the Telescope Azimuth Structure (the LGSF laser rooms and part of the LGSF Beam Transfer Optics Optical Path).

[REQ-1-OAD-1255] The height of elevation axis above the azimuth journal shall be 19.5 meters.

[REQ-1-OAD-1260] The foundation of the telescope shall be separated from the foundations of the enclosure and summit facilities.

[REQ-1-OAD-1265] The vibration isolation between the foundations of the telescope and enclosure or summit facilities shall be at least TBD.

[REQ-1-OAD-1270] Except when observing or when necessary in servicing and maintenance mode, the telescope shall be parked in a horizon pointing orientation.

[REQ-1-OAD-1275] The telescope structure shall have repeatable deflections under expected thermal and gravitational loading conditions. Any non-repeatable deflections of the telescope structure (i.e., creep) shall introduce pointing changes no greater than 0.5 arc seconds RMS per month.

[REQ-1-OAD-1280] The telescope structure shall be instrumented with temperature and wind speed sensors to enable configuration of the enclosure vents to manage the local seeing effects.

4.1.3.2 Telescope Azimuth Structure

[REQ-1-OAD-1285] The telescope shall operate from -270º to 270º azimuth angle continuously, without unwrapping.

[REQ-1-OAD-1290] Power and services for all systems mounted on the telescope shall be routed through a cable wrap centered on the azimuth rotational axis.

[REQ-1-OAD-1295] The height of azimuth journal above ground shall be 3.5 meters.

[REQ-1-OAD-1310] The telescope shall support a pair of laser rooms mounted within the azimuth structure on both sides of the _-X_{ECRS} axis.

[REQ-1-OAD-1312] The telescope structure shall provide appropriate stairways and walkways for access and servicing of the laser service enclosures from the observing floor.

Discussion: This includes the LSE, but also the LSE Air Handling Unit and associated pipes as well as the BTO Azimuth Optical Path components located along the side of the LSE.

[REQ-1-OAD-1313] The telescope structure shall be designed to allow the installation and the maintenance of the LSE and the lasers

4.1.3.3 Telescope Elevation Structure

[REQ-1-OAD-1300] The telescope elevation structure shall be mass-moment balanced about the elevation axis.

[REQ-1-OAD-1305] Power and services shall be routed to the telescope elevation mounted systems through a trailing cable train located below the elevation axis.

[REQ-1-OAD-1315] The height of elevation axis above primary mirror vertex shall be 3.5 meters.

[REQ-1-OAD-1320] The maximum transverse wind cross-sectional height of the upper tripod members shall not exceed 0.6 m.

[REQ-1-OAD-1321] The maximum deflections of the interface planes between the telescope and the M2S and LGSF laser launch telescope shall not exceed the values given in Table 12. These limits apply at any observing temperature combined with any elevation angle between 0 and 65º.

Table 12 Maximum allowable deflection of the telescope top end

Requirement Number	Direction	Maximum Allowed Deflection
[REQ-1-OAD-1322]	Axial motion along the primary mirror optical axis relative to the M1 vertex	+/-4mm
[REQ-1-OAD-1323]	Tilt relative to the M1 optical axis	+/-2.5mrad
[REQ-1-OAD-1324]	Translation perpendicular to the M1 optical axis	+/-15mm

4.1.3.4 Telescope Pier

[REQ-1-OAD-1325] The telescope pier structure shall support all load combinations of the telescope and other components supported by the telescope under all operating conditions.

[REQ-1-OAD-1330] The telescope pier design shall incorporate vibration mitigation to minimize the generation and transmission of vibrations to the telescope, instruments, adaptive optics, alignment & phasing, and calibration subsystems (reference error budget).

[REQ-1-OAD-1332] Personnel access shall be provided to the interior of the telescope pier, in order to service the cable wraps and pintle bearing areas.

[REQ-1-OAD-1333] Emergency egress from the pier shall be possible regardless of the position of the telescope in azimuth.

4.1.3.5 Cable Wraps

[REQ-1-OAD-1335] There shall be cable wraps to accommodate the azimuth and elevation motions of the telescope with range and speed compatible to the requirements already specified for azimuth angle range, zenith angle range and maximum slew rates.

[REQ-1-OAD-1340] The cable wrap shall have minimal internal friction and influence on the mount control system. The cable wrap design and performance shall be consistent to the image jitter quality error budget as partitioned to the mount control system.

Discussion: This may result in the need for an actively driven system.

[REQ-1-OAD-1345] The cable wraps will accommodate the distribution of all utilities (coolant, high pressure oil, LN2, etc), power, data and control lines throughout the telescope structure.

Discussion: Feeds to the telescope that bypass the cable wraps are not permitted.

[REQ-1-OAD-1350] The cable wraps shall be sized to have 50% (TBC) reserve capacity for utilities and 100% (TBC) reserve capacity for data and control lines.

[REQ-1-OAD-1355] The cable wrap system, including the associated support structure, shall be designed to facilitate in-situ removal and installation of cables and hoses.

[REQ-1-OAD-1360] The cable wrap system shall provide status and alarm information to the Telescope Safety System for telescope motion interlock during service and repair.

[REQ-1-OAD-1365] The utilities and cables running through the cable wrap system, shall not be damaged from failures of either the cable wrap or telescope drive systems.

[REQ-1-OAD-1370] The lifetime of all cables, hoses and conduits running through the cable wrap system subjected to the cable wrap function shall be greater than the observatory lifetime..

Discussion: It is not for example permitted for the design to be such that cables in the cable wrap need replacement in order to meet the observatory downtime requirements, or for the design to assume the use of redundant cables. It is also possible that a 'design' lifetime is not available for many of the cables when subjected to the constraints of the wrap. For example data sheets for cables are unlikely to account for the additional friction between adjacent lines or between lines and the wrap system itself. In such situations this requirement might be met using a mock-up and an accelerated life test to demonstrate sufficient lifetime.

4.1.3.6 Mount Control System and Drives

[REQ-1-OAD-1375] The mount control system as implemented on the telescope shall exhibit a torque disturbance rejection transfer function relative to open loop, that is equal to or better than that shown in Figure 3.

Discussion: The mount control systems for both elevation and azimuth axes are expected to have bandwidth (loop cross-over frequencies) between 1 and 1.5 Hz while maintaining minimum 6 dB gain margin and 45° phase margin with respect to the ideal structural system. The -3 dB bandwidth for both control systems should be at least 0.5 Hz (the frequency below which the torque rejection is at least a factor of 2 better than open-loop). The ratio of closed-loop to open-loop performance is defined as the Sensitivity transfer function; for open-loop system G and control K then $S=(1+GK)^{-1}$*. The peak magnitude of the sensitivity transfer function should be no more than 2, so that the overall sensitivity is approximately bounded by* $2s^3/(0.5+s^3)$ *where* $s = jf$ *(defined in Hz, not rad/sec). Small deviations from this bound are acceptable, particularly for the azimuth axis. This bound is plotted below, along with representative sensitivity transfer functions for controllers designed for the elevation and azimuth axes of the structure.*

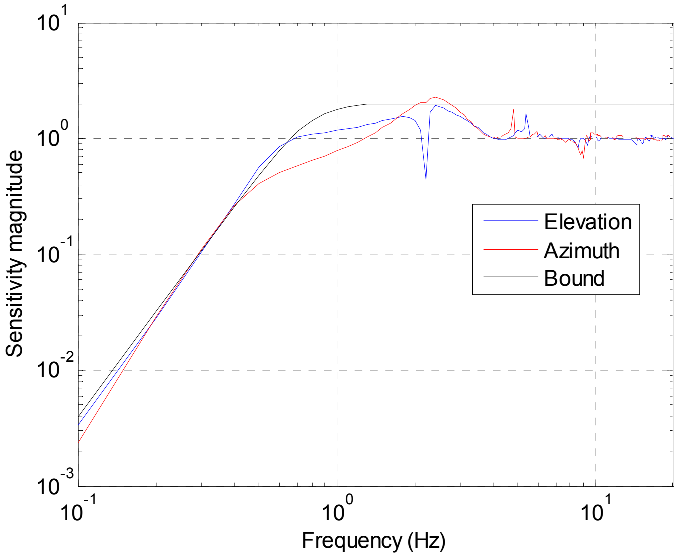


Figure 3. Bound on mount control torque rejection with respect to open-loop. The mount control rejection achieved with the current design is shown for comparison.

4.1.3.7 Nasmyth Platforms and Instrumentation Support

4.1.3.7.1 Performance

[REQ-1-OAD-1380] The telescope shall deliver the image with jitter due to wind effects, relative to an instrument mounted on the Nasmyth platform, less than or equal to the PSD shown in Figure 4.

[REQ-1-OAD-1385] The total image motion at frequencies greater than 10 Hz due to self excitation from internal observatory sources shall be less than 0.23 mas RMS (TBC).

Discussion: Equivalent to encircled energy of 1 mas θ(80). Other vibration sources will increase the overall image jitter and these are difficult to quantify. It is reasonable to expect machinery vibrations at ~30 Hz.

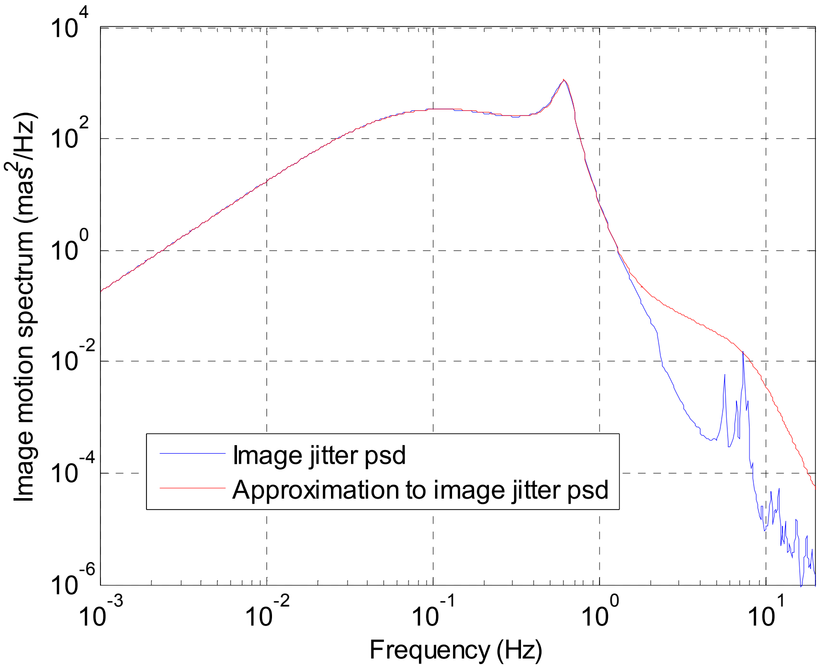


Figure 4 Allowable image jitter as seen by an instrument mounted on the Nasmyth Platform

Discussion: The image jitter below 10 Hz is primarily due to wind. The requirement is derived from a model of the wind loads, the telescope structure, and the telescope control system based on the design as of June 2007, and documented in TMT.SEN.TEC.07.017.REL01. The allowable wind-induced image jitter power spectrum as seen by an instrument on the Nasmyth platform is given in the figure, with the amplitude scaling described below. The approximation, useful for analysis, is

$$k\frac{\left(f^{2}\right)}{\left|1+2\zeta_{0}jf/f_{0}-(f/f_{0})^{2}\right|^{2}\cdot\left|1+2\zeta_{1}jf/f_{1}-(f/f_{1})^{2}\right|^{2}}\cdot\frac{\left|1+2\zeta_{2}jf/f_{2}-(f/f_{2})^{2}\right|^{2}}{\left|1+2\zeta_{3}jf/f_{3}-(f/f_{3})^{2}\right|^{2}}$$

where k is chosen to scale the overall amplitude. For the 75th percentile wind and upwind (0° azimuth, 30° zenith) orientation used to generate the above spectrum, then $f_0 = 0.105$ Hz, $f_1 = 0.625$ Hz, $f_2 = 1.5$ Hz, $f_3 = 8$ Hz and $\zeta_0 = 1.25$, $\zeta_1 = 0.1$, $\zeta_2 = 0.5$, $\zeta_3 = 0.5$. Changes in the overall amplitude will also shift the frequency response, but this effect is relatively small - the most significant influence on the shape of the response results from the control systems and is thus independent of conditions (orientation or wind speed). The image jitter is predominantly one-dimensional; at least 5 times larger in rotation about x than rotation about y. The median, 75th, 85th and 95th percentile overall image jitter due to wind is 13, 28, 45, and 90mas respectively.

4.1.3.7.2 Configuration

[REQ-1-OAD-1390] The Nasmyth platforms and instruments must not extend into the volume defined between two planes at X = -16 and +16 m in the X axis of the ECS coordinate system.

[REQ-1-OAD-1395] The Nasmyth platforms shall provide a permanent platform at an elevation of 7 m below the elevation axis. All structure above this level shall be reconfigurable.

[REQ-1-OAD-1400] At early light, the Nasmyth Platforms shall be implemented in a way that supports the Alignment and Phasing System, on-axis at early light, and at a position approximately 14 degrees off the elevation axis.

[REQ-1-OAD-1405] In the early light configuration, the APS system shall be moveable between the on and off axis positions without reconfiguration of any early light instruments.

[REQ-1-OAD-1410] At early light, the Nasmyth Platforms shall provide support for the following instruments as defined in the ORD, each at their own foci: NFIRAOS with the NSCU, feeding IRIS and IRMS, at the 174.5 degree position on the -X platform, WFOS at the 0 degree position on the +X platform, and APS at the 180 degree position on-axis and beside NFIRAOS. The location of these instruments is shown in Figure 5.

Discussion: The Nasmyth sides are designated –X and +X corresponding to directions in the Elevation Coordinate System. This coordinate system is located above the vertex of the primary mirror, on the elevation axis, defined by +Z pointing towards the stars, and +Y pointing towards the zenith when the telescope is pointed at the horizon. The foci locations are designated by their angular position, where 0 degrees is on the elevation axis of the +X platform, increasing counter clockwise as viewed from above.

Discussion: At the 174.5 degree position, primary mirror clears the beam to NFIRAOS by 100 mm when the telescope is pointed 65 degrees off zenith.

[REQ-1-OAD-1415] The Nasmyth Platforms shall be designed to be upgradeable to additionally support the following second and future generation instruments, as defined in the ORD, each at their own foci and with their required field of view: IRMOS, MIRES, PFI, NIRES, HROS, and WIRC.

Discussion: IRMS is expected to be decommissioned when IRMOS is commissioned.

Discussion: The instrument locations for the full SAC instrument suite (early light plus future instrumentation) on the Nasmyth Platforms shall be as shown in Figure 29 in the Appendix.

[REQ-1-OAD-1425] Instruments shall not exceed the volumes, and shall meet the focal plane position requirements listed in Table 13.

Discussion: These volumes and focal plane positions are required to meet the instrument arrangement as shown in Figure 5.

Table 13 Instrument Volumes (not including electronics cabinets and other support equipment)

Instrument	Shape	Width or Dia (m)	Height (m)	Depth (m)	Focal Plane Position	Notes
APS	Box	3	1	4	1m inside box, 0.5m from right hand face (viewed from front) 0.5m up	
HROS	See drawing TMT.INS.HROS.ENV					UC Envelope
IRIS	Cylinder	2	4		0.75m inside, on axis	Mounted on NFIRAOS bottom port
IRMOS	Cylinder	4		5.9	On cylindrical side, 0.9m from top 3m from side	Florida envelope
MIRAO	Box	1.3	2.85	2.2	Input on front of box, at the bottom right, 0.3m from each edge. Output on bottom, in 1m and centered on width	
MIRES	Cylinder	1.5	3.8	9.2	Centred on front face	
NFIRAOS	See drawing TMT.INS.NFIRAOS.ENV					
NIRES-B	Cylinder	1	1.5		0.5m inside, on axis	Mounted on NFIRAOS side port
NIRES-R	Cylinder	1	1.5		0.5m inside, on axis	Fed by MIRAO
NSCU	Box	1.225	3.65	1.07		Optical axis is 2m from bottom, 0.325m from right hand face (viewed from front). This is coincident with NFIRAOS input optical axis
PFI	Box	3.5	3.5	7	Centered vertically on from, 1m from left, 1.m inside volume	
WFOS	Cylinder	7		11.4	Centered on front face, 3.2m into volume	

4.1.3.7.3 Instrument Mounting Points

[REQ-1-OAD-1430] Each lower Nasmyth platform shall provide a grid of hard points for attaching instrument support structures.

[REQ-1-OAD-1435] The instrument support structures shall support each instrument in a manner that meets: (1) the image size error budget terms for optical alignment (image jitter and image blur); (2) the pointing error budget; and (3) the pupil shift error budget.

Discussion: To avoid inducing stress into the instrument structures from motion of the Nasmyth platforms, it is recommended that the interface be kinematic in nature, and that the instrument develop a structure that transitions from a few support points at the interface, to the appropriate support points at the instrument.

[REQ-1-OAD-1440] The instrument support structures shall also enable access to the instruments for servicing, and shall support auxiliary equipment such as electronics enclosures, as agreed upon in the instrument to telescope interface requirements.

[REQ-1-OAD-1445] The instrument support structure interface hard points shall only be required to resist linear forces, and shall not be required to provide resistance to moments applied by the instruments. The required support points, loads and stiffnesses shall be specified in interfaces between the telescope and instrument teams on an instrument by instrument basis.

[REQ-1-OAD-1450] The Nasmyth platforms and instrument support structures shall be designed to have minimal obstruction of air flow across the primary mirror.

Discussion: Location of equipment away from areas that obstruct the primary, and use of slender members, air permeable surfaces is advised.

4.1.3.7.4 Services

[REQ-1-OAD-1455] The general services supplied to the Nasmyth Platforms shall be compressed air, coolant and cryogens, utility power, UPS, copper wire and optical fiber for control and communication.

4.1.3.7.5 Access to Platforms and Instrument Locations

[REQ-1-OAD-1460] All permanent Nasmyth platform levels shall be accessible by personnel and equipment from the elevation of the observatory fixed base floor.

[REQ-1-OAD-1461] Access to and from Nasmyth areas shall not place any requirements on the position or movement of the enclosure system.

Discussion: Operations staff will need to get on and off the Nasmyth areas many times a day. It is operationally inefficient to constrain the position of the enclosure when personel are transiting to and from the Nasmyth areas.

[REQ-1-OAD-1465] An elevator shall be provided to lift personnel and pieces of equipment up to 1.5 x 1.5 x 1.5 m and 500 kg to the Nasmyth platform on the side of the primary mirror.

[REQ-1-OAD-1467] As a goal, elevator access to and from the Nasmyth areas shall be possible at any or at many telescope azimuth position(s).

Discussion: It is advantageous to minimize the coupling between telescope azimuth position and access to and from the Nasmyth areas.

[REQ-1-OAD-1470] The elevator shall be attached to the telescope azimuth structure, and the lower level shall be at the azimuth walkway adjacent to the telescope pier.

[REQ-1-OAD-1472] Each Nasmyth platform shall be directly accessible by one or more stairways, that don’t require crossing to the other side of the telescope.

Discussion: In case of emergency, it must be possible to descend directly from each Nasmyth platform without the need to cross over to the other platform in order to descend.

[REQ-1-OAD-1473] Stairway access to and from the Nasmyth areas shall be possible at any telescope azimuth position.

[REQ-1-OAD-1475] The enclosure subsystem shall provide a compliment of cranes and / or hoists that are able to reach and reposition loads anywhere within the perimeter of each Nasmyth platform.

Discussion: It is understood that repositioning may include motions of the telescope and / or the enclosure. The outer radius of the Nasmyth platform shall be defined as the intersection between the 28.5 m stay in radius and the -7 m platform level, which is a radius of 27.6 m. The inner edge of the Nasmyth platform of 16 m is defined in REQ-1-OAD-1390.

[REQ-1-OAD-1476] The enclosure mounted cranes and hoists shall be able to reposition loads within their entire working volume, including lowering to the observatory floor.

Discussion: Crane and hoist working volumes are defined in Section 4.5.1 of the OAD. [REQ-1-OAD-1475] The enclosure crane shall be able to reach loads anywhere within the perimeter of each Nasmyth platform.

[REQ-1-OAD-1480] Sufficient space shall be provided between instruments to allow access for servicing.

[REQ-1-OAD-1482] All instruments shall provide a pathway at the Nasmyth platform level, at least 1.5 m wide and 2.5 m high, for personnel and equipment to transit between the +Y and -Y ends of the Nasmyth areas.

Discussion: For example, WFOS must not create a complete barrier for access between ends of the Nasmyth areas.

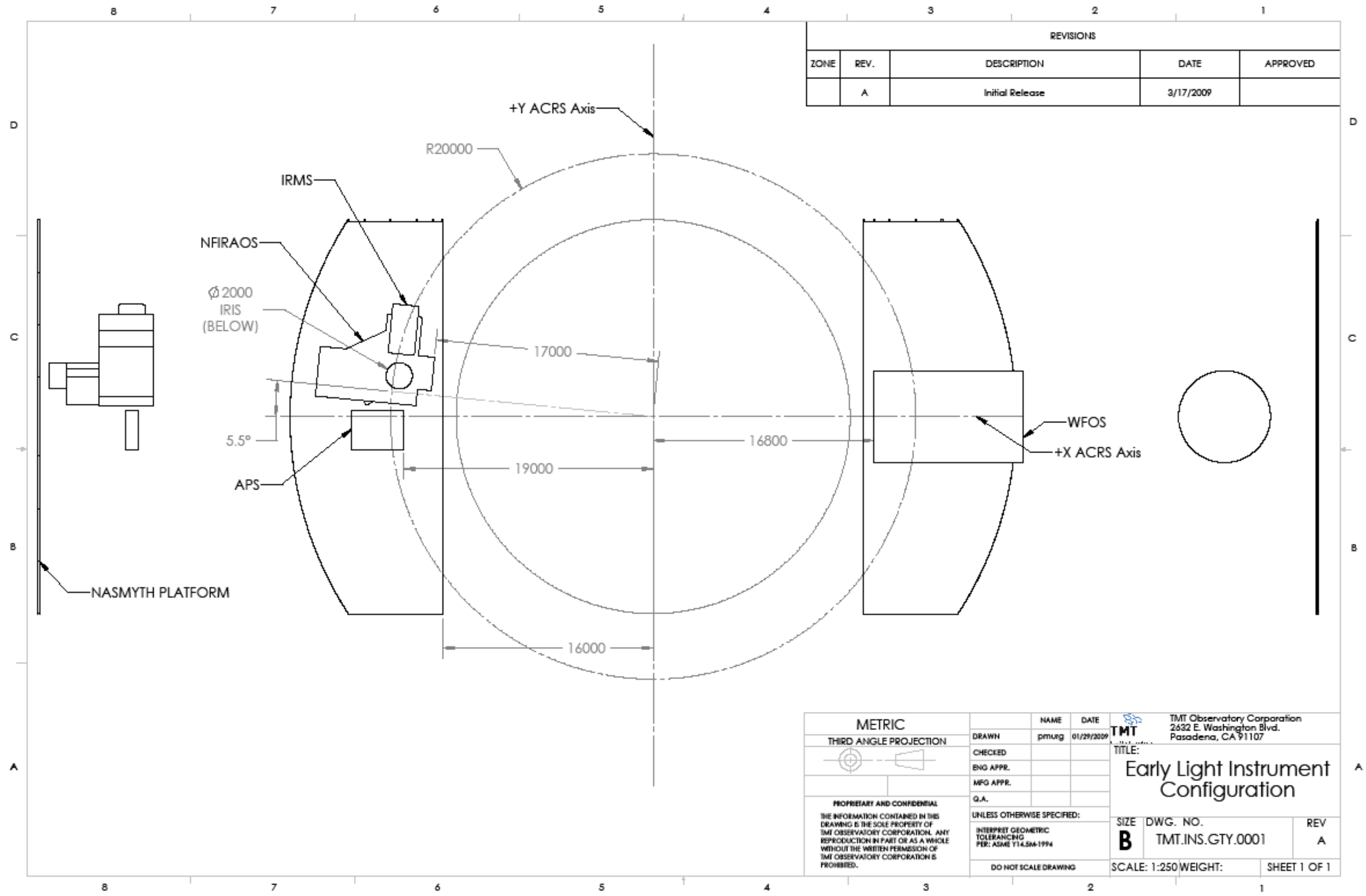


Figure 5 Nasmyth Platform Reference Instrument Layout (NFIRAOS, IRIS, IRMS and APS at left, WFOS at right)

4.1.3.7.6 Access to Instruments

[REQ-1-OAD-1485] Access to all required instrument locations for regular servicing and maintenance shall be provided via walkways, elevators, lifts and stairs. Sufficient space shall be provided for personnel and the required equipment to access the service locations.

4.1.3.7.7 Access between Platforms

[REQ-1-OAD-1490] Walkway access must be provided between the –X and +X Nasmyth platforms. The walkway must be accessible at all telescope elevation angles.

[REQ-1-OAD-1492] The walkways between the +X and -X Nasmyth areas shall be >1.5 m wide.

Discussion: This will be a high traffic area, requiring the ability to move equipment along the platform and pass around people and other equipment on the walkway.

4.1.3.7.8 Instrument Handling, Installation and Removal

[REQ-1-OAD-1500] The Nasmyth platform infrastructure, combined with the enclosure crane, shall provide for the safe installation, handling and removal of instrument components up to TBD size and TBD mass.

[REQ-1-OAD-1505] The size and volume limit for lifting instrument components is defined by the capacity of the enclosure crane. Instrument assembly procedures must not rely on the use of the enclosure crane for extended periods of time. As a goal, no instrument AIV plan shall require the use of the observatory crane for more than TBD hours per day, for more than TBD days total.

[REQ-1-OAD-1510] Instrument teams may elect to temporarily use their own smaller cranes, lifts etc, on the Nasmyth platforms for the assembly of instruments.

[REQ-1-OAD-1515] A lay down area for staging and assembly of equipment shall be provided on at least one Nasmyth platform. This area will be used for unpacking and assembly of instrument components prior to lifting them into place at the instrument location. The lay down area shall have a footprint of at least 5 x 7 m, and shall be located such that a temporary clean room, up to 5 m high, can be assembled above it, to create environmental conditions suitable for handling precision mechanisms and optics. As a goal, this area will be equipped as permanent instrument lab where entire instruments can be assembled and then lifted to their final location.

[REQ-1-OAD-1520] Instruments shall be designed in a manner such that a temporary clean and controlled environment can be provided for assembling an instrument in-situ.

[REQ-1-OAD-1525] The Nasmyth platforms are in close proximity to the primary mirror, which will not have a protective mirror cover. All Nasmyth instrument handling, installation and removal activities shall be compatible with the requirements of the operating observatory environment. Activities such as welding, cutting and grinding are considered incompatible with this environment and must be avoided in all circumstances. Activities shall be planned, and equipment shall be designed in such a manner that any damage to the telescope optics is highly unlikely.

[REQ-1-OAD-1530] The Nasmyth platforms shall be designed in such a way as to enable the addition of new instruments without affecting the productivity of the already commissioned instrument suite.

4.1.3.7.9 Requirements for Regular Maintenance and Servicing of Instruments

[REQ-1-OAD-1535] Servicing equipment required for regular use, including platform lifts, small cranes, personnel lifts, vacuum pumps, tool cabinets, workbenches, shall be stored on the Nasmyth platforms.

4.1.3.7.10 Floor Space and Storage Requirements

[REQ-1-OAD-1540] Allowance shall be made for 21 m^2 of floor space with at least 3 m overhead clearance on the –X platform for instrument electronics, equipment and tools.

[REQ-1-OAD-1545] Allowance shall be made in the Summit Facilities for a storage area of 9 m^2 of floor space with at least 3 m overhead clearance for the storage of instrument spare parts and additional tools related to instruments on the –X platform.

[REQ-1-OAD-1550] Allowance shall be made in the Summit or Support Facilities for an additional storage area of 39 m^2 of floor space with at least 3 m overhead clearance for the storage of instrument handling equipment related to instruments on the –X platform.

[REQ-1-OAD-1555] Allowance shall be made for 38 m^2 of floor space with at least 2.5 m overhead clearance on the +X platform for instrument electronics, equipment and tools.

[REQ-1-OAD-1560] Allowance shall be made in the Summit Facilites for a storage area of 22 m^2 of floor space with at least 3.5 m overhead clearance for the storage of instrument spare parts and additional tools related to instruments on the +X platform.

[REQ-1-OAD-1565] Allowance shall be made in the Summit or Support Facilities for an additional storage area of 12 m^2 of floor space with at least 3.5 m overhead clearance for the storage of instrument handling equipment related to instruments on the +X platform.

4.1.3.7.11 Safety and Personnel Considerations

[REQ-1-OAD-1570] An escape system shall be provided to allow personnel to exit the Nasmyth Platforms in the case of emergency.

[REQ-1-OAD-1575] As a goal, a personnel refuge and rest area shall be provided on each of the +X and –X Nasmyth platforms.

[REQ-1-OAD-1580] Elevators for access to the Nasmyth areas shall be designed such that safety is achieved through design for minimum risk, and with the incorporation of automatic safety devices where necessary.

Discussion: See REQ-1-ORD-7005 for the hierarchy of allowable safety system precedence. This requirement states that safety must be achieved by either item 1 or 2 of this requirement, and that achieving safety through warning devices, or procedures and training (items 3 or 4 of the ORD requirement) is not acceptable. For example, this prohibits the elevator from sweeping out an area of the observing floor at a level that could crush a person against portable equipment that might be placed there. The elevator is a high use item that has the potential of a high risk to personnel safety, so an extremely safe system is required.

[REQ-1-OAD-1585] Areas on the telescope or enclosure where personnel need to work frequently at a height more than 1.8 meters above the observing floor shall be equipped with safety rails having kick plates to prevent loose items from being kicked over the edge.

Discussion: These areas include the primary mirror cell, the Nasmyth platforms, service walkways around the instruments and service walkways on the enclosure.

[REQ-1-OAD-1590] Areas on the telescope or enclosure where personnel need to work frequently at a height more than 1.8 meters above the observing floor shall be provided with at least two paths of egress not requiring the use of elevators, in case fire or some other emergency blocks one escape route.

4.1.4 Telescope Mirror Optical Coating Requirements

Discussion: Table 14 lists the requirements for the optical coatings on each of the M1, M2 and M3 mirror surfaces. These requirements are based on what is achievable with existing coatings (see example coating plots in the Appendix 7.5).

Table 14 Requirements for M1, M2 and M3 Optical Coatings

Requirement Number	Description	Wavelength Range	Requirement	Goal
[REQ-1-OAD-1600]	**Minimum Reflectivity per Surface**	0.31 - 0.34 µm	N/A	0.8
		0.34 - 0.36 µm	0.8	0.9
		0.36 - 0.40 µm	0.8 → 0.9	0.9 → 0.95
		0.4 - 0.5 µm	0.9 → 0.95	0.95 → 0.98
		0.5 - 0.7 µm	0.95 → 0.97	0.98
		0.7 - 28 µm	0.97	0.98
[REQ-1-OAD-1603]	**Maximum Emissivity per Surface**	0.7 - 28 µm	0.015	0.013
[REQ-1-OAD-1606]	**∆R / Wavelength**	0.31 - 28 µm	< 0.003 / nm	
[REQ-1-OAD-1609]	**Lifetime**		(TBD)	(TBD)

4.1.5 M1 Optics System

4.1.5.1 General

[REQ-1-OAD-1650] The M1 optics system shall not include a mirror cover.

Discussion: A mirror cover is not practical to implement. This implies that the telescope should spend most of the non-observing time in a horizon pointing orientation.

[REQ-1-OAD-1652] The primary mirror system shall be cleaned on a regular basis with C02 snow.

[REQ-1-OAD-1655] The optical surfaces of the M1 segments shall have a smooth specular surface finish that scatters less than 0.15 % of the light at the shortest observing wavelength specified in Section 3.3.2 of the ORD.

Discussion: This corresponds to ~ 20 angstroms RMS surface finish.

[REQ-1-OAD-1660] The segment shall be less than 50 mm thick to reduce the overall mass and thermal inertia.

Discussion: Minimizing glass thickness helps to reduce mirror seeing effects.

[REQ-1-OAD-1665] The M1 system shall be designed to allow in situ CO2 cleaning of the mirror.

[REQ-1-OAD-1670] As a goal, the M1 system shall be designed to allow in situ washing of the mirror.

[REQ-1-OAD-1675] The Primary Segment Assemblies shall be designed to be serviced by personnel working in the mirror cell with the telescope zenith pointing. All components that are expected to fail at some point during use shall be replaceable without removing the segment.

Discussion: A Primary Segment Assembly includes the segment with its edge sensors, the segment support assembly (SSA) and the subcell.

[REQ-1-OAD-1680] The Primary Segment Assemblies shall be designed so that they can be quickly inspected by personnel working inside the mirror cell to identify any damage caused by an earthquake.

[REQ-1-OAD-1685] The segment and the portions of the SSA that will stay with it in the coating chamber must be compatible with the vacuum and coating environment.

[REQ-1-OAD-1690] The segments shall be dimensionally stable such that the relative heights of the segment edges comply with the error budget term for M1-F Segment Out of Plane Displacement (REQ-1-OAD-0418) for periods of at least 30 days without updates from the APS.

[REQ-1-OAD-1692] As a goal, it should be possible for personnel to directly access the primary mirror cell from each of the Nasmyth platforms when the telescope is zenith pointing.

[REQ-1-OAD-1694] Lift platforms, 100 kg capacity, or other means shall be provided to allow small wheeled equipment items to be rolled from the Nasmyth elevator to the work level of the primary mirror cell.

4.1.5.2 Segmentation

[REQ-1-OAD-1700] The primary mirror of the system shall be segmented as shown in Figure 6 ; it contains 492 segments.

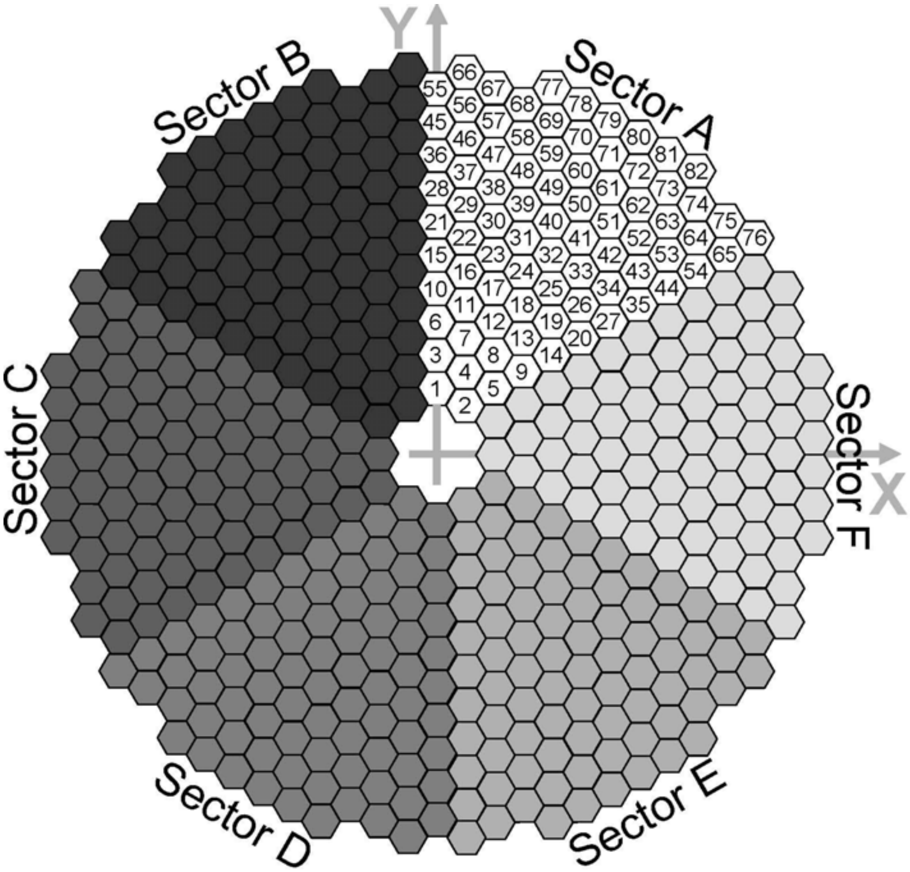


Figure 6 Layout of the segmented primary mirror, as projected on the X-Y plane of the Elevation Coordinate System (ECRS). The capital letters denote identical sectors rotated by 60 degrees relative to each other.

[REQ-1-OAD-1705] Each segment shall be supported on 3 actuators that enable tip/tilt and piston motion of the segments.

[REQ-1-OAD-1710] Segment edge sensors shall have a dynamic range equivalent to the maximum possible piston difference between segments.

[REQ-1-OAD-1715] The pupil obscuration due to segment gaps and beveled edges shall be a maximum of 0.6% of the pupil area.

Discussion: The nominal gap between segments will be 2.5 mm.

[REQ-1-OAD-1720] The primary segment assembly shall be compatible with an actuator stroke range as specified in Section 3.8.1 of this document.

[REQ-1-OAD-1725] The segment support assembly and M1CS actuators shall provide a segment tilt range greater than +/- 0.1 degree mechanical motion at the mirror surface.

*Discussion: This range is easily achieved by the actuator stroke spe*cified in Section 3.8.1 of this document.

[REQ-1-OAD-1730] The segment support assembly must accommodate, without damage, the maximum tilt that can be imposed by the M1CS actuators. The maximum lateral displacement of the segment when subjected to this maximum tilt shall be less than 0.5 mm.

[REQ-1-OAD-1735] The telescope structure and primary mirror cell shall be designed such that relative in-plane motion between any two adjacent segments is less than 0.5 mm under all operating conditions, and is less than 1.0 mm under all servicing and maintenance conditions.

[REQ-1-OAD-1740] The telescope structure and primary mirror cell shall be designed such that segment to segment contact does not occur under Operational Basis Survival Conditions and Very Infrequent Earthquake Conditions.

Discussion: Segment to segment contact will cause damage.

[REQ-1-OAD-1745] The telescope structure and primary mirror cell shall be designed such that rotations of segments around their local Z_{PSA} axes shall not exceed +/-1.0 mrad under all operating, servicing and maintenance conditions.

[REQ-1-OAD-1750] The projections of the segments on the X-Y plane of the ECRS shall be hexagons radially scaled from 492 regular hexagons with side length of approximately 0.716 m, by the factor of

$$s = \frac{1+\alpha\left(\frac{R_{\max}}{R_1}\right)^2}{1+\alpha\left(\frac{r}{R_1}\right)^2}$$

$\alpha =$ radial scaling coefficient

$R_{\max} =$ Primary mirror nominal radius

$R_1 =$ Primary mirror radius of curvature

$r =$ Distance from the origin of ECRS in the projected plane

[REQ-1-OAD-1775] The radial scaling coefficient, α, shall be 0.1650.

4.1.5.3 Positioning

[REQ-1-OAD-1755] Each segment shall have a subcell that will be permanently attached to the mirror cell and serve as the precision interface to the Polished Mirror Assembly (i.e., the segment and SSA). The subcell shall incorporate alignment targets suitable for use with precision surveying equipment and mechanisms that provide rigid body adjustments for all 6 degrees of freedom and that can be permanently locked in position once the adjustments have been made.

[REQ-1-OAD-1760] Each subcell shall have a provision for mounting a dummy segment weight. The weight must not block the line of sight to the multiple surveying instruments used to position the subcell.

[REQ-1-OAD-1765] Each segment shall have interface features that allow it to be positioned precisely in the correct position and orientation when it is substituted into any of six locations in the array.

[REQ-1-OAD-1770] The M1 shall incorporate alignment features that allow its global position to be accurately and quickly measured by the Global Metrology System (GMS).

4.1.6 M2 System

4.1.6.1 General

[REQ-1-OAD-1800] The telescope design shall support interchangeable conventional and adaptive secondary mirror subsystems. The M2 positioner shall be designed with an interface that will work with either secondary mirror.

[REQ-1-OAD-1805] The M2 System shall be designed to be compatible with the Laser Launch Telescope. No component of the M2 Assembly shall extend beyond a plane perpendicular to the M1 optical axis located 1.5 (TBC) meters behind the vertex of the M2.

[REQ-1-OAD-1825] The outer diameter of the M2 system shall be less than or equal to 3.6 m.

[REQ-1-OAD-1830] The M2 shall incorporate alignment features that allow its position and orientation to be accurately and quickly measured by the Global Metrology System (GMS).

4.1.6.2 Removal, Cleaning and Coating

[REQ-1-OAD-1835] The M2 system shall be designed to allow the removal of the mirror for coating.

[REQ-1-OAD-1840] The M2 shall be compatible with all equipment and processes involved in stripping and replacing the reflective coating, including the vacuum and temperature conditions in the coating chamber.

[REQ-1-OAD-1845] The M2 system shall be designed to allow in situ CO2 cleaning of the mirror.

[REQ-1-OAD-1850] As a goal, the M2 system shall be designed to allow in situ washing of the mirror.

4.1.6.3 Control

[REQ-1-OAD-1855] The M2 System shall provide 5 degree of freedom motion of the secondary mirror relative to the telescope structure and shall control the sixth degree of freedom (rotation around the optical axis) so that it does not change.

[REQ-1-OAD-1860] In addition to any other motion requirements, the mechanical range of motion of the M2 system shall be sufficient to accommodate any combination of the telescope top end deflections as specified in Table 12.

[REQ-1-OAD-1870] The M2 System shall provide bandwidths in tip/tilt and de-center of greater than 0.1 Hz.

[REQ-1-OAD-1875] The M2 System shall provide bandwidths in piston of greater than 0.1Hz.

[REQ-1-OAD-1880] The M2 mirror support shall be active, and shall be able to correct low-order aberrations including: focus (i.e., curvature), astigmatism, trefoil, and quatrefoil with sufficient amplitude and fidelity that the M2 can satisfy all requirements of the Image Size Error Budget over: (1) the full field of view; (2) the full operational range of zenith angles; and (3) all performance conditions as stated in ORD Section 3.1.2.2.

[REQ-1-OAD-1885] The M2 mirror support active optics system shall be able to operate in an open-loop mode (i.e., without wavefront sensor feedback) with look-up tables for zenith angle and temperature, based on calibration measurements by the Alignment and Phasing System (APS).

[REQ-1-OAD-1890] The M2 System shall include two independent low level control systems, one to control the M2 positioner and the other to control the M2 support system. The M2 positioner control system shall be able to operate successfully in the absence of the M2 Cell Assembly, for example, when the conventional M2 has been replaced with an adaptive M2.

[REQ-1-OAD-1895] The M2 System shall receive and execute real time tip/tilt, de-center, and piston commands issued by the Telescope Control System.

[REQ-1-OAD-1900] The M2 System shall accept and execute mirror figure updates from the Telescope Control System

4.1.6.4 *Optical Quality*

[REQ-1-OAD-1910] The optical surface of the secondary mirror shall have a smooth specular surface finish that scatters less than 0.15 % of the light at the shortest observing wavelength specified in Section 3.3.2 of the ORD.

Discussion: This corresponds to ~ 20 angstroms RMS surface finish.

4.1.7 M3 System

4.1.7.1 *General*

[REQ-1-OAD-1950] The optical surface of the M3 shall pass through the intersection of the telescope elevation and azimuth axes and shall rotate and tilt about that point.
Discussion: The intersection of the M3 rotation and tilt axes is coincident with the intersection of the telescope elevation and azimuth axes.

[REQ-1-OAD-1955] The M3 shall incorporate alignment features that allow its position and orientation to be accurately and quickly measured by the Global Metrology System (GMS).

[REQ-1-OAD-1957] Except when observing or when necessary in servicing and maintenance mode, the M3 System shall be parked in an orientation that minimizes the risk of damage and collection of dust.

4.1.7.2 *Removal, Cleaning and Coating*

[REQ-1-OAD-1960] The M3 system shall be designed to allow the removal of the mirror for coating.

[REQ-1-OAD-1965] The M3 shall be compatible with all equipment and processes involved in stripping and replacing the reflective coating, including the vacuum and temperature conditions in the coating chamber.

[REQ-1-OAD-1970] The M3 system shall be designed to allow in situ CO2 cleaning of the mirror.

[REQ-1-OAD-1975] The M3 system shall be designed to allow in-situ washing of the mirror. Catchments shall be provided to catch all the fluids used in the washing operation, for proper disposal. No washing fluids shall be allowed to drip onto the primary mirror.

[REQ-1-OAD-1985] The entire M3 Assembly must fit within a 3.50 m diameter cylinder centered about the M1 optical axis, at all observing orientations, to avoid obscuration of the telescope entrance pupil.

[REQ-1-OAD-1990] The overall dimensions of the M3 Assembly shall leave adequate clearance for the segment handling cranes to reach the innermost segments.

[REQ-1-OAD-1995] The M3 assembly shall be serviceable in telescope zenith-pointing orientation by personnel who ascend into the center of the assembly through the rotation bearing of the M3 positioner. The cable wraps shall leave adequate room for this access.

4.1.7.3 Control

[REQ-1-OAD-2000] The M3 System shall provide two degree of freedom motion of the tertiary mirror relative to the telescope structure. The required mechanical range of motion shall be sufficient to redirect a beam of light from the secondary mirror towards the Nasmyth platform instrument locations as shown in Figure 7. The motion shall be achieved over a telescope zenith angle range of 0 to 65 degrees.

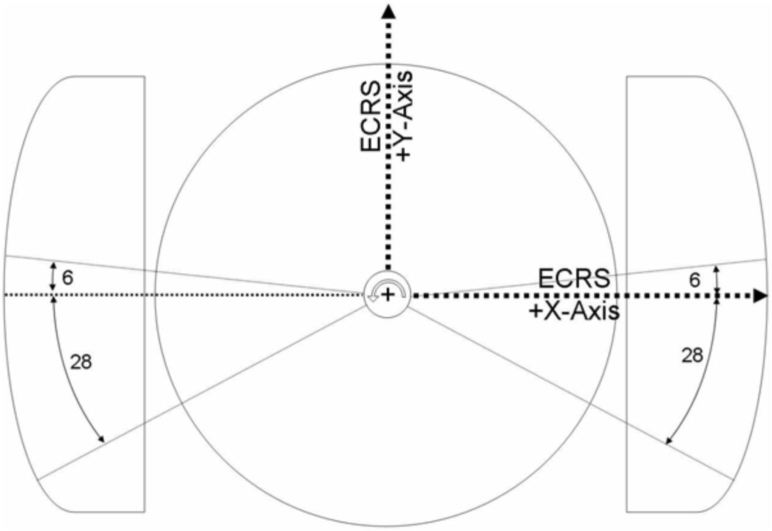


Figure 7 Nasmyth positions addressed by the M3 mirror

[REQ-1-OAD-2010] The M3 System shall provide bandwidths in tilt and rotation of not less than 0.1 Hz.

[REQ-1-OAD-2015] The M3 System shall be able to redirect the beam between any two instruments in less than three (3) minutes.

[REQ-1-OAD-2020] The M3 shall be able to track to maintain the alignment of the science beam with any instrument.

[REQ-1-OAD-2025] The M3 shall have a tracking error of less than 20 mas RMS at M3.

[REQ-1-OAD-2030] The M3 shall have a pointing repeatability of < 2.5 arcsec mirror motion on the rotation axis.

[REQ-1-OAD-2035] The M3 shall have a pointing repeatability of < 5 arcsec mirror motion on the tilt axis.

[REQ-1-OAD-2040] The M3 mirror support shall be active, and shall be able to correct low-order aberrations including: focus (i.e., curvature), astigmatism, trefoil, and quatrefoil with sufficient amplitude and fidelity that the M3 can satisfy all requirements of the Image Size Error Budget over: (1) the full field of view; (2) the full operational range of zenith angles; (3) all instrument positions; and (4) all performance conditions as stated in ORD Section 3.1.2.2.

[REQ-1-OAD-2045] The M3 mirror support active optics system shall be able to operate in an open-loop mode (i.e., without wavefront sensor feedback) with look-up tables for mirror orientation and temperature, based on calibration measurements by the Alignment and Phasing System (APS).

[REQ-1-OAD-2050] The M3 System shall include two independent low level control systems, one to control the M3 positioner and the other to control the M3 support system. The M3 positioner control system shall be able to operate successfully in the absence of the M3 Cell Assembly.

[REQ-1-OAD-2055] The M3 System shall receive and execute real time tilt and rotation commands issued by the Telescope Control System.

[REQ-1-OAD-2060] The M3 System shall accept and execute mirror figure updates as commanded by the Telescope Control System.

4.1.7.4 Optical Quality

[REQ-1-OAD-2070] The optical surface of the tertiary mirror shall have a smooth specular surface finish that scatters less than 0.15% of the light at the shortest observing wavelength specified in Section 3.3.2 of the ORD.
Discussion: This corresponds to ~ 20 angstroms RMS surface finish.

4.1.8 Primary Mirror Control System (M1CS)

[REQ-1-OAD-2100] The static stiffness of the combined segment support shall be no less than 10 N/um in the z direction for all frequencies below 1 Hz.

Discussion: The "combined segment support" is intended to include all in-situ segment support structure elements; this includes the Primary Mirror Assembly, the Subcell, three actuators, and the mirror cell. The static stiffness of the "combined segment support" is defined by the slope of the force versus displacement curve for forces applied normal to, and at the center of, the front surface of a segment properly installed in the telescope.
[REQ-1-OAD-1955]. The M1CS bandwidth (3dB) shall be no less than 0.5 Hz.

Discussion: The wind rejection characteristics of the M1 system are defined by the temporal and spatial character of the wind and the wind rejection capability of the M1CS. Both of these parameters are complex and difficult to define in a concise manner. Defining a static stiffness of the M1 system along with a M1CS bandwidth provides a reasonable approximation to the comprehensive requirement. Since the wind disturbance has finite content up to, and even beyond 1 Hz, defining a static stiffness number doesn't define the complete response. Below 1 Hz the stiffness characteristics of the relevant structural components won't vary greatly; on the other hand the stiffness of the actuator may vary considerably over this range compromising the wind disturbance rejection as predicted by a static stiffness model. For this reason performance prediction models will utilize more accurate models of M1 wind rejection. The allowable image motion and image blur on M1 due to wind is addressed in section TBD.

[REQ-1-OAD-2102] The stiffness of the combined segment support shall be no less than 1 N/um in the z direction for frequencies between 10 and 20Hz (TBC)

[REQ-1-OAD-2103] The stiffness of the combined segment support shall be no less than (11-f) N/um in the z direction for frequencies between 1 and 10Hz (TBC)

Discussion: The requirement between 1 and 10 Hz is simply a linear relationship joining the requirements at 1 and 10 Hz. There is no stiffness requirement for frequencies above 20 Hz. These numbers are guidelines. REQ-1-OAD-2100 states that the static stiffness of the combined segment support is to be no less than 10 N/um in the z direction. The current PSA design uses the entire 10N/micron. These numbers are nonetheless reasonable targets. There are advantages to make the actuators as stiff as possible up through 20 Hz. Presently the disturbance environment between 1 and 20 Hz is not well understood.

[REQ-1-OAD-2105] The PSD of M1 segment motion driven by a vibration disturbance characterized by curve 1 below (TBD) and located on each of the top layer mirror cell nodes directly below the segment shall be contained within the PSD envelope illustrated in curve 2 below (TBD).

FIGURE TBD

Figure 8 Maximum allowable PSD of M1 Segment Motion driven by vibration disturbances

Discussion: Ground based vibration disturbances have compromised AO performance at Keck. In particular vibration sources emanating from rotating machinery have been problematic. Predicting and characterizing the vibration environment at TMT is difficult and will take time. As a starting point the vibration characteristics at Keck at points similar to the mirror cell nodes described in the Requirement will be utilized. It is understood that this may be an overly conservative approach but it provides a starting point. Although not required it is likely that the isolation and damping capabilities of the voice coil actuators will be used in the final design and hence in the performance prediction models. The allowable image blur on M1 due to wind is addressed in section TBD.

[REQ-1-OAD-2107] The M1 control system shall have a 3 dB wind rejection bandwidth of no less than 1Hz (TBC).

Discussion: The 3dB wind rejection requirement is 1 Hz but bandwidths up to approximately 2 Hz provide additional benefit and should be considered if achievable with little extra cost. On the other hand the wind rejection capability of the M1 system is likely to be constrained by Control Structure Interaction. The achievable M1 rejection bandwidth is under study via analysis and modeling.

[REQ-1-OAD-2110] The M1CS shall be able to tilt any uncontrolled segments at least 40 arcseconds on the sky from the controlled segments.

Discussion: This is for the Alignment and Phasing System (APS) functionality.

4.1.9 Alignment and Phasing System (APS)

Discussion: The APS has two pointing modes and two performance modes, which can be used in any combination, making a total of four operating modes.

The two pointing modes are on-axis and off-axis. During on-axis alignment the following degrees of freedom are measured and adjusted: M1 segment piston, tip, tilt, M1 figures, M2 piston and either M2 tip/tilt or x/y decenter. During off-axis alignment potentially all degrees of freedom are measured and adjusted.

The two performance modes are post-segment exchange and alignment maintenance. These are defined by how well aligned M1, M2, and M3 are to start with, and thus how long *it will take APS to align them. APS will have the ability to capture and align optics that are misaligned by more than the post-segment exchange alignment tolerances, but in these cases there are no time constraints as this is an off-nominal operation.*

[REQ-1-OAD-2200] The APS shall use starlight to measure the overall wavefront errors and then determine the appropriate commands to send to align the optics.

[REQ-1-OAD-2205] The APS shall have an acquisition camera with a 1 (goal 2) arcminute diameter field of view for use in pointing, acquisition and tracking tests.

[REQ-1-OAD-2210] The APS shall provide a location for mounting an On-Instrument Wavefront Sensor (OIWFS).

[REQ-1-OAD-2215] The APS shall incorporate any pupil steering systems necessary to achieve its pupil stability requirements relative to what the telescope system delivers.

[REQ-1-OAD-2220] The APS shall operate with segments missing from the primary mirror, or uncontrolled segments on the primary mirror.

[REQ-1-OAD-2225] The APS shall not be required to phase the M1 when there are groups of segments isolated from others.

[REQ-1-OAD-2230] The APS shall measure the on-axis alignment such that the errors associated with these measurements are less than an 80% enclosed energy diameter of 0.040 arcseconds.

[REQ-1-OAD-2235] The APS shall measure the on-axis alignment such that the errors associated with these measurements after AO correction by an ideal order 60x60 AO system are less than TBD nm.

Discussion: An "ideal" AO system consists of a linear DM and a linear SH WFS, with no servo lag, non-common path error, WFS measurement noise, or DM hysteresis.

[REQ-1-OAD-2240] The APS shall measure the on-axis alignment such that the errors associated with these measurements after AO correction by an ideal 120x120 DM are less than TBD nm.

[REQ-1-OAD-2245] The APS shall measure the off-axis alignment such that the errors associated with the measurements do not exceed the larger of (1) the on-axis alignment requirement or (2) errors which increase the ideal telescope 80% enclosed energy diameter by more than 7% over the telescope field of view.

[REQ-1-OAD-2250] The APS shall measure the M3 tip and tilt such that the errors associated with the measurements are less than a pupil shift of 0.1% the diameter of the pupil.

[REQ-1-OAD-2255] In alignment maintenance mode the initial M1, M2 and M3 optics shall not exceed the error shown in Table 15.

Table 15 Alignment maintenance mode capture range

	Optical Element	Maximum Error	Units
[REQ-1-OAD-2260]	M1 segment tip/tilt	+/- 1	arcseconds in one dimension on the sky
[REQ-1-OAD-2262]	M1 segment piston	+/- 110	nm (surface)
[REQ-1-OAD-2264]	M1 surface shape	+/- 0.25	arcseconds relative in one dimension on the sky between Shack-Hartmann subapertures 20cm apart.
[REQ-1-OAD-2266]	M2 tip/tilt	+/- 30	arcseconds in one dimension on the sky
[REQ-1-OAD-2268]	M2 piston	+/- 2	mm (surface)
[REQ-1-OAD-2270]	M2 X/Y decenter	+/- 100	microns
[REQ-1-OAD-2272]	M2 surface Shape	TBD	
[REQ-1-OAD-2274]	M3 tip/tilt	TBD	
[REQ-1-OAD-2276]	M3 surface shape	TBD	

REQ-1-OAD-2285] In post-segment exchange mode the initial M1, M2 and M3 optics shall not exceed the error shown in Table 16.

Table 16 Post-segment exchange mode capture range

	Optical Element	Maximum error	Units
[REQ-1-OAD-2290]	M1 segment tip/tilt	+/- 10	arcseconds in one dimension on the sky
[REQ-1-OAD-2292]	M1 segment piston	+/- 30	microns (surface)
[REQ-1-OAD-2294]	M1 surface shape	+/- 0.5	arcseconds relative in one dimension on the sky between Shack-Hartmann subapertures 20cm apart.
[REQ-1-OAD-2296]	M2 tip/tilt	+/- 30	arcseconds in one dimension on the sky
[REQ-1-OAD-2298]	M2 piston	+/- 2	mm (surface)
[REQ-1-OAD-2300]	M2 X/Y decenter	+/- 100	microns
[REQ-1-OAD-2302]	M2 surface Shape	TBD	
[REQ-1-OAD-2304]	M3 tip/tilt	TBD	
[REQ-1-OAD-2306]	M3 surface shape	TBD	

[REQ-1-OAD-2320] The APS shall be able to perform off-axis alignment (which includes on-axis) in less than 90 minutes (at a single elevation angle) when all optics are within the alignment maintenance specifications.

[REQ-1-OAD-2325] The APS shall be able to perform on-axis alignment in less than 30 minutes (at a single elevation angle) when all optics are within the alignment maintenance specifications.

[REQ-1-OAD-2230] The APS shall be able to perform on-axis alignment in less than 120 minutes when all optics are within the post-segment exchange specifications.

[REQ-1-OAD-2335] At first light, the APS shall be located on the elevation axis on one of the Nasmyth platforms.

[REQ-1-OAD-2340] The APS system shall be designed such that it can be upgraded to align an AM2.

Discussion: The fundamental differences between the AM2 and M2S are that the AM2 is segmented, and that the figure of AM2 will be controllable in 250 to 400 modes. The APS *optical design will support the insertion of necessary optics to align and phase an AM2. However, the specific optics will not be purchased nor will any algorithm be devised nor analysis work be performed as part of the planned APS effort.*

4.1.10 Servicing and Maintenance

4.1.10.1 Telescope Structure

[REQ-1-OAD-2400] The telescope structure shall be designed to be consistent with the servicing and replacement intervals and scenarios shown in Table 17.

Discussion: These entries are intitial estimates, and are subject to change.

Table 17 Telescope structure Servicing Requirements

TBD

4.1.10.2 Telescope Optics

[REQ-1-OAD-2500] The telescope optics shall be designed to be consistent with the servicing and replacement intervals and scenarios shown in Table 18.

Discussion: These entries are intitial estimates, and are subject to change.

Table 18 Telescope Optics Servicing Requirements

TBD

4.1.10.3 Telescope Controls

[REQ-1-OAD-2600] The telescope controls shall be designed to be consistent with the servicing and replacement intervals and scenarios shown in Table 19.

Discussion: These entries are intitial estimates, and are subject to change.

Table 19 Telescope Controls Servicing Requirements

TBD

4.2 INSTRUMENTATION

4.2.1 General

[REQ-1-OAD-2700] Instruments shall be designed to routinely acquire objects given a telescope pointing RMS accuracy of 3 (TBC) arcseconds RMS.

Discussion: This specification is looser than the telescope pointing requirement for risk reduction in case the requirement is not met.

[REQ-1-OAD-2705] TMT Instrumentation shall incorporate all hardware necessary for calibration.

Discussion: The facility will not provide a general calibration facility. Flat fields, wavelength calibration etc are the responsibility of the instruments.

[REQ-1-OAD-2708] No equipment whose weight is supported by the NFIRAOS instrument support tower may use fans or other vibrating machinery, including closed cycle cryopumps.

Discussion: Electronics on the instrument support tower should be passively cooled with e.g. cold plates in private enclosures

4.2.2 Facility AO System

[REQ-1-OAD-2710] The facility AO system shall utilize laser guidestars to improve sky coverage

[REQ-1-OAD-2715] The facility AO system shall utilize multiple laser guide stars in the mesospheric sodium layer and atmospheric tomography to minimize the impact of the cone effect.

[REQ-1-OAD-2720] The facility AO system shall utilize multi-conjugate adaptive optics to widen the compensated field of view.

Discussion: This significantly improves sky coverage by “sharpening” the natural guide stars used for tip/tilt sensing, and also improves astrometric and photometric accuracy on the IRIS and WIRC science fields.

[REQ-1-OAD-2730] The facility AO system shall utilize IR tip/tilt natural guide star wavefront sensors to improve sky coverage.

[REQ-1-OAD-2735] The facility AO system shall utilize multiple tip/tilt natural guide stars to improve sky coverage.

Discussion: Interpolating between the measurements from multiple tip/tilt guide stars corrects for much of the tilt anisoplanatism error that would be suffered with a single, off-axis tip/tilt guidestar.

[REQ-1-OAD-2740] The facility AO system shall utilize existing and near-term component technology whenever possible to reduce cost and schedule risk.

[REQ-1-OAD-2745] The facility AO system shall be upgradeable to meet all of the specifications for the narrow- and moderate-field AO systems as listed in the ORD.

Discussion: This corresponds to IRIS (ORD section 3.3.18.2), IRMS (ORD section 3.3.18.3), WIRC (ORD section 3.3.19.8) and NIRES (ORD section 3.3.19.6).

[REQ-1-OAD-2750] The facility AO system shall meet its requirements with a pupil amplitude profile defined by the M1 segment geometry, M2 support struts, and a maximum (single axis) pupil decentration of D/360, with a goal of D/240.

Discussion: D/240 corresponds to one-quarter of a subaperture. The facility AO system should not impose unnecessary requirements on telescope stability.

[REQ-1-OAD-2755] The facility AO system shall meet its requirements without pupil derotation.

Discussion: Pupil derotation reduces optical throughput and/or increases opto-mechanical complexity.

[REQ-1-OAD-2760] The facility AO system shall compensate for wavefront distortions introduced by dome/mirror seeing, telescope optics, and instrument optics, with the residual errors included as part of the AO system error budget.

Discussion: This implies requirements upon both the AO system and the other observatory subsystems introducing these disturbances. The telescope and instrument requirements include specifications on the amplitude of these wavefront errors, and the allowable residual wavefront errors for an idealized (linear, noise-free) AO system with order 60x60 wavefront compensation and a -3dB error rejection bandwidth of 30 Hz (see sections 3.4.1 and 3.4.4).

[REQ-1-OAD-2765] The facility AO system shall operate off-null in order to compensate non-common path aberrations in science instruments, with a maximum offset of 0.125 arc sec (TBC) on each wavefront sensing subaperture.

[REQ-1-OAD-2770] The AO facility system shall implement fast tip/tilt control of the Laser Guide Star (LGS) position on the sky to maintain their centering within the wavefront sensor field of view and minimize the errors due to sensor non-linearity.

Discussion: This implies that the fast tip/tilt control of the LGS is applied via fast tip/tilt mirrors located in the LGSF, with their commands computed by NFIRAOS.

4.2.3 NFIRAOS

4.2.3.1 General

[REQ-1-OAD-2800] NFIRAOS AO system shall have 2 deformable mirrors conjugate to 0 km and 12 km.

[REQ-1-OAD-2805] The early light implementation of NFIRAOS shall utilize piezo stack deformable mirrors.

Discussion: It is understood that either higher density piezostack mirrors or MEMS deformable mirrors may be utilized to improve image quality for the future upgrade of NFIRAOS.

[REQ-1-OAD-2810] NFIRAOS shall utilize six Na (Sodium) laser guide stars.

[REQ-1-OAD-2815] The NGS images shall be compensated via adaptive optics to improve tip/tilt measurement precision.

[REQ-1-OAD-2820] The early light facility AO system shall support the IRIS and IRMS system configurations.

[REQ-1-OAD-2825] NFIRAOS shall be designed to be upgradeable to a higher order AO system that interfaces to a wider-field near infra-red science instruments as envisioned in the SAC first decade instrument suite.

Discussion: The early light implementation of NFIRAOS provides acceptable image quality for the early light adaptive optics instrument suite, IRIS and IRMS. However, an upgrade of this instrument will be required to meet the full SRD performance requirements for these two instruments and additional first decade instrumentation including NIRES and WIRC.

[REQ-1-OAD-2830] NFIRAOS client instruments shall incorporate, and NFIRAOS shall utilize in closed loop, up to three (3) near infra-red natural guidestar tip/tilt wavefront sensors to maximize sky coverage.

[REQ-1-OAD-2840] NFIRAOS shall provide a high spatial resolution, slow "truth" NGS WFS to prevent long term drifts in the corrected wavefront due to variations in the sodium layer profile, WFS background noise due to Rayleigh backscatter, or other system calibration errors.

4.2.3.2 Servicing and Maintenance

[REQ-1-OAD-2845] NFIRAOS shall be designed to be consistent with the servicing and replacement intervals and scenarios shown in Table 20.

Discussion: These entries are intitial estimates, and are subject to change.

Table 20 NFIRAOS Servicing Requirements

TBD

4.2.4 LGSF

[REQ-1-OAD-2900] At early light, the LGSF shall be capable of projecting a sodium laser guide star asterism for NFIRAOS, as shown in Figure 9.

[REQ-1-OAD-2905] The LGSF shall be upgradeable to project other asterisms as required by the AO modes described in the ORD, with up to 9 LGS and radii varying from 5 arcsec to 510 arcsec, as shown in Figure 9. As a goal, this functionality shall be available at early light.

Discussion: The asterisms for the early light and first decade AO systems have been defined and are summarized in Figure 9:

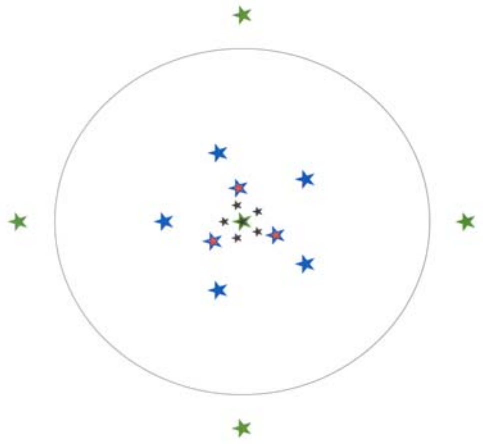


*Figure 9 LGSF asterisms supporting different AO modes: **NFIRAOS** (black) 1 on-axis, 5 on a 35 arcsec radius; **MIRAO** (red) 3 on a 70 arcsec radius; **MOAO** (blue) 3 on a 70 arcsec radius, 5 on a 150 arcsec radius; **GLAO** (green) 1 on-axis, 4 on a 510 arcsec radius*

[REQ-1-OAD-2910] The LGSF system shall be able to switch between asterisms within 2 minutes (TBC).

[REQ-1-OAD-2915] The baseline LGSF shall generate Laser Guide Stars with a signal level and image quality consistent with the first light NFIRAOS wavefront error budget defined in the ORD.

Discussion: NFIRAOS first light system will deliver images with an RMS wavefront error of 187 nm on axis, 191 nm over a 10 arcsec FOV and 208 nm over a 30 arcsec FOV. Based on current modeling, a total laser power of 150 W is appropriate to satisfy the NFIRAOS error budget during times with low sodium column density, i.e.25 W per beacon. This signal level may be reduced by ~65% if a laser pulse format that enables dynamic refocusing (in order to eliminate LGS elongation) is utilized.

[REQ-1-OAD-2920] The baseline LGSF shall use multiple lasers, and be operational with one laser down.

[REQ-1-OAD-2925] The LGSF shall use solid state, sum frequency generation (SFG) lasers with either a continuous wave (CW) or mode locked CW pulse format.

[REQ-1-OAD-2930] The Beam Transfer Optics of the LGSF shall use conventional optics to transport the beams from the Laser Room to the Laser Launch Telescope.

Discussion: Fiber transport is not considered as the baseline for the early light LGSF system because of the stressing TMT requirements in terms of laser peak power and optical path length.

[REQ-1-OAD-2935] The Laser Launch Telescope of the LGSF shall be mounted behind the secondary mirror of the telescope (M2).

[REQ-1-OAD-2937] In addition to any other motion requirements, the LGSF shall be capable of correcting for any combination of the deflections at the telescope top end as specified in Table 12.

[REQ-1-OAD-2940] The Laser Room (s) of the early light LGSF system shall be mounted within the (-X ECRS, -Y ECRS) location of the telescope azimuth structure.

REQ-1-OAD-2942: The LGSF Beam Transfer Optics shall transport the laser beams from the laser room up to the LGSF Laser Launch Telescope via the following path:

- The Beam Transfer Optics Azimuth Optical Path from the output of the laser room location up to the -X Nasmyth Platform at a location beneath the telescope elevation axis,
- The Beam Transfer Optics Deployable Optical Path from the previous location across to the -X ECRS telescope elevation journal via the telescope elevation axis
- The Beam Transfer Optics Elevation Optical Path from the –X ECRS telescope elevation journal up to the laser launch telescope via the (-X ECRS, +Y ECRS) vertical column of the telescope elevation structure and the connecting tripod leg.

REQ-1-OAD-2943: The Beam Transfer Optics Deployable Optical Path shall be parked (i) to allow observations with the on axis instrument located on the $–X_{ECRS}$ Nasmyth platform and (ii) to prevent vignetting of the on-axis instrument field of view.

Discussion: APS will be the early light on-axis instrument.

REQ-1-OAD-2944: The Beam Transfer Optics Deployable Optical Path shall never vignette the field of view of the off-axis instruments located on the $–X_{ECRS}$ Nasmyth platform, whatever the telescope orientation and whatever the Deployable Optical Path position (deployed or parked).

Discussion: The off-axis instruments include NFIRAOS.

[REQ-1-OAD-2945] In its parked configuration, the Beam Transfer Optics Deployable Optical Path shall not block access to instruments located on the $\_X_{ECRS}$ Nasmyth platform, whatever the telescope elevation orientation.

[REQ-1-OAD-2946] Interference between the deployed Beam Transfer Optics Deployable Path and access to the instruments located on the $-X_{ECRS}$ Nasmyth platform shall be minimized.

[REQ-1-OAD-2950] The LGSF system shall include all the necessary safety systems that are required with the use of the selected LGSF lasers.

Discussion: The LGSF safety system will provide interlocks to prevent laser damage to the personnel, the TMT observatory or to the LGSF itself. In addition, the LGSF will provide safety systems to avoid accidental illumination of aircraft, satellites and to avoid beam collision with neighboring telescopes.

[REQ-1-OAD-2955] The LGSF system shall be upgradeable to provide Laser Guide Stars with the signal level and image quality consistent with the wavefront error budget of an upgraded version of NFIRAOS as defined in the ORD.

Discussion: The upgraded version of NFIRAOS will achieve an on-axis, higher-order RMS wavefront error of about 120 nm. The proposed concept for this upgrade is to replace the order 60^2 DM and WFS components with compatible higher-order 120^2 components, and to upgrade the LGSF laser power correspondingly. The laser power requirements would normally be expected to scale by a factor of approximately 4, but this can be reduced to about a factor of 2 if pulsed lasers are used to eliminate guidestar elongation. The resulting laser power requirement is then roughly 6x50W=300W for the NFIRAOS asterism of 6 guidestars; it is possible that this requirement may be further relaxed by some combination of reduced detector read noise and "uplink AO" to sharpen the LGS that is projected onto the sky. It is expected that an ULAO system may reduce the required signal level by ~33%.

4.2.4.1 Servicing and Maintenance

[REQ-1-OAD-2960] The LGSF shall be designed to be consistent with the servicing and replacement intervals and scenarios shown in Table 21.

Discussion: These entries are initial estimates, and are subject to change.

Table 21 LGSF Servicing Requirements

[REQ-1-OAD-2990] Access shall be provided to the LGSF Top End when the telescope is horizon pointing.

[REQ-1-OAD-2992] Access shall be provided to those components of the LGSF Beam Transfer Optics Elevation Optical Path which are located along the telescope vertical column when the telescope is horizon pointing.

[REQ-1-OAD-2994] Access shall be provided to those components of the LGSF Beam Transfer Optics Elevation of the Optical Path which are located along the telescope tripod leg when the telescope is horizon pointing.

Discussion: No such components are defined in the current design.

[REQ-1-OAD-2996] Access shall be provided to the components of the LGSF Beam Transfer Optics Deployable Optical Path when the telescope is zenith pointing

4.2.5 Adaptive Optics Executive Software (AOESW)

4.2.5.1 General

[REQ-1-OAD-3000] The AO Executive Software shall include a AO Sequencer to sequence and coordinate the actions of the NFIRAOS, the LGSF, and the early light instrument wavefront sensors, before, during and after each observation.

Discussion: This includes, but is not limited to, configuring the AO systems at the beginning of an observation, acquiring the guide stars, performing necessary calibrations, and managing the AO loops.

[REQ-1-OAD-3005] The AO Sequencer shall be upgradeable to control the first decade AO system upgrades as defined in the ORD

Discussion: This includes, but is not limited to, the control of the MIRAO, MOAO, GLAO, and ExAO modes for the associated first decade science instruments, as well as AM2.

[REQ-1-OAD-3010] The AO Sequencer shall offload tip, tilt, focus, coma, and up to 100 M1 modes, as computed by either an AO system or a seeing limited instrument, to the Telescope Control System.

Discussion: This corresponds to the “offload router” functionality described in section 3.1.4

[REQ-1-OAD-3015] The AO Executive Software shall generate the AO reconstructor parameters needed by NFIRAOS to perform the AO real time reconstruction.

[REQ-1-OAD-3020] The AO Executive Software shall post process the AO PSF from the NFIRAOS AO real time data.

4.2.5.2 Servicing and Maintenance

[REQ-1-OAD-3050] The AOESW shall be designed to be consistent with the servicing and replacement intervals and scenarios shown in Table 22.

Discussion: These entries are intitial estimates, and are subject to change.

Table 22 AOESW Servicing Requirements

TBD

4.2.6 IRIS

4.2.6.1 General

4.2.6.2 Servicing and Maintenance

[REQ-1-OAD-3150] IRIS shall be designed to be consistent with the servicing and replacement intervals and scenarios shown in Table 23.

Discussion: These entries are intitial estimates, and are subject to change.

Table 23 IRIS Servicing Requirements

TBD

4.2.7 IRMS

4.2.7.1 General

4.2.7.2 Servicing and Maintenance

[REQ-1-OAD-3250] IRMS shall be designed to be consistent with the servicing and replacement intervals and scenarios shown in Table 24.

Discussion: These entries are intitial estimates, and are subject to change.

Table 24 IRMS Servicing Requirements

TBD

4.2.8 WFOS

4.2.8.1 General

4.2.8.2 Servicing and Maintenance

[REQ-1-OAD-3350] WFOS shall be designed to be consistent with the servicing and replacement intervals and scenarios shown in Table 25.

Discussion: These entries are intitial estimates, and are subject to change.

Table 25 WFOS Servicing Requirements

TBD

4.3 SERVICES

4.3.1 Power, Lighting and Grounding

4.3.1.1 General

[REQ-1-OAD-4500] The power, lighting and grounding system shall distribute dedicated and general purpose AC power throughout the telescope structure.

4.3.1.2 Power Allocation for Subsystems

[REQ-1-OAD-4550] A portion of the power shall be conditioned and backed up via Uninterruptible Power Supplies (UPS).

[REQ-1-OAD-4555] Dedicated power shall be made available to, at a minimum, the following systems: Instruments and AO systems, Telescope Drives, Cable Wraps, M1, M2, and M3 systems; and the LGSF Systems (Laser Rooms, the Beam Transfer Optics Optical Path and the LGSF Top End).

[REQ-1-OAD-4560] General power shall be made available via industry standard keyed and color coded power outlets.

[REQ-1-OAD-4565] Single and Three Phase power will be available; voltages and frequency characteristics are dependent on the site location.

This section will allocate the observatory power usage budget amongst the telescope systems. TBD

4.3.1.3 Lighting Requirements

[REQ-1-OAD-4600] Spot and emergency lighting will be available on the mirror cell, Nasmyth Platforms, and cat walks.

4.3.1.4 Grounding Requirements

[REQ-1-OAD-4650] Dedicated isolated grounds will be utilized for sensitive equipment.

4.3.2 Coolant

4.3.2.1 General

[REQ-1-OAD-4700] Chilled glycol coolant shall be provided to the Nasmyth areas for removal of heat from instrumentation and telescope control systems electronics.

[REQ-1-OAD-4705] Compressed refrigerant (e.g. Hydrochlorofluorocarbon (HCFC) shall be provided to the Nasmyth areas for removal of heat from instrumentation.

Discussion: NFIRAOS plans to use a refrigerant system to cool their instrument enclosure.

[REQ-1-OAD-4710] Pressurized helium shall be provided to the Nasmyth areas for use in cooling cryogenic instruments.

[REQ-1-OAD-4715] Chilled glycol coolant shall be provided to the LGSF Top End for removal of heat from the LGSF Top End and the associated electronics enclosures.

[REQ-1-OAD-4720] Chilled glycol coolant shall be provided to the LGSF Laser rooms for removal of heat from the laser rooms, laser systems and associated electronics enclosures.

[REQ-1-OAD-4725] Chilled glycol coolant shall be provided to the different locations of the LGSF Beam Transfer Optics Optical Path, included but not limited to, the Deployable Optical Path and the Azimuth Optical Path.

4.3.3 Communications and Information Services (CIS)

4.3.3.1 Local Area Network (LAN)

[REQ-1-OAD-4800] An observatory-wide local area network (LAN) shall be established. The LAN reference design is Ethernet based on TCP/IP protocols running on twist-pair copper or fiber-optic cables.

[REQ-1-OAD-4805] The observatory LAN must support mean data rates of 0.02 Gbits/sec and peak rates of 0.5 Gbits/sec.

[REQ-1-OAD-4810] A standard star topology is the LAN design reference architecture. In this model, a central server/router area is connected by fiber to local wiring centers that are in turn connected to service points by structured cabling.

[REQ-1-OAD-4815] The LAN shall be connected to the Internet with enough bandwidth to support general communications activity, remote observing, remote diagnostics, and data transfer from the Observatory to other Internet sites (especially Internet sites within continental North America).

[REQ-1-OAD-4820] Internet bandwidth requirements are still TBD.

[REQ-1-OAD-4825] Internet connectivity will be established using existing physical connections or via microwave links to the nearest Internet service point.

[REQ-1-OAD-4830] All LAN servers must be connected to UPS systems.

[REQ-1-OAD-4835] Redundant IT hardware capacity (including pre-configured spares) must be available to allow return to service in less than 30 minutes.

[REQ-1-OAD-4840] Multiple redundant physical connections must be available between wiring centers and service points. It must be possible to switch between physical connections rapidly.

[REQ-1-OAD-4845] LAN network traffic shall be partitioned so that the following major components do not interfere with each other: general communications, TMT software system communication and synchronization traffic, science data traffic, and technical data traffic.

[REQ-1-OAD-4850] Standard Internet services (e-mail, Web, video conferencing, voice-over-IP, etc.) must be supported.

[REQ-1-OAD-4855] A hardware time bus system shall be implemented consisting of a central GPS receiver (with antenna) and a cable-based distribution system out to patch panels on the telescope structure.

4.4 FACILITIES

4.4.1 Enclosure

4.4.1.1 General

[REQ-1-OAD-5050] The TMT enclosure shall be of a Calotte style, consisting of three major structures: the base, cap and shutter.

[REQ-1-OAD-5055] The enclosure shall be capable of moving in azimuth and zenith position between observations within 3 minutes (reference availability requirements).

[REQ-1-OAD-5060] The enclosure azimuth and cap axes shall accelerate at a rotational rate of at least TBD rad/s^2.

[REQ-1-OAD-5065] The enclosure aperture shall be capable of tracking the telescope pointing during guiding with a maximum error of 1 (TBC) degree on the sky.

[REQ-1-OAD-5070] For all equipment in the observatory that requires servicing there shall be safe and efficient access by personnel, provisions for transporting tools and supplies to the servicing locations, and provisions for access and lifting of the equipment for installation, removal and replacement, as appropriate.

[REQ-1-OAD-5075] The enclosure design shall incorporate vibration mitigation to manage the generation and transmission of vibrations to the telescope, instruments, adaptive optics, alignment & phasing, and calibration subsystems (reference error budget).

[REQ-1-OAD-5080] The enclosure aperture opening and closing shall be designed to prevent water, ice or snow from falling into the enclosure.

[REQ-1-OAD-5085] Fixed facility lighting on the interior of the fixed and rotating enclosure shall be capable of illuminating the interior of the enclosure at a light level of 100 lux everywhere, and at 300 lux on walkways and stairways.

Discussion: Additional, higher illumination lighting may need to be provided for localized work areas on a portable basis.

[REQ-1-OAD-5090] The enclosure and summit fixed base shall provide a safe environment for all observatory employees and visitors.

[REQ-1-OAD-5095] The enclosure design and maintenance plan shall minimize the loss of observing time (reference reliability budget).

[REQ-1-OAD-5100] During observations, the enclosure shall limit the vibration transmitted to the summit facility fixed base to less than the PSD shown in Figure 10 Allowable enclosure vibration PSD.

TBD

Figure 10 Allowable enclosure vibration PSD

4.4.1.2 Enclosure Geometry

[REQ-1-OAD-5150] No point of the inner enclosure shall be closer to the origin of the ECRS than 29 meters. It is understood that this value ensures a 0.5 meter gap between the telescope and enclosure. This gap may be bridged at particular places in order to provide access to various areas of the telescope, like the Nasmyth platform. Such bridges may create pinch points, which must be addressed by the Observatory Safety System.

Discussion; This requirement applies at all points above TCRS z = 0

[REQ-1-OAD-5155] The plane of contact between the enclosure azimuth track and the summit facility fixed base mounted bogey wheels shall be 6.4 m above the X-Y plane of the ACRS.

[REQ-1-OAD-5160] The external radius of the enclosure shall be 33 meters.

4.4.1.3 Wind, Thermal and Environmental Management

[REQ-1-OAD-5175] The enclosure and summit fixed base shall be instrumented with wind speed and temperature measurement sensors such that the thermal and wind environment can be sensed and managed through the use of enclosure vents.

[REQ-1-OAD-5180] The enclosure vents shall be individually controlled to allow all opening positions between closed and fully open, and used to enable natural ventilation of the enclosure interior during observation.

[REQ-1-OAD-5185] The enclosure vent assemblies shall designed for a duty cycle that allows regular movement during Observing Mode.

Discussion: In observing mode it is expected that the vent positions will be moved often.

[REQ-1-OAD-5190] The projected vented area on the enclosure shall be adequate to allow the mean wind velocity at the primary mirror to reach at least 50% of the external mean wind velocity.

Discussion: It is understood that in order to achieve adequate wind reduction at the secondary mirror deflectors may be deployed around the edge of the aperture. Their size and orientation should be such that the ratio of distance between EA and top of M2 to enclosure outer diameter should not exceed 0.92. (private communication from K. Vogiatzis).

[REQ-1-OAD-5195] The enclosure environment shall be insulated to manage heat flow into the enclosure during the daytime to a degree that enables suitable thermal management with the addition of a practical and cost effective active air conditioning system.

[REQ-1-OAD-5200] The enclosure shall not utilize an active forced air ventilation system for the thermal management of the enclosure during aperture-open observing mode.

Discussion: We assume we can meet the error budget allocation for enclosure and M1 seeing with a passive ventilation system at night, and active enclosure thermal management system in the daytime.

[REQ-1-OAD-5205] The enclosure system shall provide sufficient protection from wind loading on the telescope to allow the observatory system to meet operational requirements and dynamic image motion error budget requirements.

[REQ-1-OAD-5207] The enclosure shall incorporate aperture flaps to deflect wind at the aperture opening to reduce dynamic loading on the top end of the telescope.

Discussion: This is an observatory architecture decision to enable a smaller sized enclosure, as per System Engineering Meeting Minutes TMT.SEN.COR.06.033, with a supporting technical note TMT.SEN.TEC.06.029. Aperture flaps increase the effective diameter of the enclosure for protection of the telescope top end from wind buffeting. The aerodynamic characteristics and shape of the deployed aperture flaps shall be agreed with TMT systems engineering and referenced in the Enclosure DRD.

[REQ-1-OAD-5210] The enclosure and summit facility fixed base shall be sealed to minimize influx of air and dust when in non-observing, aperture-closed mode.

Discussion: Sealing and positive pressure is necessary to reduce heat flow into the observatory during the daytime, and to keep equipment and optics clean. Positive pressurization should be considered.

4.4.1.4 Summit Facility Fixed Base

[REQ-1-OAD-5240] The summit facility fixed base shall provide the support and foundation for the enclosure.

Discussion: The summit facility fixed base is a deliverable of the summit facility subsystem

[REQ-1-OAD-5245] The summit facility shall provide a central pier and foundation to support the telescope.

[REQ-1-OAD-5250] The summit facility fixed base wall structure shall support all load combinations of the rotating enclosure under all environmental and operating conditions.

[REQ-1-OAD-5255] The summit facility fixed base floor structure shall support the expected load combinations of equipment and components that need to be moved within the enclosure.

[REQ-1-OAD-5257] The observing floor shall be flat and continuous and free from obstructions in the area from the central pier to the interior of the enclosure fixed base, at radial distances between 18 meters and 28 meters, over at least +/- 20 degrees in azimuth from the exterior overhead door and +/- 20 degrees from the door into the summit support facility.

[REQ-1-OAD-5258] As a goal, the observing floor shall be flat and continuous and free from obstructions at all azimuth positions, at radial distances between 18 meters and 28 meters.

[REQ-1-OAD-5260] The summit facility fixed base shall provide an access door to the exterior of the facility at grade with an opening of at least TBD m wide by TBD m high for equipment and component movement.

[REQ-1-OAD-5265] The summit facility fixed base shall provide access doors to the adjacent summit facilities structure for mirror, instrument, and people movements.

[REQ-1-OAD-5270] The summit facility fixed base shall provide a path for delivery of utility services to the telescope and instruments that does not restrict movement within the enclosure.

[REQ-1-OAD-5275] The summit facility fixed base design shall incorporate vibration mitigation to minimize the generation and transmission of vibrations to the telescope, instruments, adaptive optics, alignment & phasing, and calibration subsystems (reference error budget).

[REQ-1-OAD-5280] The summit facilities shall provide space adjacent to the mirror coating area for the storage of equipment used for in-situ optics cleaning of M1, M2 and M3.

[REQ-1-OAD-5285] The summit facilities shall provide space adjacent to the mirror coating area for the storage of equipment used for optics handling equipment.

[REQ-1-OAD-5290] The summit facility fixed base shall contain equipment to be used in the day time to air condition the enclosure to the expected night time observing temperature.

[REQ-1-OAD-5295] The summit facility fixed base shall provide appropriate personnel and equipment access to the telescope structure, telescope mounted systems, and the enclosure.

4.4.1.5 Top End Servicing Platform

[REQ-1-OAD-5325] The enclosure shall provide an access platform to allow servicing of the LGSF top end and M2S when the telescope is in the horizon pointing position.

Discussion: The top end platform may violate the 29 metre 'stay out zone' defined in REQ-1-OAD-5150 in the deployed position.

[REQ-1-OAD-5330] An interlock shall be provided that prevents any movement of the telescope or enclosure that would cause a collision between the telescope and the top end servicing platform when it is deployed.

[REQ-1-OAD-5331] An interlock system shall be provided that prevents deployment of the top end servicing platform unless the telescope is positioned correctly relative to the enclosure and both the telescope and enclosure are stationary.

Discussion: This will be the responsibility of the Observatory Safety System, interfacing with the TSS and the ENC.

[REQ-1-OAD-5332] The top end servicing platform shall accommodate a minimum total load of 650kg anywhere on the platform.

[REQ-1-OAD-5334] The top end platform shall accommodate TBD persons

[REQ-1-OAD-5336] The top end platform shall provide appropriate power outlets to allow servicing of the LGSF top end and M2S

[REQ-1-OAD-5338] The top end platform shall provide sufficient lighting to illuminate the M2S and LGSF top end during servicing.

[REQ-1-OAD-5340] The enclosure shall provide a means to control this lighting remotely and from the top end platform

4.4.1.6 Survival Loads

[REQ-1-OAD-5300] The enclosure shall meet the environmental constrain survival conditions as specified in the ORD.

[REQ-1-OAD-5305] In addition to the ORD requirements for survival, the enclosure shall withstand seismic events of up to TBD g lateral ground acceleration, with minor damage (meaning a resumption of full functionality within 1 week of event occurrence).

[REQ-1-OAD-5310] In addition to the ORD requirements for survival, the enclosure shall withstand ice loads of up to 76 mm, without sustaining any damage.

[REQ-1-OAD-5315] In addition to the ORD requirements for survival, the enclosure shall withstand snow loads of up to 150 kg/m^2, without sustaining any damage.

[REQ-1-OAD-5400] There shall be a procedure or mechanism for removal of snow and ice accumulations on the enclosure that could otherwise prevent:

1) rotatation of the enclosure cap or base.

2) operation of the aperture flaps.

3) operation of the aperture without snow or ice falling inside the enclosure.

4) operation of the vents.

5) the ability to safely observe.

6) Opening of the shutter

[REQ-1-OAD-5405] There shall be a procedure or mechanism for removal from the enclosure any snow and ice accumulations that present safety hazards to personnel in working areas within or around the summit facilities.

Discussion: Some areas external to the facilities buildings and enclosure may be designated as off limits, and therefore not considered to be working areas.

[REQ-1-OAD-5410] Snow or ice falling from the enclosure shall not cause damage to the enclosure, facility buildings or any other summit systems.

[REQ-1-OAD-5415] The enclosure and / or summit facilities shall incorporate features to mitigate the potential damage and danger related to snow or ice falls from the enclosure onto other parts of the enclosure, the facility buildings or any other summit systems.

Discussion: This could for example include systems to divert falling snow and ice to agreed areas, or gratings to reduce the size of slabs of ice falling onto the adjacent facilities building.

[REQ-1-OAD-5420] The process of removal of ice and snow accumulations to enable safe observing shall be able to be accomplished with a crew of TBD people within an 8 hour daytime period.

4.4.1.7 Enclosure Servicing and Maintenance

[REQ-1-OAD-5350] All enclosure servicing and maintenance operations shall be able to be accomplished with the enclosure cap closed.

[REQ-1-OAD-5355] The enclosure shall be designed to be consistent with the servicing and replacement intervals and scenarios shown in Table 26.

Discussion: These entries are initial estimates, and are subject to change.

Table 26 Enclosure Servicing Requirements

TBD

4.4.2 Summit Facilities

4.4.2.1 *General*

[REQ-1-OAD-5504] All equipment at the summit observatory shall at minimum follow best engineering practices to minimize the production and transmission of vibrations onto the telescope.

[REQ-1-OAD-5450] The summit facilities shall provide suitable sanitary, eating, personal storage, and rest areas to support operations and observing personnel working extended hours at the summit.

[REQ-1-OAD-5475] The summit facilities shall route power, communications and services to the telescope and enclosure.

[REQ-1-OAD-5480] The summit facilities shall provide space for equipment related to enclosure or telescope mounted systems as per agreed interfaces.

[REQ-1-OAD-5500] All regularly used summit facility building areas, excluding the enclosure environment, shall be climate controlled.

[REQ-1-OAD-5502] Telephone systems and data ports shall be provided throughout the summit facilities.

4.4.2.2 *Mirror Maintenance*

[REQ-1-OAD-5505] A mirror stripping and coating facility sufficient to process the M1 mirror segments, M2, and M3 mirrors shall be located adjacent to the enclosure to minimize mirror transportation (reference coating requirements).

[REQ-1-OAD-5510] The mirror coating and stripping facility shall be equipped with an overhead crane.

[REQ-1-OAD-5515] The mirror coating area shall be built and equipped to be capable of providing a class 10,000 clean room environment.

[REQ-1-OAD-5520] A storage facility for the spare quantity of M1 mirror segments shall be provided adjacent to the mirror stripping and coating facility.

[REQ-1-OAD-5522] The M1 segment storage room shall be temperature controlled to avoid temperature cycling of the segments.

[REQ-1-OAD-5525] The mirror storage area shall be positively pressurized to minimize the ingress of dust.

4.4.2.3 *Operations Spaces*

[REQ-1-OAD-5540] The summit facilities shall provide infrastructure to support daytime and night time observatory operations.

[REQ-1-OAD-5545] A control room shall be provided adjacent to the enclosure with sufficient space for observing staff and associated computers and monitors.

[REQ-1-OAD-5550] An air conditioned computer room shall be provided adjacent to the enclosure with sufficient space for all centrally located observatory information technology resources.

4.4.2.4 *Lab & Shop Spaces*

[REQ-1-OAD-5565] A mechanical workshop shall be provided adjacent to the enclosure.

Discussion: This workshop will contain sufficient machining, fabricating equipment, tools, consumables, and associated storage to support day to day maintenance activities at the summit.

[REQ-1-OAD-5570] An engineering workshop and optical lab shall be provided adjacent to the enclosure.

Discussion: This workshop will contain sufficient optical and electronic equipment, tools, consumables, and associated storage to support day to day engineering activities at the summit.

[REQ-1-OAD-5575] The summit facility mechanical and engineering workshops shall be equipped with overhead bridge cranes with sufficient hook height for associated component movements.

Discussion: Instrument servicing and maintenance will be done on the Nasmyth platforms.

4.4.2.5 Personnel Spaces

[REQ-1-OAD-5590] Personnel spaces, including entry lobby, conference room, offices, kitchenette, bathrooms, first aid, janitorial and associated storage shall be provided adjacent to the enclosure to support the direct day time maintenance crew and night time observing crew.

Discussion: Personnel spaces for indirect operations, administration, site services, indirect engineering staff, and visitors are provided at the support facility.

[REQ-1-OAD-5592] A viewing gallery shall be provided with a window to the enclosure space.

[REQ-1-OAD-5594] The viewing gallery shall have a separate entrance and shall contain bathrooms.

[REQ-1-OAD-5596] The viewing gallery area shall provide toilets for access by the general public.

4.4.2.6 Shipping & Receiving

[REQ-1-OAD-5605] A shipping and receiving area shall be provided adjacent to the enclosure for delivery/uncrating and removal/crating of components and equipment to/from the summit facilities.

[REQ-1-OAD-5610] The shipping & receiving area shall be equipped with an overhead bridge crane with sufficient hook height for associated component movements.

Discussion: It is anticipated that larger sized components and instruments will be delivered/removed directly to/from the enclosure through the access doorway in the enclosure.

4.4.2.7 Mechanical Plant

[REQ-1-OAD-5620] A mechanical plant building that is physically separate from the summit facilities building will be provided to house equipment that has significant heat and vibration output.

[REQ-1-OAD-5622] The mechanical plant building shall be positioned so that equipment thermal and vibration effects have a minimal influence on the observatory performance, and that the building has minimal aerodynamic influence on the observatory.

[REQ-1-OAD-5625] The mechanical plant shall supply the mechanical services required at the summit facilities, including chilled and circulated water/glycol, compressed/dry air, telescope and instrument hydraulic oil and power unit(s), cryogenic closed cycle coolers and/or facility helium circulation, instrument refrigerant systems, enclosure pressurization, building air conditioning, fire suppression, water & waste storage, LN2 storage.

Discussion: Portions of the mechanical plant may need to be separated from the enclosure and adjacent summit building structure to minimize vibration, thermal, and aerodynamic interference with the observatory.

[REQ-1-OAD-5630] The summit facility mechanical plant shall incorporate chillers, to be used in the daytime with the air conditioning system in the fixed base, with sufficient capacity to maintain the internal air temperature of the enclosure at the expected night time outside temperature.

Discussion: Air conditioning of the enclosure during the daytime is required to make sure that the primary mirror temperature is close to optimal when we open the dome. It is to be determined what the optimal prediction scheme is for setting the daytime temperature.

4.4.2.8 Electrical Plant

[REQ-1-OAD-5640] The summit facility shall provide an electrical plant to supply the electrical services required at the summit facilities, including power transmission, voltage transformation, power conditioning, and uninterruptible power supply.

Discussion: The electrical generators are located at the nearby support facility in the Armazones reference model. This may need to be reconsidered for other sites.

4.4.2.9 Roads & Parking

[REQ-1-OAD-5655] The roadway away from the summit facility shall be paved or otherwise treated for a sufficient distance to minimize the generation of dust directed towards the summit facility.

[REQ-1-OAD-5657] The roadway close to the summit facility shall be covered with gravel or another material to minimize detrimental night time thermal effects.

[REQ-1-OAD-5660] Road vehicle parking shall be provided close to the summit facility building entry/lobby with sufficient spaces to support the day time maintenance crew and the night time observing crew.

[REQ-1-OAD-5665] Transport vehicle access and loading/unloading space shall be provided close to the summit facility building shipping/receiving area and close to the direct access doorway into the enclosure.

4.4.2.10 Grounding and Lightning Protection

[REQ-1-OAD-5680] The summit facility fixed base and summit buildings shall have copper mesh grounding arrangements embedded in the foundations and surrounding grounds.

[REQ-1-OAD-5682] The enclosure and summit buildings shall provide transient surge suppression on all electrical supplies, electrical circuits, and communication circuits.

[REQ-1-OAD-5685] The external lightning protection system shall comply with the National Fire Protection association (NFPA) standard for installation of lightning protection systems 780-2004 edition.

Discussion: An additional active lightning dissipation system may be required.

4.4.2.11 Fire Protection and Safety

[REQ-1-OAD-5690] The summit facilities shall provide a fire suppression system for all infrastructure and equipment at the observatory summit.

[REQ-1-OAD-5692] The summit facilities shall support first aid treatment of personnel.

4.4.2.12 Summit Facility Servicing and Maintenance

[REQ-1-OAD-5700] The summit facility shall be designed to be consistent with the servicing and replacement intervals and scenarios shown in Table 27.

Discussion: These entries are intitial estimates, and are subject to change.

Table 27 Summit Facility Servicing Requirements

TBD

4.4.3 Support Facilities

4.4.3.1 General

[REQ-1-OAD-5740] All regularly used support facility building areas shall be climate controlled.

4.4.3.2 Electrical Generators

[REQ-1-OAD-5750] The electrical power needs of the summit, support and construction camp facilities shall be provided by a set of electrical generators and transmission infrastructure located within reasonable distance of the support facilities.

Discussion: The electrical generators are located at the nearby support facility in the Armazones reference model. This may need to reconsidered for other sites. If prime power is available, such as from HELCO at Mauna Kau, then the electrical generators would be sized to provide backup power.

[REQ-1-OAD-5755] The electrical generators shall be configured to have redundancy to allow continued full operation with one generator set or prime power source out of service.

4.4.3.3 Accommodations

[REQ-1-OAD-5765] Accommodation facilities, including sleeping, dining, sanitation, recreation, and communication capabilities shall be provided at the support facility to support personnel who are required to remain close to observatory (reference operations plan/OCD).

Discussion: The remote nature of the observatory site may necessitate an operations scenario with staff rotation and the need for staff to remain close to the observatory for multiple days or weeks.

4.4.3.4 Maintenance Yard

[REQ-1-OAD-5775] A maintenance yard, including technical workshops, vehicle and rolling stock storage, and offices shall be provided at the support facility to support site services, roadway maintenance, vehicle and rolling stock maintenance, repairs and reconditioning of observatory components, and staging of new observatory components.

4.4.3.5 Administration

[REQ-1-OAD-5785] Personnel spaces, including reception, conference room, offices, kitchenette/lounge, bathrooms, first aid, janitorial and associated storage shall be provided at the support facility to support on-duty indirect operations, administration, site services, engineering staff, and visitors.

Discussion: Personnel spaces to support the direct day time maintenance crew and night time observing crew are provided at the summit facility.

[REQ-1-OAD-5790] An air conditioned computer room with a gaseous fire suppression system shall be provided at the support facility with sufficient space for all centrally located support facility information technology resources, including network gear, servers, and a second site for backup data storage.

Discussion: It is not anticipated that a control room will not be required at the support facility for the Armazones site.

4.4.3.6 Lab & Shop Spaces

[REQ-1-OAD-5810] A mechanical workshop shall be provided at the support facility with sufficient machining, welding, and fabricating equipment, tools, consumables, and associated storage to support extended maintenance and staging of new component activities for the observatory.

[REQ-1-OAD-5815] An engineering workshop shall be provided, containing sufficient optical and electronic equipment, tools, consumables, and associated storage to support extended maintenance and staging of new component activities for the observatory.

[REQ-1-OAD-5820] The support facility mechanical and engineering workshops shall be equipped with overhead bridge cranes with sufficient hook height for associated component movements.

4.4.3.7 Storage

[REQ-1-OAD-5830] Storage and warehousing capacity shall be provided at the support facility that is sufficient to house the recommended spare components and extended consumables for the observatory.

Discussion: The storage and warehousing area will be used for to store telescope components, and provide a laydown area for telescope components during erection.

Discussion: Some spare components and consumables could be stored at locations further away if they are not required to prevent observatory downtime (reference reliability budget).

4.4.3.8 Shipping & Receiving

[REQ-1-OAD-5840] A shipping and receiving area shall be provided at the support facility for delivery/uncrating and removal/crating of components and equipment to/from the support facility.

[REQ-1-OAD-5845] The shipping & receiving area shall be equipped with an overhead bridge crane with sufficient hook height for associated component movements.

4.4.3.9 Mechanical Plant

[REQ-1-OAD-5855] Mechanical plant shall be provided to supply the mechanical services required at the support facility.

Discussion: Notionally this is just support facility heating, air conditioning, domestic water and waste, but there may be need for mechanical plant to support extended observatory maintenance and staging of new components.

4.4.3.10 Electrical Plant

[REQ-1-OAD-5860] Electrical plant shall be provided to supply the electrical services required at the support facility.

Discussion: Notionally this is just support facility mains power, power conditioning, uninterruptible power supply, fire alarms, etc., but there may be need for electrical plant to support extended observatory maintenance and staging of new components.

4.4.3.11 *Roads & Parking*

[REQ-1-OAD-5870] The roadways around the support facility shall be paved or otherwise treated for a sufficient distance to minimize the generation of dust directed towards the support facilities.

[REQ-1-OAD-5875] People vehicle parking shall be provided close to the support facility building entries with sufficient spaces to support the extended maintenance, administration, and visitor personnel.

[REQ-1-OAD-5880] Transport vehicle access and loading/unloading space shall be provided close to the support facility shipping/receiving and maintenance yard areas.

4.4.3.12 *Fire Systems*

[REQ-1-OAD-5890] The support facility shall provide a fault tolerant water system for fire safety at the support and summit facilities.

4.4.4 Site Construction Camp

4.4.4.1 Accommodations

[REQ-1-OAD-5900] Accommodation facilities, including sleeping, dining, sanitation, recreation, and communication capabilities shall be provided near the eventual support facility location to support construction personnel who are required to remain close to observatory (reference site preparation, erection, and AIV plans).

Discussion: The remote nature of the observatory site may necessitate a construction scenario with personnel rotation and the need for personnel to remain close to the observatory for multiple weeks or months.

[REQ-1-OAD-5905] It is desirable that the construction camp accommodations be reusable after the end of construction as additional overflow accommodations to the eventual support facility accommodations.

[REQ-1-OAD-5907] A subset of the construction camp accommodations shall be of sufficient quality for use by professional staff, including scientists and engineers.

4.4.4.2 Staging Areas

[REQ-1-OAD-5915] Staging areas for observatory construction components shall be provided near the eventual support facility location (reference site preparation, erection, and AIV plans).

4.4.4.3 Mechanical Plant

[REQ-1-OAD-5925] Temporary mechanical plant shall be provided to supply the mechanical services required for the construction camp and staging areas.

Discussion: Notionally this is just camp heating, air conditioning, domestic water and waste, but there may be need for mechanical plant to support construction staging and preassembly.

4.4.4.4 Electrical Plant

[REQ-1-OAD-5935] Temporary electrical plant shall be provided to supply the electrical services required at the construction camp and staging areas.

Discussion: Notionally this is just camp mains power, power conditioning, uninterruptible power supply, fire alarms, etc., but there may be need for electrical plant to support construction staging and preassembly.

4.4.4.5 Roads & Parking

[REQ-1-OAD-5945] People vehicle parking shall be provided close to the construction camp building entries with sufficient spaces to support the construction personnel.

[REQ-1-OAD-5950] Transport vehicle access and loading/unloading space shall be provided close to the staging areas.

4.5 SERVICING AND MAINTENANCE

4.5.1 Crane Systems

Discussion: Listed capacities for crane systems are safe working loads that include appropriate factors of safety.

[REQ-1-OAD-6200] The entire interior of the enclosure, including the inside surface of the dome and the all components of the telescope shall be accessible by personnel lifts and freight cranes.

[REQ-1-OAD-6210] There shall be a 20 metric tonne capacity enclosure base mounted crane that shall have the following features:

- The maximum reach shall be no less than R 17.0 m to R 25.7 m relative to the TCRS z-axis.
- The maximum hook height shall be at least 34.5 m above the TCRS XY plane, including any hydra sets needed to achieve the required motion.
- The minimum hook vertical speed shall be no greater than 0.3 m/min.
- The minimum hook horizontal speed shall be no greater than 0.3 m/min.
- The crane shall have a mode in which the vertical hook acceleration is no greater than 0.05g.
- The minimum horizontal hook position resolution shall be no greater than Ø 25.0 mm.
- The minimum increment of vertical motion shall be no greater than 2mm.

Discussion: The crane will principally be used to service instruments on the Nasmyth platforms.

[REQ-1-OAD-6211] In addition to the 20t winch the crane described in REQ-1-OAD-6210 (above) shall have a 5t winch.

[REQ-1-OAD-6212] The 5 tonne and 20 tonne enclosure base mounted cranes shall be rated for lifting up to 2 persons in a man basket.

[REQ-1-OAD-6213] There shall be a 10 metric tonne capacity, enclosure base mounted jib crane, capable of servicing components on and in the vicinity of enclosure-mounted telescope top end service platform. The jib crane shall have the following features:

- The maximum reach shall be no less than 6.5m (between R 22.5m to R 29.0 m relative to the TCRS z-axis)
- The maximum hook height shall be at least 24.5 m above the TCRS XY plane including any hydra sets needed to achieve the required motion.
- The minimum hook vertical speed shall be no greater than 0.3 m/min.
- The minimum hook horizontal speed shall be no greater than 0.3 m/min.
- The crane shall have a mode in which the vertical hook acceleration is no greater than 0.05g.
- The minimum horizontal hook position resolution shall be no greater than Ø 25.0 mm.
- The minimum increment of vertical motion shall be no greater than 2mm.

[REQ-1-OAD-6216] There shall be a 10 metric tonne capacity, enclosure shutter mounted hoist. The hoist shall have the following features:

- The maximum reach shall be no less than R 0.0m to R 27.5m relative to the TCRS z-axis
- At 27.5 m radius, the maximum hook height shall be at least 35.5 m above the TCRS XY plane, including any hydra sets needed to achieve the required motion.

- At 0.0 m radius, the maximum hook height shall be at least 49.5 m above the TCRS XY plane, including any hydra sets needed to achieve the required motion.
- The minimum hook vertical speed shall be no greater than 0.3 m/min.
- The minimum hook horizontal speed shall be no greater than 0.3 m/min.
- The hoist shall have a mode in which the vertical hook acceleration is no greater than 0.05g.
- The minimum horizontal hoist position resolution shall be no greater than Ø 50.0 mm.
- The minimum increment of vertical motion shall be no greater than 2mm.

[REQ-1-OAD-6218] The shutter mounted hoist control will be achieved using motion commands in a locally defined coordinate system.

> *Discussion: The shutter mounted hoist horizontal motion is achieved through coordinated motion of the enclosure base and cap, which must be resolved into a local Cartesian or other coordinate system for operator ease of use.*

[REQ-1-OAD-6219] The shutter mounted hoist shall be rated for lifting up to 2 persons in a man basket.

[REQ-1-OAD-6230] There shall be a crane with a minimum 0.5 tonne capacity for handling primary mirror segment assemblies.

> *Discussion: Mass estimate for primary mirror segment assemblies is 210 kg and 150 kg for the lifting talon.*

[REQ-1-OAD-6235] There shall be a crane with a minimum capacity of 2.5 tonnes for handling enclosure azimuth bogies.

> *Discussion: Mass estimate for azimuth bogies is 2000 kg*

[REQ-1-OAD-6236] There shall be a crane with a minimum capacity of 0.5 tonnes for handling enclosure cap bogies.

> *Discussion: Mass estimate for azimuth bogies is 440 kg*

[REQ-1-OAD-6240] There shall be a crane with a minimum 2 tonne capacity for assembling and servicing the LGSF laser rooms.

> *Discussion: The laser rooms are located within the azimuth telescope structure. Mass estimate for the laser bench is 1500 kg. This is the heaviest component in the laser room. The laser rooms shall be assembled piece by piece.*

[REQ-1-OAD-6250] A mobile platform lift (500 kg capacity and 9 meters reach) shall be available to provide access to instruments and some part of the LGSF Beam Transfer Optics Optical Path (Deployable Optical Path and part of the Elevation Optical Path).

[REQ-1-OAD-6255] There shall be a mobile crane, with 2 tonne capacity, and 24 meters reach, located on the observatory floor.

Overhead cranes shall be available in the following places:

- [REQ-1-OAD-6260] Freight and delivery areas: bridge crane with 3 tonnes capacity.
- [REQ-1-OAD-6270] Mirror coating area: 10 tonnes capacity, 2-speed electric hoist with slow speed of 30 cm per minute, one degree of motion and oil shields.
- [REQ-1-OAD-6271] Mirror stripping area: 10 tonnes capacity, 2-speed electric hoist with slow speed about 30 cm per minute, one degree of freedom horizontal motion along a rail, and oil shields.
- *Discussion: A movable crane can be shared between the coating area and stripping area.*

- [REQ-1-OAD-6272] Mirror storage area: 3 tonnes capacity, bridge crane with oil shields, 2-speed electric hoist with slow speed about 30 cm per minute, and oil shields.
- [REQ-1-OAD-6275] Mechanical workshops: 3 tonnes capacity bridge crane, 2-speed electric hoist with slow speed about 30 cm per minute, and oil shields.

4.6 SAFETY

Discussion: Top level safety requirements are in the ORD.

4.6.1 General

[REQ-1-OAD-7000] The summit facility shall incorporate video and audio systems to allow operations staff to monitor the enclosure environment.

4.6.2 Hardware Interlocks

[REQ-1-OAD-7050] The observatory shall incorporate a hardware based safety interlock system that is an independent system, without reliance on other observatory systems.

[REQ-1-OAD-7055] The hardware interlock system shall be capable of locking out the power to systems, or the operation of systems, or preventing access to hazardous areas or operations while they are in their hazardous state.

[REQ-1-OAD-7060] All equipment with functions or malfunctions potentially capable of harming people or causing significant financial loss shall be protected by the hardware interlock system.

[REQ-1-OAD-7065] Where hardware interlock are not practical, other systems shall be implemented that achieve equivalent levels of protection.

Discussion: For example, all sky cameras will be used to prevent laser illumination of aircraft.

[REQ-1-OAD-7070] All system interlocks shall be additionally encoded at least at the sub-assembly level to indicate where the interlock has been triggered.

[REQ-1-OAD-7075] The Observatory Safety System shall monitor and report all the location of all interlock occurrences within the summit facility to at least the sub-assembly level.

4.6.3 Emergency Stop (E-Stop)

[REQ-1-OAD-7100] The observatory shall incorporate a hardware based emergency stop (E-Stop) system that is an independent system, without reliance on other observatory systems.

[REQ-1-OAD-7105] Triggering of the E-Stop system shall shut down of all power within the summit facility, with the exception of emergency lighting and the observatory safety system, and stop all telescope and enclosure motion.

Discussion: The system is envisioned as a stop chain running through all protected systems. An open circuit of the stop chain will trigger an E-Stop.

[REQ-1-OAD-7110] The E-Stop shall be connected through emergency stop buttons located at all regular operations, servicing and maintenance locations in the summit facility.

[REQ-1-OAD-7115] All equipment shall be designed to withstand multiple E-stop occurrences without damage.

[REQ-1-OAD-7120] All system interlocks shall be additionally encoded to indicate where the E-Stop has been triggered.

[REQ-1-OAD-7125] The Observatory Safety System shall monitor and report all interlock occurrences within the summit facility.

4.6.4 Telescope Safety

4.6.4.1 General

[REQ-1-OAD-7200] The elevation structure of the telescope shall be physically restrained to inhibit motion or damage even under Infrequent Earthquake Conditions, for any servicing or maintenance operation that involves more than 10000 (TBC) kg-m mass imbalance of the elevation axis.

[REQ-1-OAD-7205] The telescope shall incorporate earthquake stops on the elevation and azimuth axes that are capable of restraining the system during an Infrequent earthquake event as defined in the ORD.

[REQ-1-OAD-7210] The telescope shall provide a secondary emergency means of egress for personnel from the Nasmyth platforms that is available at any telescope azimuth position.

[REQ-1-OAD-7215] There shall be a secondary emergency means of egress for personnel from all permanent walkways within the summit facility.

[REQ-1-OAD-7220] In an emergency situation, it shall take no longer than 2 minutes (TBC) to exit the summit facility from any regularly accessed location.

[REQ-1-OAD-7225] The TSS shall monitor and protect the system from damage and personnel from injury under the following conditions:

- Telescope azimuth and elevation over-speed condition.
- Telescope azimuth and elevation over-travel limit condition.
- Telescope mount drive over-current condition.
- Dome crane not stowed during telescope motion.
- Segment crane not stowed during telescope motion.
- TCS failure.
- Cable wrap failure.
- Telescope out of balance.
- Seismic events
- Personnel in the primary mirror cell.

[REQ-1-OAD-7230] Under an emergency stop condition, the deceleration rate of the telescope azimuth axis shall be 2 degrees/sec^2.

Discussion: For a maximum azimuth speed of 2.2 deg/s, the stopping time, stopping distance and deceleration at the edge of the Nasmyth platform are:

Table 28 Telescope azimuth stopping deceleration, time and distance

Azimuth deceleration rate, deg/s^2	Stopping time, sec	Stopping distance at Nasmyth platform edge, m	Deceleration at Nasmyth Platform edge, g
1.75	1.26	0.67	0.086
2.00	1.10	0.58	0.098
2.25	0.98	0.52	0.110

[REQ-1-OAD-7235] Under an emergency stop condition, the deceleration rate of the telescope elevation axis shall be 2.0 degrees/sec^2.

Discussion: For a maximum elevation speed of 0.6 deg/s, the stopping time, stopping distance and deceleration at the elevation journal and the top end are:

Table 29 Telescope elevation stopping deceleration, time and distance

Elevation deceleration rate, deg/s^2	Stopping Time, s	Stopping distance at elevation journal, m	Deceleration at elevation journal, g	Stopping distance at top end, m	Deceleration at top end, g
2.00	0.30	0.02	0.038	0.04	0.098
2.25	0.26	0.01	0.043	0.04	0.110
2.50	0.24	0.01	0.048	0.03	0.123

4.6.5 Enclosure Safety

4.6.5.1 General

[REQ-1-OAD-7300] The Enclosure shall incorporate an emergency lighting system to illuminate the interior of the enclosure and emergency exit paths during a power failure or E-stop occurrence.

4.6.5.2 Enclosure Safety System

[REQ-1-OAD-7350] The Enclosure Safety System shall monitor and protect the system from damage for the following conditions:

- Enclosure cap, base and shutter over-speed condition.
- Enclosure cap, base and shutter drive over-current condition.
- Enclosure control system failure.
- Seismic events
- Unstowed cranes
- Over temperature conditions
- Deployable platforms

4.6.6 Laser Guide Star Facility

[REQ-1-OAD-7500] The System shall follow the safety rules defined for the class 4 lasers used in the LGSF system.

[REQ-1-OAD-7505]: The Laser Guide Star Facility Safety System shall monitor and protect the system from damage and personnel injury under the following conditions:

- Stray laser light caused by scatter or misalignment
- Smoke produced by laser(s) damage
- Seismic events
- AO system failure (laser faults, shutters fault, detection system faults...)
- TCS failure

Discussion: The laser safety requirements are dictated by the need to avoid laser-induced damage to personnel, to the TMT observatory, or to the LGSF itself, and the need to avoid accidental illumination of aircraft, satellites or projection of the laser beams within the field of view of neighboring telescopes.

[REQ-1-OAD-7510]: The Laser Guide Star Facility Safety System shall monitor and protect aircraft from accidental laser illumination via a combination of visible all sky and infrared boresighted narrow field cameras.

[REQ-1-OAD-7511] The All Sky Camera (ASCAM) shall be mounted in 2 locations, positioned 180 degrees from one another on opposite sides of the observatory, TBD metres from the observatory.

Discussion: The ASCAM locations will be site specific. The Cerro Armazones ASCAM will be a dedicated system for TMT. In the event that another site is selected then this system may be shared with existing facilities. Also the ASCAM locations may be common with the SCMS.

[REQ-1-OAD-7512] The summit facilities shall provide all necessary power, communication and control cables and any other services to the ASCAM locations via underground conduits.

[REQ-1-OAD-7513] The Bore Sighted Camera (BOCAM) shall be mounted on the telescope top end and bore sighted with the telescope.

[REQ-1-OAD-7514] The BOCAM shall also detect clouds prior to the interference with the laser beams.

Discussion: This is a safety requirement. The clouds may prevent the detection of aircraft.

[REQ-1-OAD-7515]: The Observatory procedures and the Observatory Executive Software shall protect satellites from accidental laser illumination

[REQ-1-OAD-7520]: The Laser Guide Star Facility Safety System shall monitor and protect neighboring telescopes from projection of the laser beams within their field of view.

5. SYSTEM ARCHITECTURE

5.1 OBSERVATORY CONTROL ARCHITECTURE

5.1.1 Pointing, Offsetting, Tracking, Guiding and Dithering

Definition: Pointing is the blind operation establishing the initial alignment of the telescope and instrument foci to the sky. Pointing is not supported by optical feedback (like acquisition camera or WFS) as its very objective is to establish the appropriate conditions for closing any optical loop. Pointing is aided by the pointing model to achieve the required accuracy. The pointing model is a Look-Up-Table (LUT) based or best fit estimated correction to the theoretical commands to the mount actuators. The pointing model comprises the relevant imperfections of the telescope and its control systems for various environmental and operating conditions, most prominently temperature and elevation angle. It also contains astrometry corrections.

Definition: Offsetting is the process of moving from one pointing to another over a small angular distance.

Definition: Tracking i.e. following the virtual sky motion without the aid of any sky reference is a special sequence of pointing, possibly with pre-calculated trajectory. Tracking relies on calculating mount coordinates from the sky coordinates of the target, and correcting them with the pointing model. It is understood that a significant portion of tracking error comes from the imperfect smoothness of the required motion.

Definition: Guiding is defined as tracking with closed loop control based on optical position feedback from a guide star.

Definition: Dithering is the process of repetitively offsetting between two or more pointings.

[REQ-1-OAD-8010] The system shall establish the alignment of the telescope and instrument foci relative to the sky primarily by means of mount actuators setting the telescope azimuth and elevation angles, and the tertiary mirror steering the beam to the instrument foci.

Discussion: The mount actuators consist of the elevation and azimuth drives with the corresponding position encoders and possibly rate sensors for local mechanical feedback. There are several instrument foci on the Nasmyth platforms that are selected by steering the tertiary mirror in azimuth and elevation.

[REQ-1-OAD-8015] The system shall improve the alignment of the telescope relative to the sky by means of closed optical loop guiding.

[REQ-1-OAD-8020] Guiding shall correct residual image motions by reconstructing image motion (OPD tip/tilt) into mount elevation and azimuth angles

[REQ-1-OAD-8025] The bandwidth for the closed optical guide loop shall be 0.3 Hz.

[REQ-1-OAD-8030] In seeing limited operation, guiding errors shall be directly calculated from the slopes of a guiding NGS WFS by a Mini Real Time Controller (RTC) (See Figure 11).

Discussion: This is a working decision, to be reviewed.

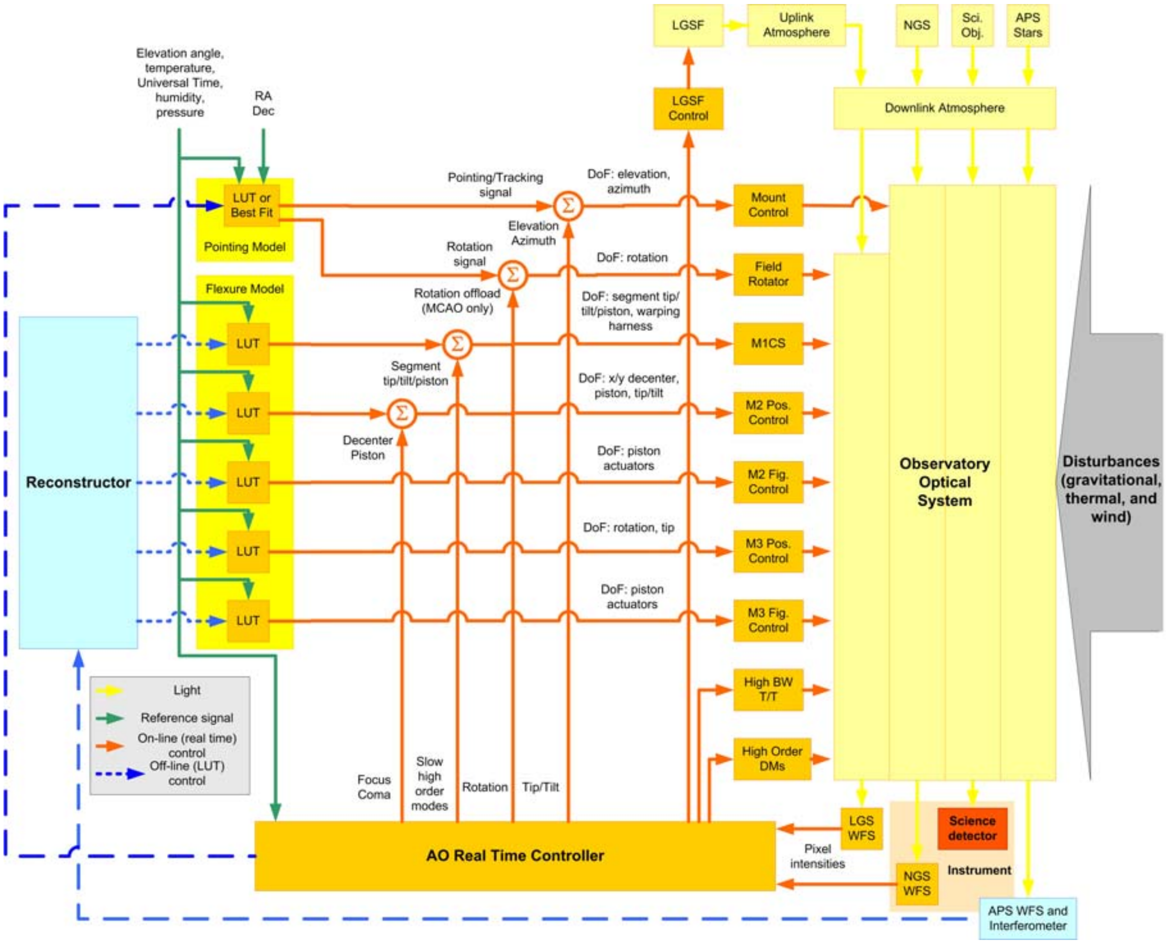


Figure 11 Control architecture for adaptive optics observations. For seeing limited observations, the Laser Guide Star beam path, the high order deformable mirrors, and the high bandwidth tip/tilt stage are not operational; the AO RTC is replaced by a miniRTC

[REQ-1-OAD-8035] In adaptive optics operation, guiding errors shall be computed by averaging the AO fast tip/tilt mirror commands or, if AM2 is used, by averaging the AM2 tip/tilt modes. In both cases, the guiding errors are computed by the AO RTC.

[REQ-1-OAD-8040] OPD information from guiders shall be scaled and rotated into telescope modes (degrees of freedoms) that are transferred to the Telescope Control System via the AO Sequencer (Figure 12).

[REQ-1-OAD-8045] The guiding NGS WFS(s) shall be either adjacent to the entrance window of the instrument, or preferably located inside the instrument.

[REQ-1-OAD-8050] The telescope control system (TCS) shall control NGS WFS probe positioning in coordination with the mount to perform non-sidereal tracking, dithering, and differential refraction compensation.

[REQ-1-OAD-8055] During dithering, the coordinated trajectories of the mount and the NGS WFS probes shall be complementary to within 0.5 (TBC) arcseconds.

Discussion: The intent is to stay within the capture range of WFSs and to limit transients induced onto tip-tilt mirrors during AO guiding.

[REQ-1-OAD-8060] The system shall be able to validate pointing independent of an instrument

Discussion: Instruments and AO systems are integral parts of the pointing and wavefront control architecture, in that they provide acquisition and guiding cameras, and wavefront feedback to the system. This requirement mandates that there be another system, independent of science instruments and AO systems, that provides components and interfaces that enable validation of these functions.

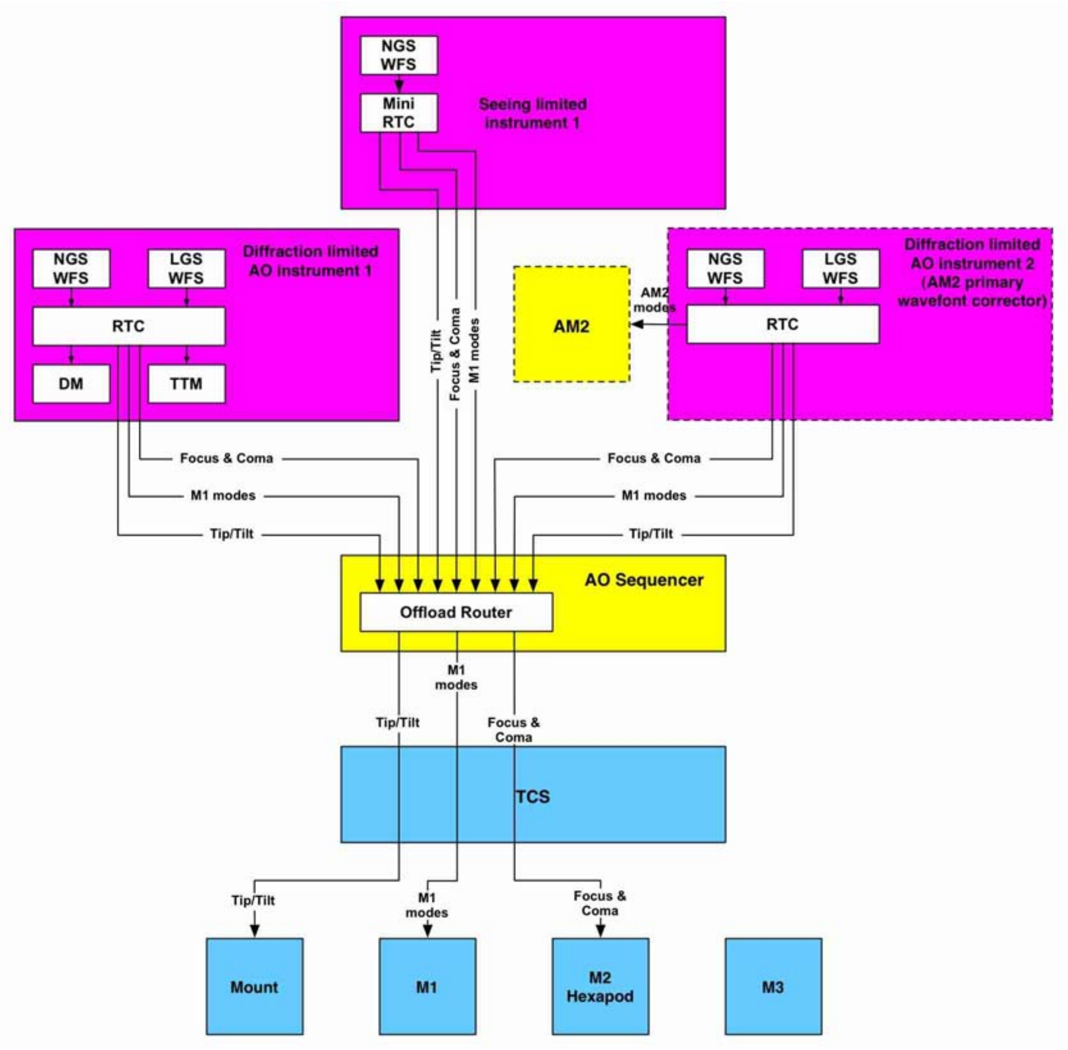


Figure 12 Wavefront error data flow for seeing limited instrument and AO aided instruments. The different branches are active depending on the instrument choice for observation

5.1.2 Field De-rotation

[REQ-1-OAD-8100] Field de-rotation opto-mechanical components shall be the responsibility of the instruments or adaptive optics systems.

[REQ-1-OAD-8105] Field de-rotation shall be a “blind” i.e. open optical loop operation driven by the rotation command calculated by the pointing model in the telescope control system.

Discussion: Since the calculation of field rotation requires RA, Dec, and sidereal time as inputs, this model is a part of the observatory. This results in a testable interface to instruments via mechanical angle commands.

[REQ-1-OAD-8110] Instruments and AO systems that need higher field de-rotation accuracy than the seeing limited requirements shall provide the means to calibrate their de-rotator, and/or correcting rotation errors by real time optical feedback.

Discussion: It is understood that detecting rotation errors requires an extension to the guiding/aO sensors, allowing off-axis measurements. It is also understood that relatively wide field adaptive optics systems, like an MCAO system, can provide rotation error off-loads.

5.1.3 Atmospheric Dispersion Compensation

[REQ-1-OAD-8200] Atmospheric dispersion compensation commands shall be "blind" i.e. open optical loop operation calculated by the pointing model. This pointing model shall be the responsibility of the telescope control system (TCS).

[REQ-1-OAD-8210] The accuracy of the atmospheric dispersion correction shall be determined by the requirements for the particular system configuration.

5.1.4 Active and Adaptive Optics Control Architecture

5.1.4.1 General

[REQ-1-OAD-8300] The system shall maintain the shape of the optical surfaces and their alignment relative to each other, i.e. the collimation of the telescope by means of active optics compensation of thermal, gravitational, and vibration disturbances.

Discussion: The most prominent vibration disturbance is expected to be wind buffeting.

REQ-1-OAD-8310] The system shall be able to validate wavefront control independent of an instrument

Discussion: Instruments and AO systems are integral parts of the pointing and wavefront control architecture, in that they provide acquisition and guiding cameras, and wavefront feedback to the system. This requirement mandates that there be another system, independent of science instruments and AO systems, that provides components and interfaces that enable validation of these functions.

5.1.4.2 Active Optics Actuators

Discussion: The active optics system may rely on local mechanical feedback loops to stiffen up and linearize the actuators described in this section. The local feedback loops may utilize mechanical measurements, like position (encoder), force (strain gauge), and possibly acceleration.

[REQ-1-OAD-8400] The active optics system shall adjust M1 segment position in 3 DoF (tip, tilt, piston) by means of 3 piston actuators per segment.

[REQ-1-OAD-8405] The active optics system shall adjust M1 global position in 3 DoF (tip, tilt, piston) by means of 3 piston actuators per segment.

[REQ-1-OAD-8410] The active optics system shall adjust M1 segment shape by means of 21 warping harness actuators for each segment.

[REQ-1-OAD-8415] The active optics system shall adjust M2 position in 5 DoF (tip, tilt, piston, x and y decenters) by means of a hexapod.

[REQ-1-OAD-8420] The active optics system shall adjust M2 shape by means of controlled-force axial support actuators.

Discussion: The conceptual design has 60 axial actuators, but this number may change.

[REQ-1-OAD-8425] The active optics system shall adjust M3 position in 2 DoF (tip and rotation about the telescope optical axis) by means of 2 actuators.

[REQ-1-OAD-8430] The active optics system shall adjust M3 shape by means of controlled-force axial support actuators.

Discussion: The conceptual design has 60 axial-lateral actuators, but this design may change.

5.1.4.3 Active Optics Sensors

[REQ-1-OAD-8500] The active optics system shall measure M1 segment position relative to neighboring segments by means of sensors attached to all shared segment to segment edges.

[REQ-1-OAD-8510] The M1 segment position sensing system shall be capable of operating with less that a full complement of segments installed.

Discussion: Alignment and Phasing System Requirements can be found in Section 4.1.9.

The Alignment and Phasing System (APS) is responsible for measuring the alignment and shape of M1, M2, and M3, and for operating in conjunction with the respective telescope control and mirror actuator systems to adjust the alignment and figuring of the mirror segments. In particular the APS will measure and generate commands for adjusting:

- *M1 Segments in piston tip and tilt*
- *M1 Segment surface figure*
- *M2 Five degrees of rigid body motion (piston, tip, tilt, and x- and y-decenter.*
- *M2 Surface Figure*
- *M3 Two degrees of rigid body motion (tip, tilt)*
- *M3 Surface Figure*
- AM2: Five degrees of segment rigid body motion (piston, tip, tilt, and x- and ydecenter) for each of up to 6 segments.

5.1.4.4 Compensation Strategy

[REQ-1-OAD-8600] The adaptive optics system, or in absence of it an “on-instrument” NGS WFS, shall provide time averaged wavefront errors to the active optics system.

Discussion: This is necessary to limit drifts in the active optics system and correct for uncertainties due to the not completely resolved temperature distribution of the environment, structure, and glass.

[REQ-1-OAD-8605] The OPD information supplied to the aO system shall be the same in both seeing limited and near diffraction limited observations.

[REQ-1-OAD-8610] OPD focus shall be reconstructed into M2 piston.

[REQ-1-OAD-8615] The bandwidth for the aO loop feeding OPD focus back to M2 piston shall be 0.1 Hz.

[REQ-1-OAD-8620] OPD coma shall be reconstructed into M2 tilt or rotation around M2 center of curvature (zero tilt point).

Discussion: Review this decision w.r.t. to decenter adjustment of M2

[REQ-1-OAD-8625] The bandwidth for the aO loop feeding OPD coma back to M2 tilt shall be 0.01 Hz.

[REQ-1-OAD-8630] In seeing limited operations higher order OPD information including focus and coma shall be directly calculated from the slopes of a 6 x 6 (TBC) “on-instrument” NGS WFS by a Mini RTC.

Discussion: It is expected that the wavefront sensing and guiding functions can be combined into a single sensor.

[REQ-1-OAD-8635] In adaptive optics operation higher order OPD information including focus and coma shall be computed by averaging the ground conjugated deformable mirror commands, or, if AM2 is used, by averaging the AM2 modes. In both cases, the higher order OPD information are computed by the AO RTC.

[REQ-1-OAD-8640] In both seeing limited and adaptive optics operations the OPD information shall scaled and rotated into telescope modes (degrees of freedom) that are transferred to the Telescope Control System via the AO Sequencer.

[REQ-1-OAD-8645] OPD Zernike modes up to the 6th radial order (TBC) shall be reconstructed into M1 mirror modes.

[REQ-1-OAD-8650] The update rate and bandwidth for higher order OPD information fed back to M1 mirror modes shall be 0.001 Hz.

[REQ-1-OAD-8655] The 6 x 6 “on-instrument” NGS WFS shall be either adjacent to the entrance window of the instrument, or preferably located inside the instrument.

Discussion: The role of the mini RTC is solely to read the WFS and compute the required telescope modes. The number of algorithmic operations required is relatively small and a single processor computer should be able to perform the work.

Discussion: The sky coverage limitations in seeing limited operation are not expected to be significant, as the allowable anisoplanatic error is large and the required sampling rate is not greater than 5 Hz. Preliminary estimates show that with guide stars of magnitude V=20 to V=22 the required SNR can be achieved. Such guide stars are expected to be found most of the time not farther than 75 to 150 arcsec from the target.

[REQ-1-OAD-8660] Figure 12 illustrates how the wavefront information shall flow from the instrument to the telescope actuators in seeing limited and near diffraction limited observations.

Discussion: For illustrative purposes, Table 37 in the appendix includes additional suggested architectural details regarding the mount and active optics actuators and corresponding sensors.

[REQ-1-OAD-8665] There shall be no compensation, i.e. closed optical loop correction for pupil position, distortion, and plate scale variations.

Discussion: These characteristics of the system are controlled by the pointing and flexure models only.

[REQ-1-OAD-8670] The AO RTC shall collect the measurements from the various NGS and LGS WFS and compute the commands to the wavefront correctors. (Deformable Mirrors, Tip Tilt Mirrors or Tip Tilt platform, AM2 modes when AM2 is used as an AO woofer).

Discussion: Details of the early light facility AO system (NFIRAOS) are listed in Section 4.2.

[REQ-1-OAD-8675] The control architecture for near diffraction limited observations shall be as shown in *Figure 11*.

Discussion: The architecture is an extension of the active optics control architecture. New features include (i) the control of high order DMs and high bandwidth tip/tilt stages using measurements from NGS and LGS wavefront sensors, (ii) offloads from these components to M1, M2, and the mount, and (iii) pointing and centering control of the beam transfer and projection optics in the LGS facility

5.1.5 Acquisition

Definition: Acquisition is the process of (i) locking the telescope to the sky (guide star acquisition), and (ii) establishing proper alignment of the science target with the instrument (science target acquisition).

[REQ-1-OAD-8700] Both guide star and science target acquisition shall be coordinated by the Executive Software.

[REQ-1-OAD-8705] TMT instrumentation shall provide their sensors for acquisition and guiding.

Discussion: There shall be no facility acquisition and guiding system. Nevertheless, there are standard procedures detailed below that all AO systems and instruments shall support.

5.1.5.1 Acquisition Process

[REQ-1-OAD-8710] Each system configuration (instrument-AO combination) shall provide reliable means for both guide star and science target acquisition by implementing one of the following two general procedures.

- If it is feasible to design the field of view of the guide WFS large enough to accommodate telescope pointing repeatability (1 arcsec), the acquisition can be made in a single pointing step. Even in this case though, it may be necessary to re-align the wavefront sensors relative to the instrument after the initial acquisition.
- If it is technically or financially not feasible to use large enough FOV guide WFS, the instrument shall provide an at least 20 arcsec acquisition camera. After acquiring the guide star on the camera, telescope blind offset places the guide star on the WFS.

[REQ-1-OAD-8715] Early light instruments choosing the option of not having an acquisition camera shall provide provisions for dependable acquisition in the commissioning phase when the pointing precision of the telescope may not meet the pointing requirement.

[REQ-1-OAD-8720] As a goal, the acquisition camera shall have the same spectral sensitivity as the WFS in order to prevent long integration time and consequently time consuming acquisition process.

Discussion: In order to accommodate the second acquisition option, the telescope need to be able to offset without optical feedback up to 1 arcmin with 50 mas repeatability (1 sigma), as specified in the ORD. It is understood that this high precision offset is meaningful only with high order (laser guide star) adaptive optics corrections reducing image blur to the level commensurate to the FOV of the WFS. It is also understood that this offset requirement includes a blind tracking component due to the finite time of the offset operation.

Although the WFS pick-off positions are supposed to be set so that they ensure appropriate target positioning on the science detector or slit, it may be necessary to test and correct this condition with collecting and analyzing actual science data.

[REQ-1-OAD-8725] For acquisition, the positions of the NGS WFSs shall be commanded by the pointing model in the Telescope Control system.

5.1.5.2 Acquisition Sequences for Different System Configurations

Discussion: Appendix 7 illustrates some example acquisition sequences for seeing limited and adaptive optics modes of the observatory. These are for illustration purposes, and are not requirements on the system.

5.2 OBSERVATORY SOFTWARE ARCHITECTURE

5.2.1 High-level software system definition

5.2.1.1 Observation Execution System (OES)

[REQ-1-OAD-9000] An observation execution system (OES) shall be implemented to enable efficient observation of astronomical objects as well as efficient command, control, and monitoring of all observatory functions.

[REQ-1-OAD-9003] The OES shall consist of a set of software subsystems that interact through a software connectivity backbone layered on top of a physical communications network (see Figure 13).

Discussion: the OES follows a distributed (component-connector) architecture model. The connector is decomposed into a set of communication common services (discussed later).

[REQ-1-OAD-9006] It shall be possible to orchestrate a complete observation, including observatory configuration and target acquisition sequences, from an OES master process sequencer. This master sequencer shall be capable of system action flow control as well as system process synchronization and parallelization.

Discussion: OES can be viewed as a sequencing engine for the execution of science observations. Observation descriptions are generated by users using a variety of interface tools and submitted to the OES for action. Based on those descriptions, the OES orchestrates a sequence of system actions to accomplish the described observation. Science datasets are the primary output of this process.

[REQ-1-OAD-9009] The OES command-and-control architecture is hierarchical (see Figure 14). The transition from one system configuration (“observational setup”) to another results from a sequence of activities initiated and coordinated by a master sequencer. This coordination is accomplished in concert with a set of lower tier sequencers.

[REQ-1-OAD-9012] The master sequencer shall establish the appropriate OES command-and-control hierarchy depending on the requested observation (or observatory system re-configuration).

Discussion: in a logical sense, different hierarchical relationships are established for different observational setups. For example, Figure 14 shows the logical hierarchical relationship established to execute an IRIS observation using laser guide stars.

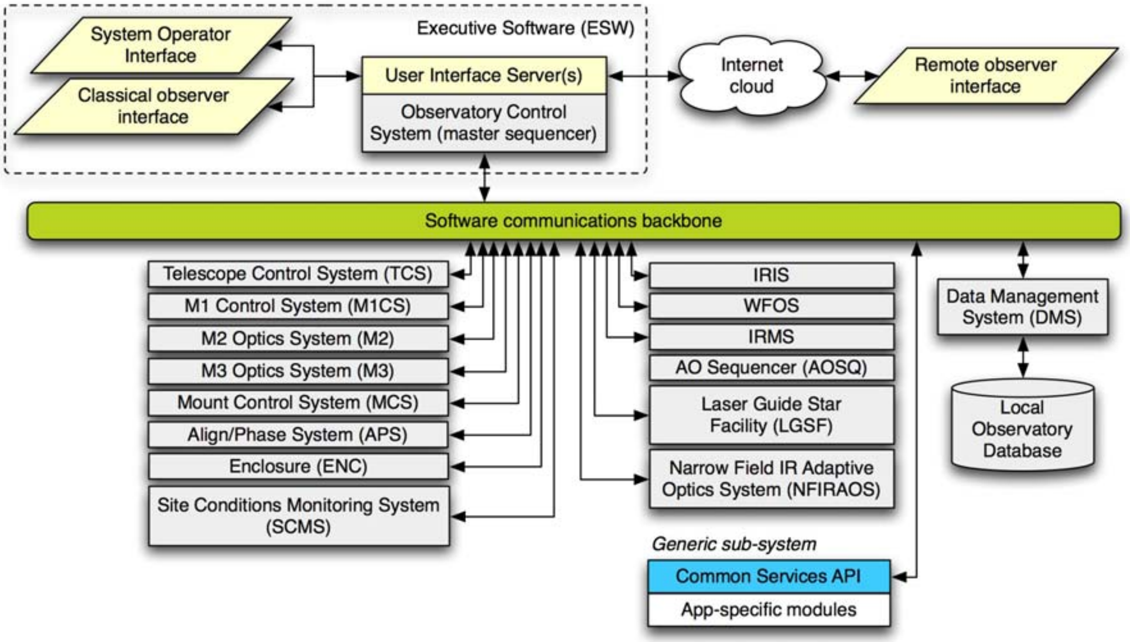


Figure 13: Observation execution system (OES) architecture (communication)

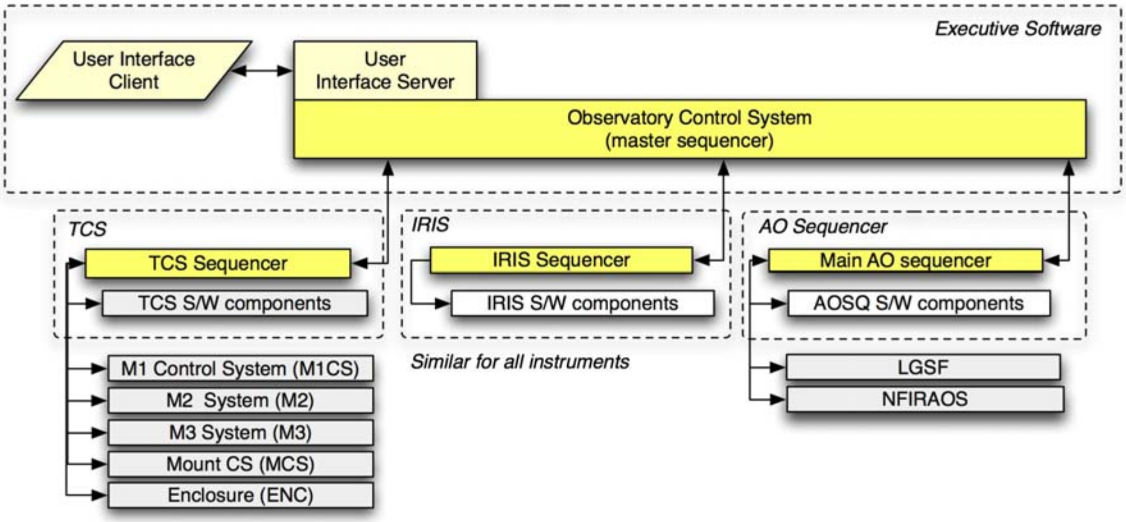


Figure 14: Observation execution system (OES) architecture (workflow)

[REQ-1-OAD-9015] OES user interfaces must be provided to accept user input, generate and submit observation requests, and process and display ("monitor") OES health and status information.

[REQ-1-OAD-9018] Only OES user interfaces running on trusted machines shall be allowed to interact with TMT. An access control system shall be implemented.

[REQ-1-OAD-9021] OES user interfaces shall be created for the following system user types shown in Table 30.

User Type	Description
System operator	On-duty TMT staff person who is responsible for controlling and monitoring the TMT software system on behalf of other system users (e.g. visiting scientists, technical teams, etc.)
Classical (on-site) observer	Anyone executing science observations and/or acquiring associated calibration data in near-real-time while physically present at TMT.
Remote (off-site) observer	Anyone executing science observations and/or acquiring associated calibration data in near-real-time while physically present at an approved remote observing facility.
Queue observer	Anyone who has submitted descriptions of science observations and/or associated calibration data acquisition sequences for the purposes of later execution as scientific priority and observing conditions permit.
Technical user	Anyone who is monitoring system performance, performing system maintenance tasks, and/or implementing system improvements.

Table 30 Software system user types

[REQ-1-OAD-9024] All TMT OES user interfaces shall have a common look-and-feel within each interface category (i.e. command-line interface, graphical user interface, Web interface).

[REQ-1-OAD-9027] Graphical user interfaces (GUIs) shall be the default interface for all normal scientific and technical operations. The standard TMT software framework shall include libraries and/or editors to support GUI development.

[REQ-1-OAD-9030] OES user interfaces shall use the communication services defined in Table 31.

[REQ-1-OAD-9033] Data visualization tools must be provided for the following situations:

- Target acquisition support (acquisition and WFS)
- Science data quick-look data quality assurance support
- Technical data presentation
- Environmental conditions presentation
- System status presentation

[REQ-1-OAD-9036] Whenever possible, data visualization tools shall re-use or be based on existing solutions.

[REQ-1-OAD-9039] Automatic system startup and shutdown processes shall be implemented.

[REQ-1-OAD-9042] It shall be possible to run the TMT software system in simulation mode.

[REQ-1-OAD-9045] All software servers shall be attached to an uninterruptible power system (UPS).

5.2.1.2 Program Execution System (PES)

Discussion: due to resource limitations, the PES shall be implemented incrementally. The PES architecture and subsystem design must take that limitation into account.

[REQ-1-OAD-9100] A program execution system (OES) shall be implemented to enable efficient management of astronomical programs from proposal creation to data delivery.

Discussion: a schematic program management workflow has been described in the OCD.

[REQ-1-OAD-9103] At each step of the way, a program shall additional information: allocated time, assigned scientific priority, observation descriptions, system status information, observing condition information, raw data frames, output from data processing systems, etc.

[REQ-1-OAD-9106] This information shall be stored in a well-structured, normalized observatory database (ODB).

[REQ-1-OAD-9109] Each PES subsystem shall support one key aspect of the PES workflow (e.g. proposal management, observation management, observation execution, data processing, and science archive management). Although each subsystem can be implemented independently, they share relational database structures within the observatory database (see Figure 15).

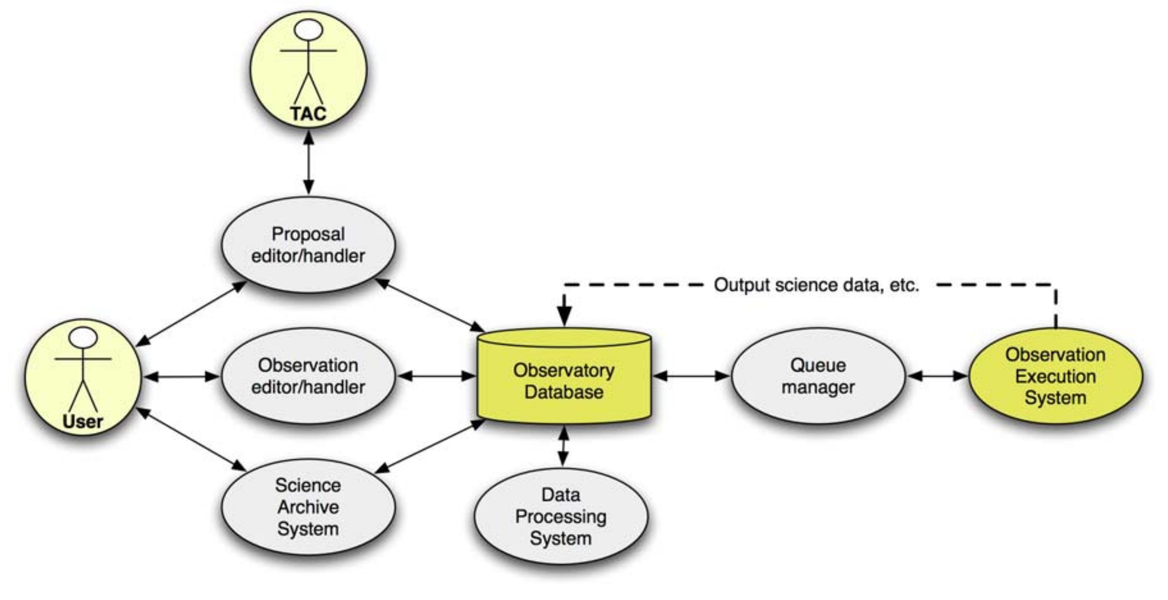


Figure 15: PES decomposition

[REQ-1-OAD-9112] Each subsystem can (but is not required to) use a different communication strategy for interacting with the observatory database. However, the chosen strategy shall always remain database server implementation neutral. It must also allow secure connections between remote clients and local servers.

5.2.2 Software system communications backbone

5.2.2.1 *General communications backbone requirements*

[REQ-1-OAD-9200] The TMT software system backbone shall be defined by a set of software communication services hereafter known as common services.

Discussion: Common services are often known as middleware in the commercial software development world.

[REQ-1-OAD-9203] Software subsystems shall access the communications backbone using TMT-provided and/or TMT-specified Application Programming Interfaces (APIs).

[REQ-1-OAD-9205] The communications backbone shall run on top of a communication protocol stack that has a physical IT communications network at its lowest level.

Discussion: it is a high priority goal to build TMT common services using the following principles: (1) use existing solutions, preferably from the open source community; (2) implement solutions that are operating system neutral to the largest extend possible; and (3) support more than one main stream software language. For example, Java Messaging Service (JMS), RTI Data Distribution Service (DDS; formerly NDDS), and Apache ActiveMQ (built on JMS) appear to satisfy the spirit of these goals already. By mid-2008, TMT will select a reference middleware solution and proceed to common services API specification.

5.2.2.2 General common services requirements

[REQ-1-OAD-9210] Each common service shall be asynchronous.

[REQ-1-OAD-9213] Each common service shall have an Application Programming Interface (API). It is a goal to make each API service implementation neutral, i.e. it shall be possible to change how a service is implemented without needing to make code modifications to subsystems using that service.

[REQ-1-OAD-9216] Common services shall run on top of a standards-based communications stack similar to what is shown in Table 31.

Discussion: this protocol stack is based on the 5-layer TCP/IP model, not the 7-layer OSI model. Actual stack implementations are service-dependent and will be described in Level-2 design documents. The physical layer is expected to be segmented (e.g. using structured cabling) to prevent data transfer collisions (e.g. between command-and-control, telemetry, and science data).

Layer	**Possible solutions**
TMT-specific standards and content	
Service-specific data structure content	TBD (TMT-specific)
Service-specific data structure syntax	TBD (TMT-specific)
Industry standards	
Data structure standard	HTML, XML, FITS
Application (inter-process communication, IPC)	HTTP, SMTP, Java RMI
Transport	TCP
Network	IP
Data Link	ATM, PPP
Physical	Ethernet, CAN, ISDN, WiFi

Table 31: Communications protocol stack

5.2.2.3 Specific common service definitions

Discussion: this is the current design reference list of common services. It will evolve as design work advances.

[REQ-1-OAD-9220] TMT software common services are listed in Table 32.

Service	Task
User single sign on	Manage user authentication/access control
Configuration	Manage system configuration
Location/connection	Manage inter-process communications connections
Event	Manage event publishing/subscription
Health	Manage health check signals
Logging	Capture/store log information
Bulk data store	Capture/store bulk data (e.g. science data)
Telemetry store	Capture/store telemetry
ODB access	Middle-tier for database access
Time	Standard GPS-based Network Time Protocol (NTP) service
Catalog	Interface to DMS astronomical catalog server

Table 32: Common services definition

[REQ-1-OAD-9223] The user single sign on (SSO) service shall enable OES users to authenticate once and gain access to authorized operations. For each user, an authorized operation profile shall be maintained.

[REQ-1-OAD-9226] The configuration service shall enable the command and control of a specific set of OES subsystems for a specific operation. A master process shall be defined. During a specific configuration, only the designated master process may command and control the OES.

[REQ-1-OAD-9229] The location service enables registered processes to find other registered process for the purpose of inter-process communication.

[REQ-1-OAD-9232] The event service enables the publication of messages indicating a change of state, completion of task etc. and the subscription to events from specific registered processes.

[REQ-1-OAD-9235] The health service enables the publication of process health, e.g. READY, FAULT, STANDBY.

Discussion: health service capability may be a subset of general event service capability and hence redundant. This needs further analysis.

[REQ-1-OAD-9238] The logging service allows processes to record a history of all actions (with time-stamps) in the local observatory database.

[REQ-1-OAD-9241] The bulk data store service facilitates the transmission of large data structures to the local observatory database.

[REQ-1-OAD-9244] The telemetry store service facilities the transmission of engineering telemetry to the local observatory database.

[REQ-1-OAD-9247] The observatory database (ODB) access service enables processes to query the local observatory database and retrieve data.

Discussion: the last four requirements imply a client-service like relationship between processes and the local observatory database. The services enable the client-side actions while the Data Management System (DMS) enables the server-side interaction.

[REQ-1-OAD-9250] The time service is a standard GPS-based Network Time Protocol (NTP) service.

[REQ-1-OAD-9253] The catalog service provides access to a defined set of astronomical catalogs stored on the local observatory database.

Discussion: a typical catalog service action is to request possible guide stars near a specific celestial coordinate.

5.2.3 High-level OES subsystem definition

5.2.3.1 General

[REQ-1-OAD-9300] Each software subsystem may consist of one or more lower-level software components.

[REQ-1-OAD-9303] It shall be possible to build, run, control, and monitor each software subsystems in stand-alone mode, i.e. without starting the entire TMT software system.

[REQ-1-OAD-9306] It shall be possible to run each software subsystem in simulation mode, either independently or in conjunction with the rest of the TMT software system.

[REQ-1-OAD-9309] Upon activation, each subsystem shall be able to initialize itself with a default configuration and be ready for operation without further human intervention. This activation process shall take less than one (1) minute (TBC).

[REQ-1-OAD-9312] All software subsystems shall be able to receive and parse TMT defined data structures containing command, control, and configuration instructions.

[REQ-1-OAD-9315] All software subsystems shall be able to transmit TMT-defined data structures containing health, status, and history (log) information as well as any science or technical data to be captured and stored by the local observatory database.

[REQ-1-OAD-9318] Each software subsystem shall transmit health information (e.g. active, idle, error, etc) at TBD intervals.

[REQ-1-OAD-9321] For the purposes of later diagnosis and analysis, each software subsystem shall transmit a time-stamped activity log to the local observatory database.

[REQ-1-OAD-9324] For the purposes of process control and synchronization, each software subsystem shall be able to transmit or receive events.

[REQ-1-OAD-9327] For the purposes of fault detection, each software subsystem shall transmit an alarm when an error that provides normal operations occurs.

[REQ-1-OAD-9330] Each subsystem shall communicate with the rest of the system using the services listed in Table 31. Each service shall be accessed via a well-defined API (see REQ-1-OAD-5000).

[REQ-1-OAD-9333] Each subsystem shall be built using the standard TMT software framework (as described in OAD Section 5.2.7). The extent to which lower level software components must comply with the TMT software framework is still TBD.

5.2.3.2 Sequencer framework definition

[REQ-1-OAD-9340] A common sequencer framework shall be developed for use by all subsystems that contain sequencers.

Discussion: the sequencer framework definition description will be extended once more analysis is completed.

5.2.3.3 Defined OES software subsystems

[REQ-1-OAD-9350] Table 33 contains the design reference list of TMT OES subsystems.

Discussion: this list corresponds to the current TMT system decomposition (see Section 2). Some subsystems (e.g. WFOS) contain both hardware and software. For the purposes of this discussion, only the software components are considered. This list may evolve.

Subsystem Name	**ShortName**
Executive Software	ESW
Telescope Control System	TCS
M1 Control System	M1CS
M2 Optics System	M2
M3 Optics System	M3
Mount Control System	MCS
Alignment & Phasing System	APS
Enclosure	ENC
AO Sequencer	AOSQ
Laser Guide Star Facility Control System	LGSF
Narrow Field Infrared Adaptive Optics System Control System	NFIRAOS
Wide-Field Optical Spectrometer	WFOS
Infrared Imaging Spectrometer	IRIS
Infrared Multi-slit Spectrometer	IRMS
Site Conditions Monitoring System	SCMS
Data Management System	DMS

Table 33: Principal TMT software subsystems

Discussion: an interface to general facility management systems may also be necessary. To be investigated.

Discussion: TMT software subsystems listed in Table 33 shall be further described in Level-2 design requirement documents. A few subsystems deserve special mention here.

[REQ-1-OAD-9353] The Executive Software (ESW) contains the master system sequencer as well as the high-level user interfaces necessary to run the system. It accepts system configuration and observation requests from various user interfaces. The master sequencer then orchestrates the event sequence necessary to satisfy such requests. Finally, it returns status and completion information to those interfaces.

[REQ-1-OAD-9356] The Facility Control System (FCS) provides a standard interface wrapper to the various low-level facility hardware systems including (but not limited to) the enclosure cap, vent, and HVAC systems.

[REQ-1-OAD-9359] The Site Conditions Monitoring System (SCMS) provides a standard interface wrapper to the equipment external to the enclosure used to monitor such things as air temperature, wind speed, and free-air seeing.

[REQ-1-OAD-9362] The Data Management System (DMS) provides the necessary software front-end services to the local observatory database. The primary service is to capture, format (as necessary), validate, and store a range of data types. Secondary DMS services include: an astronomical catalog server for the use of all other TMT software subsystems and a data package creation server (such packages to include all related science, calibration, and technical data as well as any associated information such as nightlogs).

[REQ-1-OAD-9365] Each instrument shall have an Instrument Control System (ICS) that encompasses all the software subsystems (e.g. sequencer, component controller, detector controller, etc) needed to command and control the instrument as well as interface it to the rest of the TMT software system.

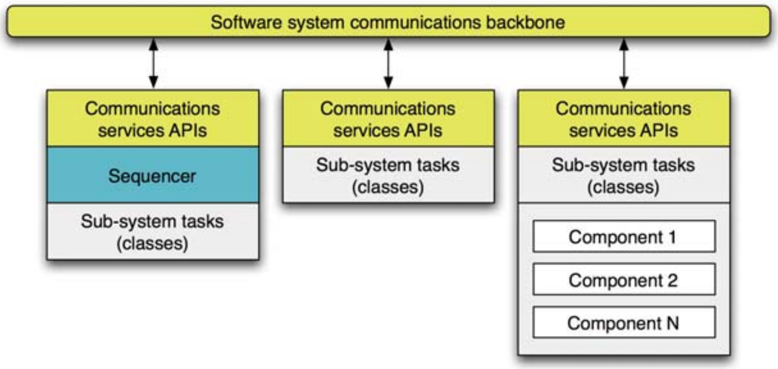


Figure 16: OES subsystem architecture templates

Discussion: for reference, Figure 16 shows three possible internal architectures for OES subsystems. On the left is the template for a sequencer subsystem (e.g OCS, TCS_SC, AOSQ). In the center is the template for monolithic application or a wrapper around a vendor supplied component (e.g. ENC, SCMS). On the right is the template for a subsystem with several key lower-level software components (e.g. LGSF, ICS-WFOS).

5.2.4 High-level PES subsystem definition

5.2.4.1 General

[REQ-1-OAD-9400] Unless otherwise noted, PES subsystems shall follow the same user interface guidelines as OES subsystems.

[REQ-1-OAD-9403] Unless otherwise noted, PES subsystems shall follow the same communication stack concept as OES subsystems.

[REQ-1-OAD-9406] Unless otherwise noted, PES subsystems shall follow the same communication backbone concepts as OES subsystems.

[REQ-1-OAD-9409] Unless otherwise noted, PES subsystems shall follow the same communication stack concept as OES subsystems.

5.2.4.2 Defined PES software subsystems

[REQ-1-OAD-9420] The proposal editor/handler (name TBC) subsystem contains all the functionality required by users to create and submit proposals and by the TMT Observatory to orchestrate the time allocation and long-term scheduling process. Additional functionality shall be provided to enable the secure, user-specific distribution of time allocation information as well as any record keeping and report generation requirements established by the TMT Board and/or partners.

[REQ-1-OAD-9423] The observation editor/handler (name TBC) subsystem contains all the functionality required by users to create and submit Observation Blocks (OBs) (as well as any required associated information) and by the TMT Observatory to orchestrate OB verification and scheduling.

[REQ-1-OAD-9426] The queue manager (name TBC) subsystem contains the functionality needed to browse the valid OB collection in the observatory database, select one or more OBs for execution, and send the selected OB(s) to the OES. It also contains the functionality needed to manage the post-execution review and fault resolution process.

[REQ-1-OAD-9429] The data processing system (DPS) subsystem contains all the functionality necessary to orchestrate automatic data processing for the purposes of quick-look analysis, system performance evaluation, and the production of science-quality data products. The DPS acts as a wrapper around instrument-specific data processing applications. A DPS goal is to be hardware compute engine independent – it should not matter if the hardware engine is a desktop machine or a multi-processor cluster, as long as the data processing applications are complied to run on the target hardware system.

Discussion: this hardware engine independence goal is aligned with common grid computing concepts related to high throughput computing (HTC). For one example, see the Condor project page: http://www.cs.uwisc.edu/condor.

[REQ-1-OAD-9432] The science archive system (SAS) contains all the functionality necessary for users to browse an external data center containing TMT data and download data of interest. Implementation of the SAS (if and when) is expected to be a joint venture between the TMT Observatory and a TBD existing data center.

[REQ-1-OAD-9435] Each instrument may have one or more tools for instrument simulation, integration time estimation, and configuration setup support (e.g. multi-object mask definition). As necessary, PES subsystems must be able to ingest and parse output from those instrument-specific tools.

5.2.5 Local observatory database

[REQ-1-OAD-9500] The local observatory database (ODB) shall provide a persistent data store for the following use cases:

- Science data produced by science instruments
- Telemetry data produced by technical systems
- Logging (history) data from all subsystems
- Astronomical catalogs
- TMT software systems that require long-term data caches (e.g. APS)
- User login and contact information

[REQ-1-OAD-9503] Two copies of all data objects shall be kept in physically separate locations. The physical separation must be large enough that local catastrophic events do not destroy both data copies.

Discussion: the minimal separation solution is one copy on summit, one copy in support facility. A more desirable solution is a separation of 10s of kilometers or more.

[REQ-1-OAD-9506] Data consistency checks between the two copies shall be run automatically on a regular basis.

[REQ-1-OAD-9509] The local observatory database shall be able to store update-oriented data – small (few byte to several KByte) data objects oriented towards an update-many, read-many, fast access model (e.g. status flags, mutable business objects). Data volume is expected to be tens of GB. These data shall be stored within relational databases.

[REQ-1-OAD-9512] The local observatory database shall be able to store read-oriented data – small (few byte to several KByte) data objects oriented towards a write-once, read-many, fast access model (e.g. subsystem telemetry data). Data volume is expected to be a tens of TB.

[REQ-1-OAD-9515] The local observatory database shall be able to store bulk data – large (several to many MByte) data objects oriented towards a write-once, read-many, slow access model (e.g. science detector pixel data). Data volume is expected to be at least 100 TB.

[REQ-1-OAD-9518] The large volume, bulk data shall be written to a disk-oriented storage system with location pointers stored in relational databases. These pointers shall be linked to the meta-data that describe the bulk data objects. This linkage enables the ability to query meta-data tables to locate appropriate bulk data objects and then use the pointers to find the bulk data objects in the bulk storage device.

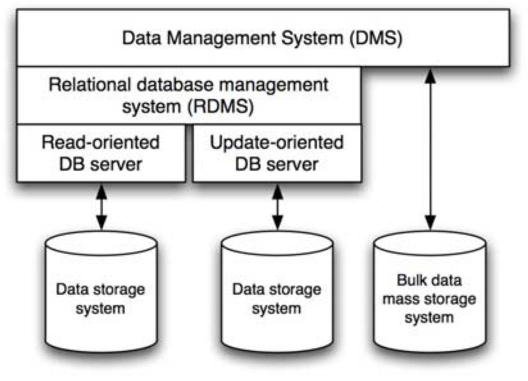


Figure 17: Observatory database architecture

[REQ-1-OAD-9521] The high-level reference design ODB architecture is shown in Figure 17.

[REQ-1-OAD-9524] For data retrieval, subsystems (clients) use the ODB access service to query and retrieve information from the observatory database.

[REQ-1-OAD-9527] Data formats, database table structures, and file system structures are all TBD.

5.2.6 Data structures

5.2.6.1 General

[REQ-1-OAD-9600] All OES and PES data formats, data structures, database table structures, and files system structures shall be documented in the TMT Data Interface Control Document (Data ICD or DICD).

5.2.6.2 Science operations business objects

[REQ-1-OAD-9610] There shall be a hierarchical set of linked science operations business objects. The reference set of such business objects is shown in Table 34.

[REQ-1-OAD-9613] Each business object references data from its predecessors(s) in a relational way.

[REQ-1-OAD-9616] Each business object shall have a defined state (e.g. READY, FAULT, COMPLETED). During the design phase, an extensible list of valid states shall be defined for each business object class.

[REQ-1-OAD-9619] Each business object shall have a revision history.

Business Object	Description
Proposal	The original user request to use the TMT Observatory, a proposal contains all the scientific and technical information needed to evaluate the scientific merit and technical feasibility of the described observing program relative to all other concurrent proposals.
Program	A proposal that has been accepted for execution (priority and conditions permitting). Fundamentally, a program consists of one or more observing runs
Observing Run	A program subset scheduled for a specific major mode of a specific instrument during a fixed time period. Each observing run contains one or more observation blocks.
Observation Block	An OB contains all the information necessary to setup, schedule, and execution a specific observation. An OB can be executed more than once. The information within an OB can be modified.
Data Frame	A self-contained data object, usually associated with a single science instrument detector readout or the hardware-averaged result of many such readouts. Raw data frames have not been processed further, while processed data frames (sometimes known as data products) have been processed.
Execution Block	When executed, each OB produces a static copy of itself known as an Execution Block.
Association Block	Contains all the information needed to process a data frame set including: all other raw data frames associated with that set, all calibration data needed to process that set, data processing module needed to process set.

Table 34: Science operations business objects

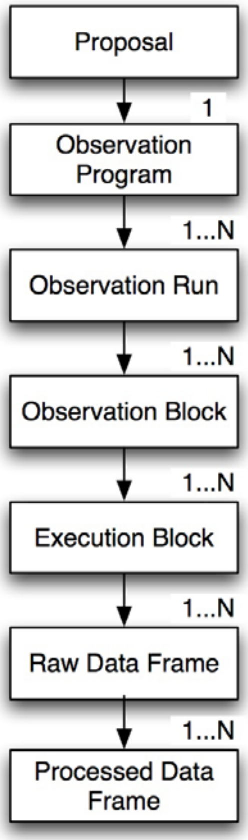


Figure 18: Science operations business objects

5.2.6.3 Observation description

[REQ-1-OAD-9630] The fundamental OES observation descriptor shall be known as an Observation Block (OB). It shall contain the following information:

- Target description
- Guide star description
- Instrument configuration
- AO system configuration
- Scheduling constraints
- TO BE COMPLETED

[REQ-1-OAD-9633] Each OB shall contain a TBD minimal set of self-describing parameters. Additional parameters shall be added as the situation warrants.

[REQ-1-OAD-9636] Internal OB structure and syntax are TBD. The design reference syntax is (keyName, value) pairs (e.g. targRA = “00 24 34.5”, wfosGrism01 = “blue”). The reference syntax may be replaced by a more sophisticated syntax based on (e.g.) XML during the design phase.

Discussion: OB parameters are input arguments to lower level software system control and configuration procedures (scripts) within the OES master sequencer. These scripts will be developed in collaboration with the instrument development teams.

[REQ-1-OAD-9639] All observation description generators shall generate OBs. Example generators include standard text editors, observer GUIs, and operator GUIs.

[REQ-1-OAD-9642] It shall be possible to create an OB as a plain text file using standard text processing tools. An application shall be available to import such OB text files and submit them to the OES for action.

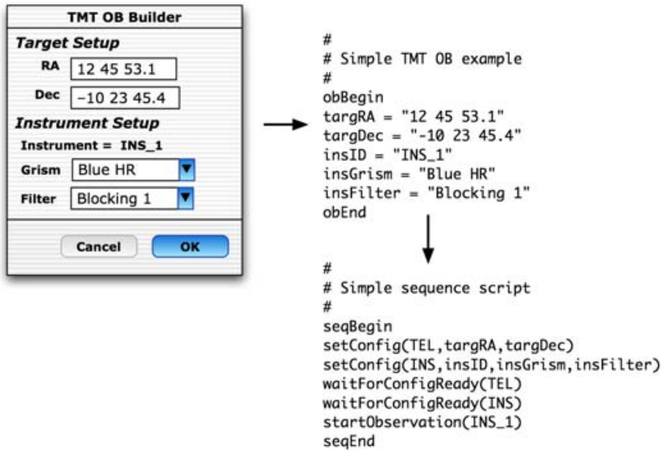
[REQ-1-OAD-9645] It shall be possible to filter and group OBs arbitrarily by any parameter.

[REQ-1-OAD-9648] It shall be possible to define ordered OB sequences using the following concepts:

- Time interval between successive OBs
- Absolute execution time windows for each OB
- Conditional execution based on outcome of previous observations
- TO BE COMPLETED

[REQ-1-OAD-9651] OB sequences shall be encoded as data structures that contain pointers to OBs – such sequences shall not be encoded into the OBs themselves.

Discussion: a simple OB example is shown in Figure 19. Further OB specifications will be provided in Science Operations Software Business Objects Specifications.



Target Setup
RA 12 45 53.1
Dec -10 23 45.4
Instrument Setup
Instrument = INS_1
Grism Blue HR
Filter Blocking 1

```
#
# Simple TMT OB example
#
obBegin
targRA = "12 45 53.1"
targDec = "-10 23 45.4"
insID = "INS_1"
insGrism = "Blue HR"
insFilter = "Blocking 1"
obEnd
```

```
#
# Simple sequence script
#
seqBegin
setConfig(TEL,targRA,targDec)
setConfig(INS,insID,insGrism,insFilter)
waitForConfigReady(TEL)
waitForConfigReady(INS)
startObservation(INS_1)
seqEnd
```

Figure 19: Simple observation block (OB) example

5.2.7 Software development framework definition

Discussion: Such a software framework has been called common software by other projects. More complete requirements shall be provided in the TMT Software Framework Definition Document.

[REQ-1-OAD-9700] All TMT software system components shall be implemented within a standard TMT software framework.

[REQ-1-OAD-9703] This framework shall have three high-level goals:

- Adopt and/or adapt commercial and/or open source solutions that are already widely used and supported within the IT industry.
- Minimize time and effort needed to install, integrate, and verify the TMT software system on-site and make it operational.
- Minimize time and effort needed to maintain and extend the TMT software system during operations.

[REQ-1-OAD-9706] The standard TMT software framework shall include (but is not necessarily limited to):

- Middleware APIs and/or supporting libraries
- GUI builders
- Data structure editors
- Build tools and process specification (e.g. Unix makefiles)
- Centralized configuration control server
- Centralized and automatic build, integrate, and test process
- Standards for
    - Data and meta-data structures
    - Languages
- Specifications for:
    - Development environment (OS, hardware, compilers…)
    - Deployment environment (OS, hardware)
    - Associated documentation

[REQ-1-OAD-9709] Items specific to real-time mechanism control and science data processing shall be added to this list after further discussion.

[REQ-1-OAD-9712] Whenever possible, the TMT software framework shall use widely used, industry standard commercial and/or open source tools, libraries, data structures, etc. Solutions that have high, long-term maintenance or licensing costs (e.g. commercial enterprise-class middleware and libraries) shall be avoided unless specifically approved by the TMT Project.

[REQ-1-OAD-9715] All non-real-time software subsystems shall have the same target deployment platform. The target platform shall be some Unix or Linux variant. The exact target deployment platform is TBD.

[REQ-1-OAD-9718] All non-real-time software subsystems shall be built using a common build strategy (e.g. Unix makefiles).

[REQ-1-OAD-9721] A centralized software problem reporting and tracking system (e.g. bugzilla) shall be maintained by the TMT project.

[REQ-1-OAD-9724] The TMT Project shall develop a TMT software system release plan that consists of intermediate releases tied to specific functionality.

[REQ-1-OAD-9727] A centralized software configuration control server shall be implemented. At TBD intervals during development, all TMT software shall be delivered to the central server and placed under configuration control.

[REQ-1-OAD-9730] The TMT Project shall implement an automatic build, integrate, and test process. This process shall run at TBD periodic intervals (e.g. every 24 hours).

[REQ-1-OAD-9734] Software stored on the central configuration server shall be considered the master copy.

[REQ-1-OAD-9737] Software installed in the operational, on-site environment shall not be considered the master copy. Changes to software made to software installed in the operational, on-site environment shall not be considered official or permanent. All such changes shall be tagged and checked into the central configuration control server as soon as possible.

[REQ-1-OAD-9740] It shall be possible to remove (completely or partially) all software from the TMT operational environment without warning and re-install it in less than eight (8) (TBC) hours based on information stored on the central configuration server supplemented by various high-level installation kits (for, e.g. operating system, common software packages, etc.) At the end of this reinstallation process, the system shall be restored to its operational state at the time of software removal.

6. DEFINITIONS

6.1 COORDINATE SYSTEMS

[REQ-1-OAD-9900] The following coordinate system are standards for the thirty meter telescope project.

Table 35 Coordinate systems for the ideal, undisturbed telescope

Coordinate System	***Origin***	***X axis***	***Y axis***	***Z axis***
Terrestrial (TCRS)	The center of the azimuth journal circle, in the plane of the azimuth journal	Points to the East, in the plane of the azimuth journal	Points to the North, in the plane of the azimuth journal	Right hand complement to x and y axes
Azimuth (ACRS)	Identical to TCRS. In southern hemisphere for ACRS=0, the telescope is pointing north.	Increases clockwise relative to the +X axis of TCRS by the azimuth angle. Is in the plane of the azimuth journal; and it is parallel to the elevation axis X axis.	Right hand complement to the X and Z axes	Identical to TCRS
Elevation (ECRS)	The intersection of the Z axis of ACRS with the elevation axis of the telescope	Parallel to the X axis of the ACRS, in the line of the elevation axis of the telescope	Rotated counter-clockwise (+ direction) around the X axis, relative to the horizontal, by the zenith angle	Right hand complement to the X and Y axes; points to the sky at zero zenith angle
Primary Mirror (M1CRS)	The intersection of the Z axis of the ECRS with the M1 optical surface	Parallel to the X axis of the ECRS	Parallel to the Y axis of the ECRS	Right hand complement to the X and Y axes
Secondary Mirror (M2CRS)	The intersection of the Z axis of the ECRS with the M2 optical surface	Parallel to the X axis of the ECRS	Right hand complement to the X and Z axes	Points to the origin of the ECRS, in the line of the Z axis of the ECRS

Coordinate System	*Origin*	*X axis*	*Y axis*	*Z axis*
Tertiary Mirror (M3CRS)	The intersection of the Z axis of the ECRS with the M3 optical surface	Points to North and parallel to the X-Y plane of the ECRS, when $\lambda = 0$ and $\mu = 45°$.	Right hand complement to the X and Z axes	Normal to M3 surface; points away from the reflective surface; M3 position is described by the polar coordinates λ and μ of this Z axis in the ECRS
Focal Surface (FCRS)	The center of the focal surface	Right hand complement to the X and Z axes	Projection of the ACRS Z axis on the plane perpendicular to the Z axis	Normal to the focal surface at the origin; points towards the tertiary mirror
Segment ($SCRS_j$)	The midpoint of the segment optical surface; midpoint is the center of the hexagon transformed as defined in Section XX	Perpendicular to the Z axis; its projection on the X-Y plane of M1CRS points to the radial direction	Right hand complement to the X and Z axes	Normal to the segment optical surface at the origin

The regular polar coordinates defined in each coordinate system as follows:

$$x = \rho \sin\theta \cos\varphi$$
$$y = \rho \sin\theta \sin\varphi$$
$$z = \rho \cos\theta$$

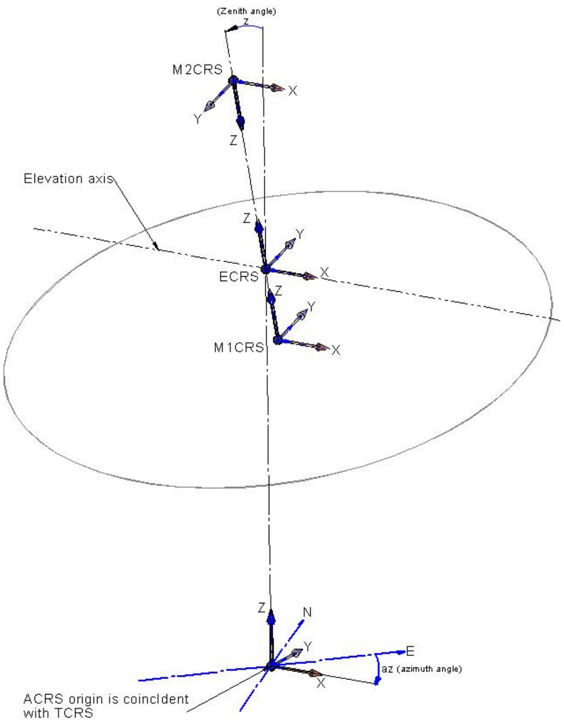


Figure 20 The basic coordinate systems of the telescope

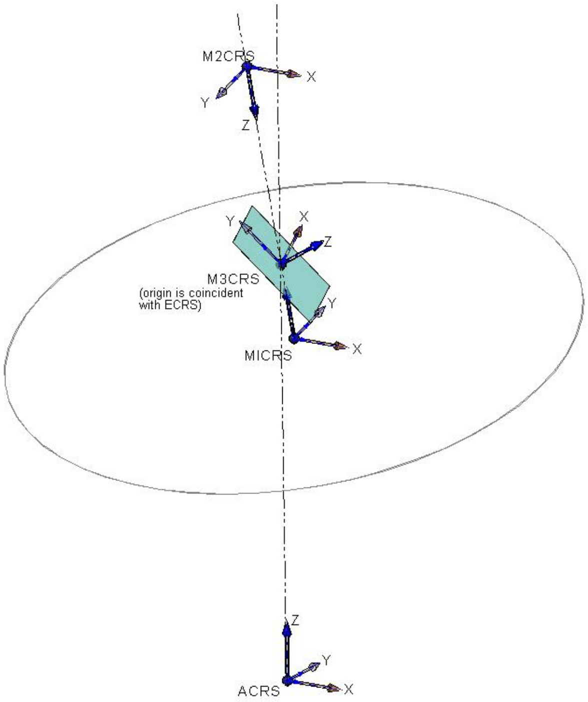


Figure 21 Tertiary mirror coordinate system (M3CRS) shown in the context of the M1CRS and M2CRS

7. APPENDIX

7.1 WAVELENGTH BANDS

7.1.1 Astronomical Filters

Table 36 Astronomical Filters

Band	Center wavelength	Bandwidth
U	0.3663 μm	0.0650 μm
B	0.4361 μm	0.0890 μm
V	0.5448 μm	0.0840 μm
R	0.6407 μm	0.1580 μm
I	0.7980 μm	0.1540 μm
J	1.250 μm	0.16 μm
H	1.635 μm	0.29 μm
K’	2.12 μm	0.34 μm
K_s	2.15 μm	0.32μm
K	2.2 μm	0.34 μm
L	3.77 μm	0.7 μm
M	4.68 μm	0.22 μm
N	10.47 μm	5.2 μm
Q	20.13 μm	7.8 μm

Data in the table is from [RD6].

7.1.2 Atmospheric Transmission Windows

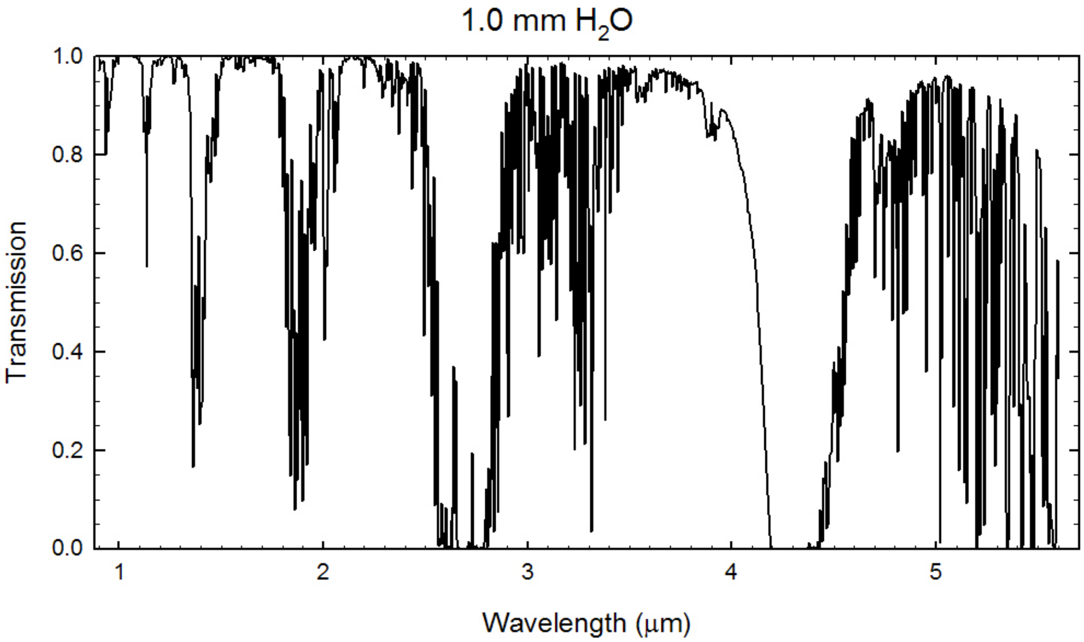


Figure 22 Near and mid infrared atmospheric transmission windows for 1 mm precipitable water vapor [RD5]

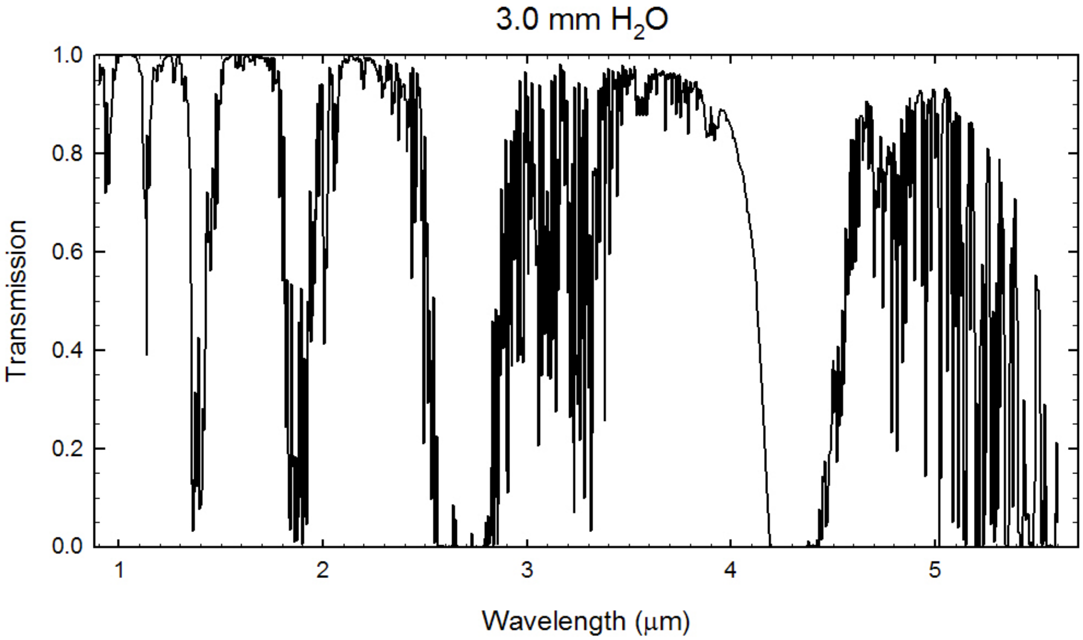


Figure 23 Near and mid infrared atmospheric transmission windows for 3 mm precipitable water vapor [RD7]

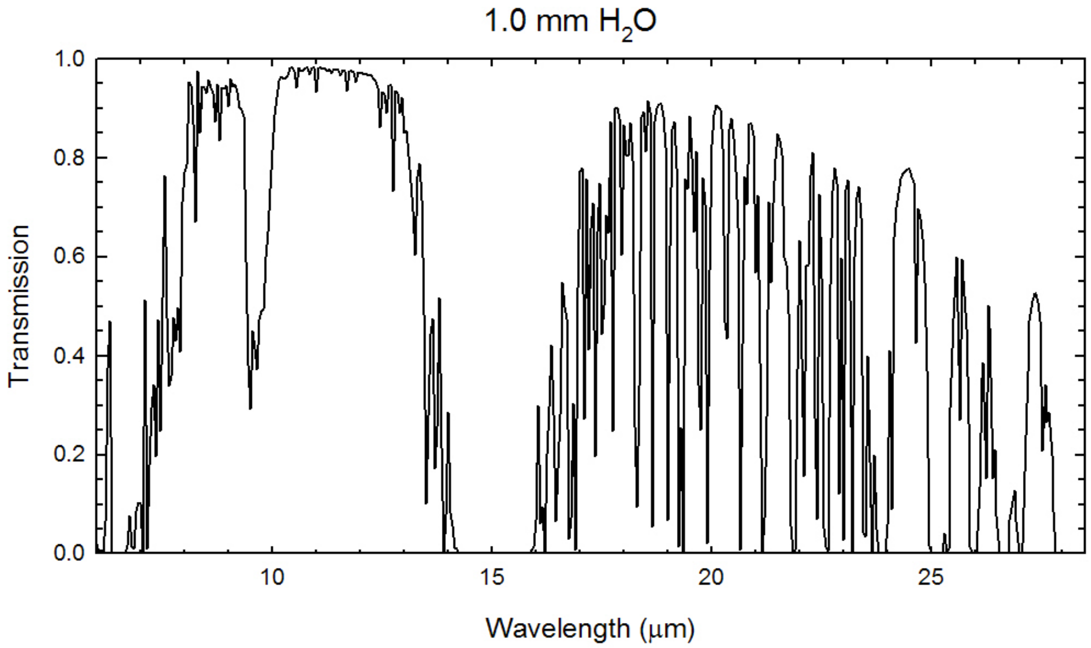


Figure 24 Infrared atmospheric transmission windows for 1 mm precipitable water vapor [RD7]

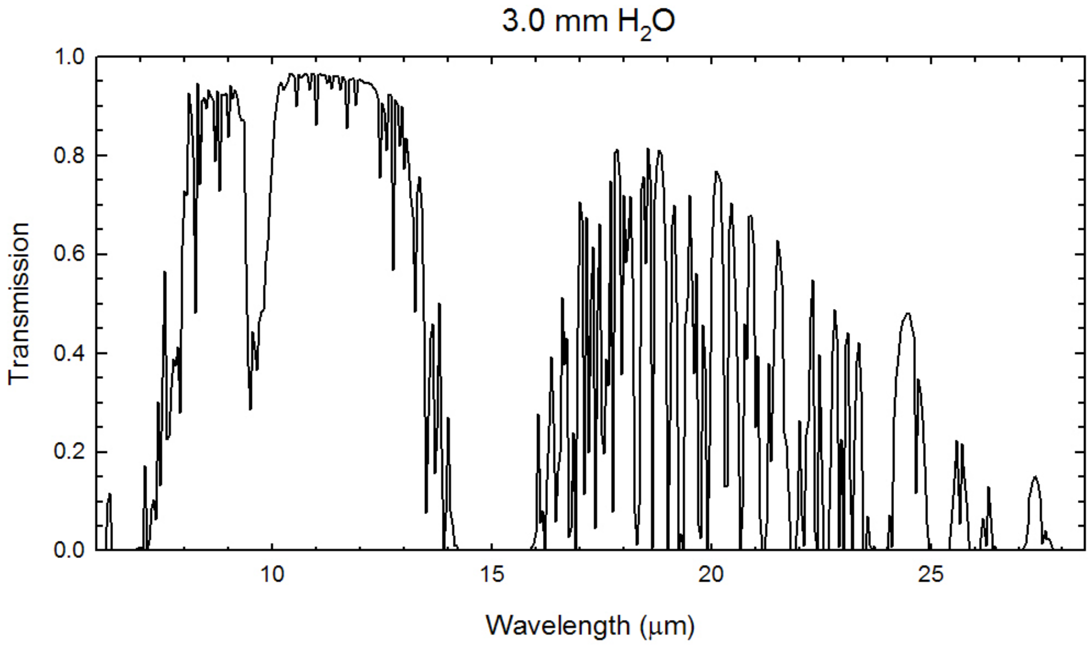


Figure 25 Infrared atmospheric transmission windows for 3 mm water vapor [RD7]

7.2 ACQUISITION

Figure 26, Figure 27, and Figure 28 show characteristic acquisition sequences for seeing limited, NGS and LGS AO operating modes. These sequences illustrate current best *estimates; they do not meet the SRD and ORD requirement of 5 minutes between observations.*

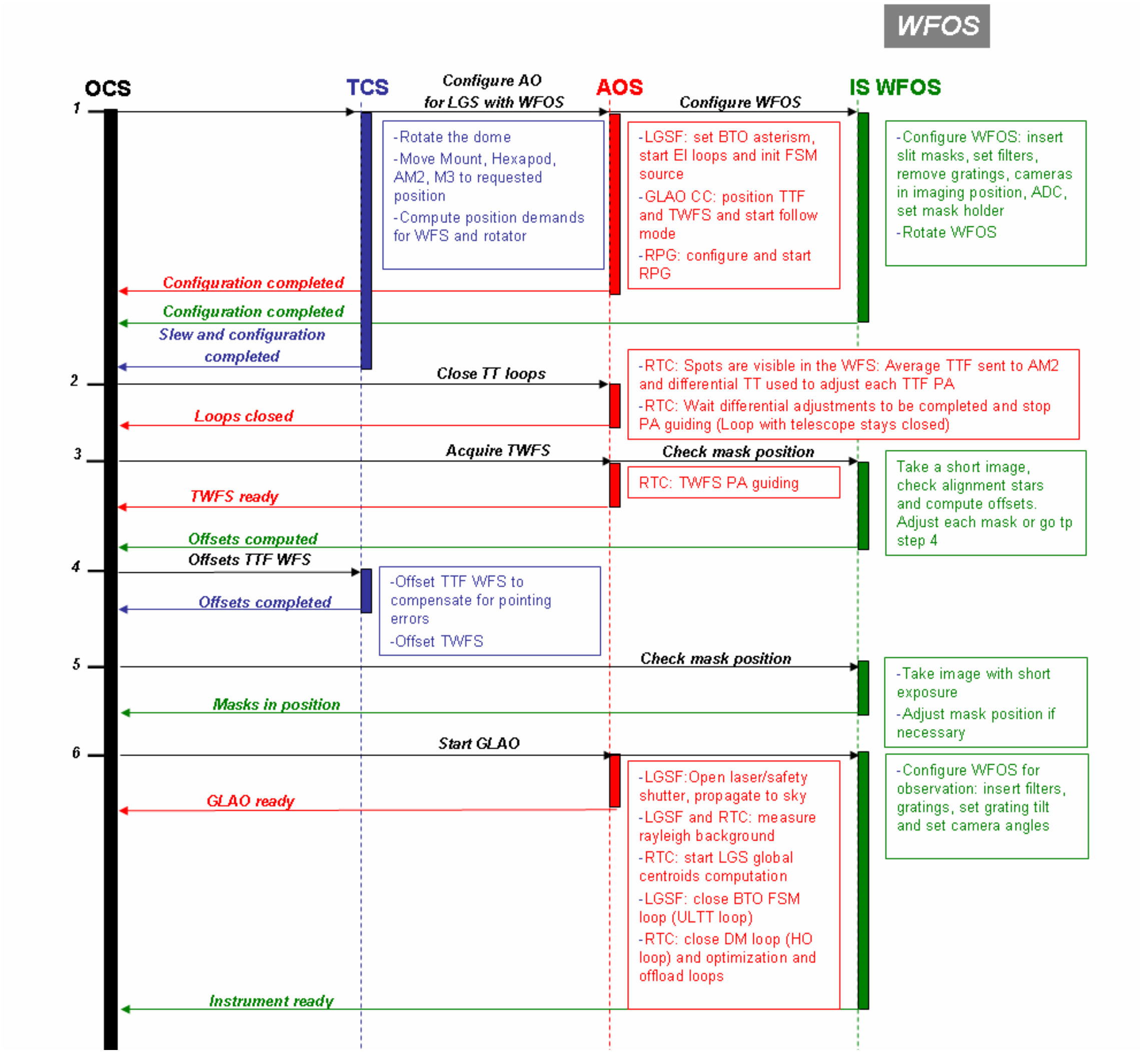


Figure 26 Example acquisition scheme for a GLAO system configuration (WFOS). FOV of guide (TT) WFS is large enough to acquire guide star in one step.

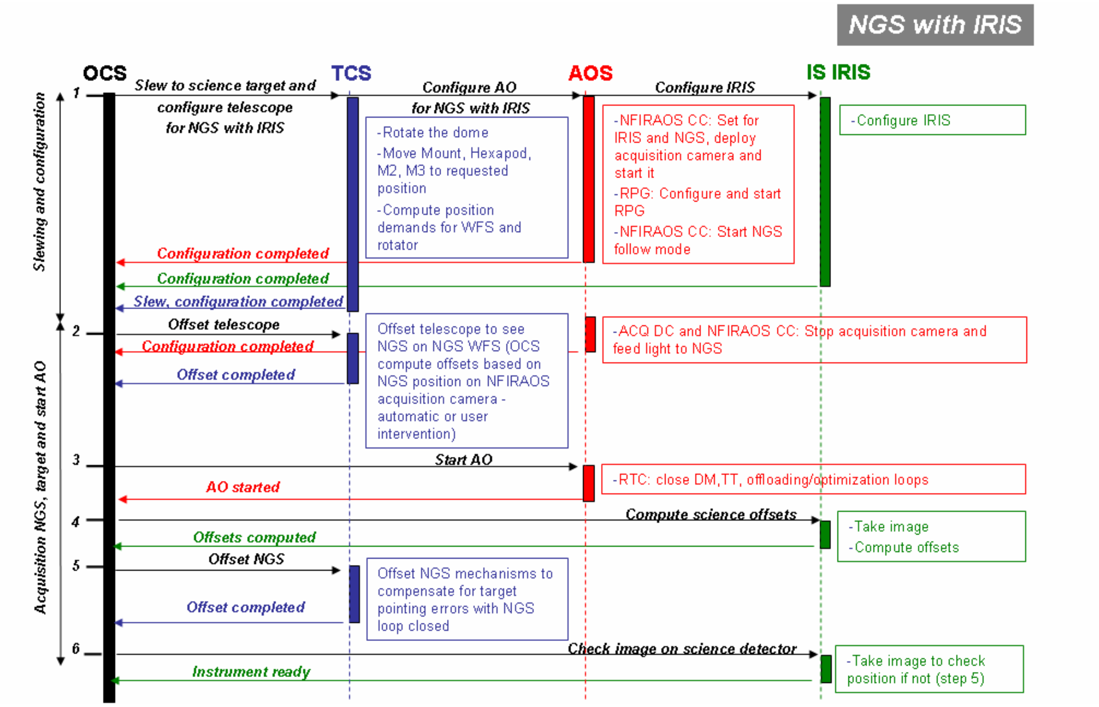


Figure 27 Example acquisition scheme for a NGS MCAO system configuration (IRIS). FOV of guide (TT) WFS is not enough for blind pointing the telescope on the WFS; Instrument acquisition camera is needed.

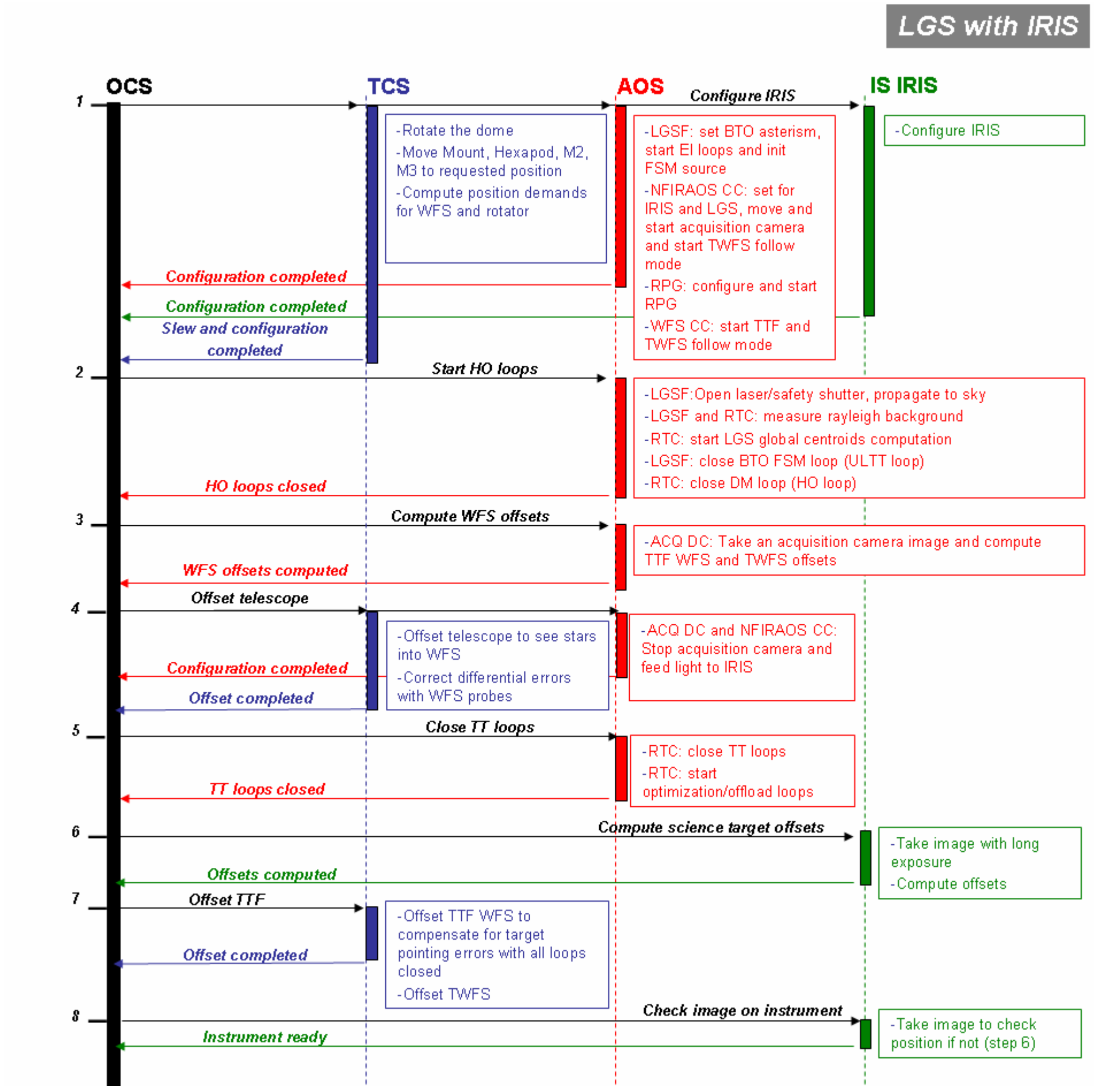
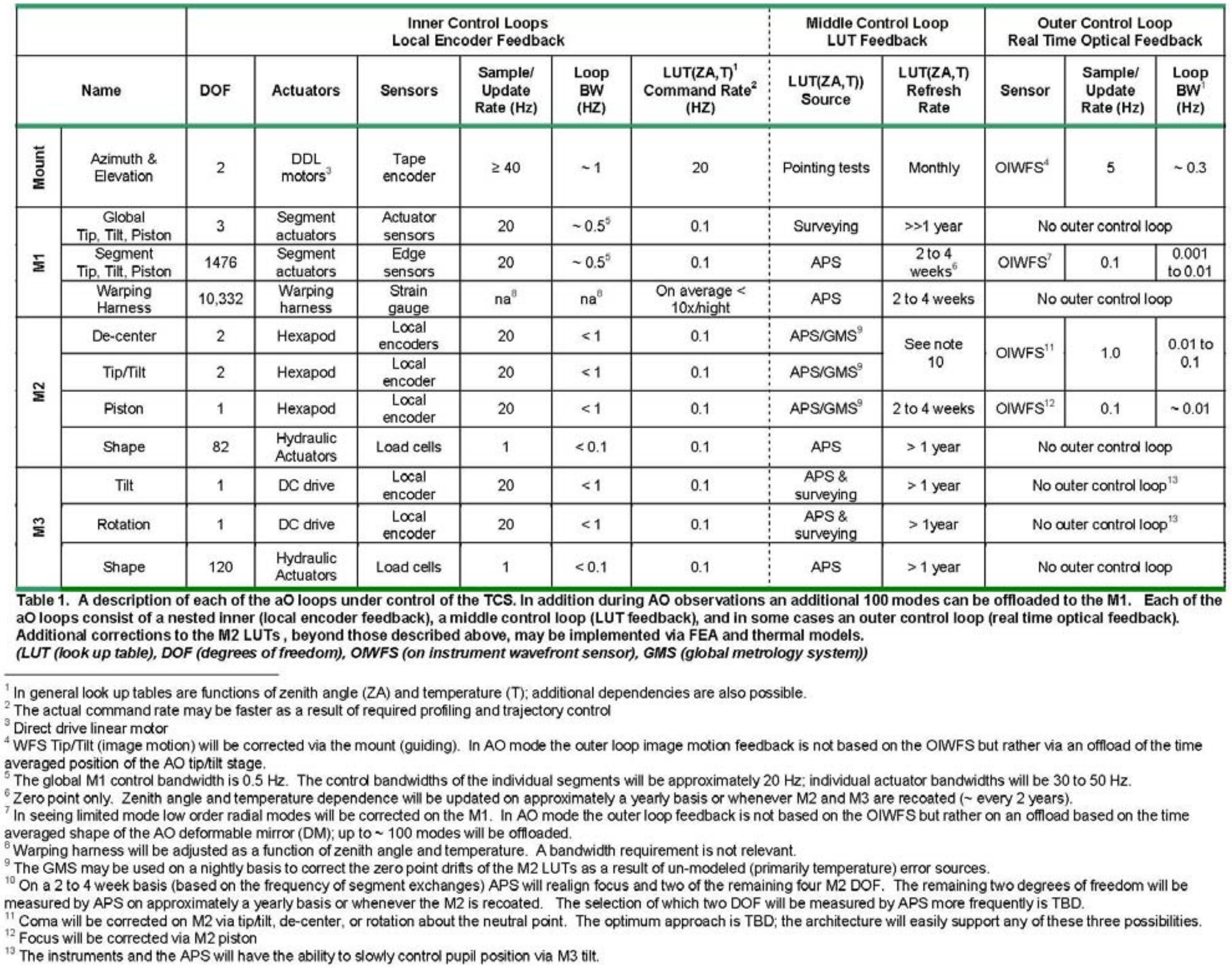


Figure 28 Example acquisition scheme for a LGS MCAO system configuration (IRIS). Procedure is similar to Figure 27, but for faint guide stars. The faint natural guide stars are enhanced by higher order, LGS based AO correction.

7.3 OBSERVATORY CONTROL ARCHITECTURE

Table 37 Mount and active optics actuators and corresponding sensors with control bandwidths



		Inner Control Loops Local Encoder Feedback						Middle Control Loop LUT Feedback		Outer Control Loop Real Time Optical Feedback		
	Name	DOF	Actuators	Sensors	Sample/ Update Rate (Hz)	Loop BW (HZ)	LUT(ZA,T)[1] Command Rate[2] (HZ)	LUT(ZA,T)) Source	LUT(ZA,T) Refresh Rate	Sensor	Sample/ Update Rate (Hz)	Loop BW[1] (Hz)
Mount	Azimuth & Elevation	2	DDL motors[3]	Tape encoder	≥ 40	~ 1	20	Pointing tests	Monthly	OIWFS[4]	5	~ 0.3
M1	Global Tip, Tilt, Piston	3	Segment actuators	Actuator sensors	20	~ 0.5[5]	0.1	Surveying	>>1 year	No outer control loop		
	Segment Tip, Tilt, Piston	1476	Segment actuators	Edge sensors	20	~ 0.5[5]	0.1	APS	2 to 4 weeks[6]	OIWFS[7]	0.1	0.001 to 0.01
	Warping Harness	10,332	Warping harness	Strain gauge	na[8]	na[8]	On average < 10x/night	APS	2 to 4 weeks	No outer control loop		
M2	De-center	2	Hexapod	Local encoders	20	< 1	0.1	APS/GMS[9]	See note 10	OIWFS[11]	1.0	0.01 to 0.1
	Tip/Tilt	2	Hexapod	Local encoder	20	< 1	0.1	APS/GMS[9]				
	Piston	1	Hexapod	Local encoder	20	< 1	0.1	APS/GMS[9]	2 to 4 weeks	OIWFS[12]	0.1	~ 0.01
	Shape	82	Hydraulic Actuators	Load cells	1	< 0.1	0.1	APS	> 1 year	No outer control loop		
M3	Tilt	1	DC drive	Local encoder	20	< 1	0.1	APS & surveying	> 1 year	No outer control loop[13]		
	Rotation	1	DC drive	Local encoder	20	< 1	0.1	APS & surveying	> 1year	No outer control loop[13]		
	Shape	120	Hydraulic Actuators	Load cells	1	< 0.1	0.1	APS	> 1 year	No outer control loop		

Table 1. A description of each of the aO loops under control of the TCS. In addition during AO observations an additional 100 modes can be offloaded to the M1. Each of the aO loops consist of a nested inner (local encoder feedback), a middle control loop (LUT feedback), and in some cases an outer control loop (real time optical feedback). Additional corrections to the M2 LUTs , beyond those described above, may be implemented via FEA and thermal models.
(LUT (look up table), DOF (degrees of freedom), OIWFS (on instrument wavefront sensor), GMS (global metrology system))

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[1] In general look up tables are functions of zenith angle (ZA) and temperature (T); additional dependencies are also possible.

[2] The actual command rate may be faster as a result of required profiling and trajectory control

[3] Direct drive linear motor

[4] WFS Tip/Tilt (image motion) will be corrected via the mount (guiding). In AO mode the outer loop image motion feedback is not based on the OIWFS but rather via an offload of the time averaged position of the AO tip/tilt stage.

[5] The global M1 control bandwidth is 0.5 Hz. The control bandwidths of the individual segments will be approximately 20 Hz; individual actuator bandwidths will be 30 to 50 Hz.

[6] Zero point only. Zenith angle and temperature dependence will be updated on approximately a yearly basis or whenever M2 and M3 are recoated (~ every 2 years).

[7] In seeing limited mode low order radial modes will be corrected on the M1. In AO mode the outer loop feedback is not based on the OIWFS but rather on an offload based on the time averaged shape of the AO deformable mirror (DM); up to ~ 100 modes will be offloaded.

[8] Warping harness will be adjusted as a function of zenith angle and temperature. A bandwidth requirement is not relevant.

[9] The GMS may be used on a nightly basis to correct the zero point drifts of the M2 LUTs as a result of un-modeled (primarily temperature) error sources.

[10] On a 2 to 4 week basis (based on the frequency of segment exchanges) APS will realign focus and two of the remaining four M2 DOF. The remaining two degrees of freedom will be measured by APS on approximately a yearly basis or whenever the M2 is recoated. The selection of which two DOF will be measured by APS more frequently is TBD.

[11] Coma will be corrected on M2 via tip/tilt, de-center, or rotation about the neutral point. The optimum approach is TBD; the architecture will easily support any of these three possibilities.

[12] Focus will be corrected via M2 piston

[13] The instruments and the APS will have the ability to slowly control pupil position via M3 tilt.

7.4 FIRST DECADE INSTRUMENT LAYOUT

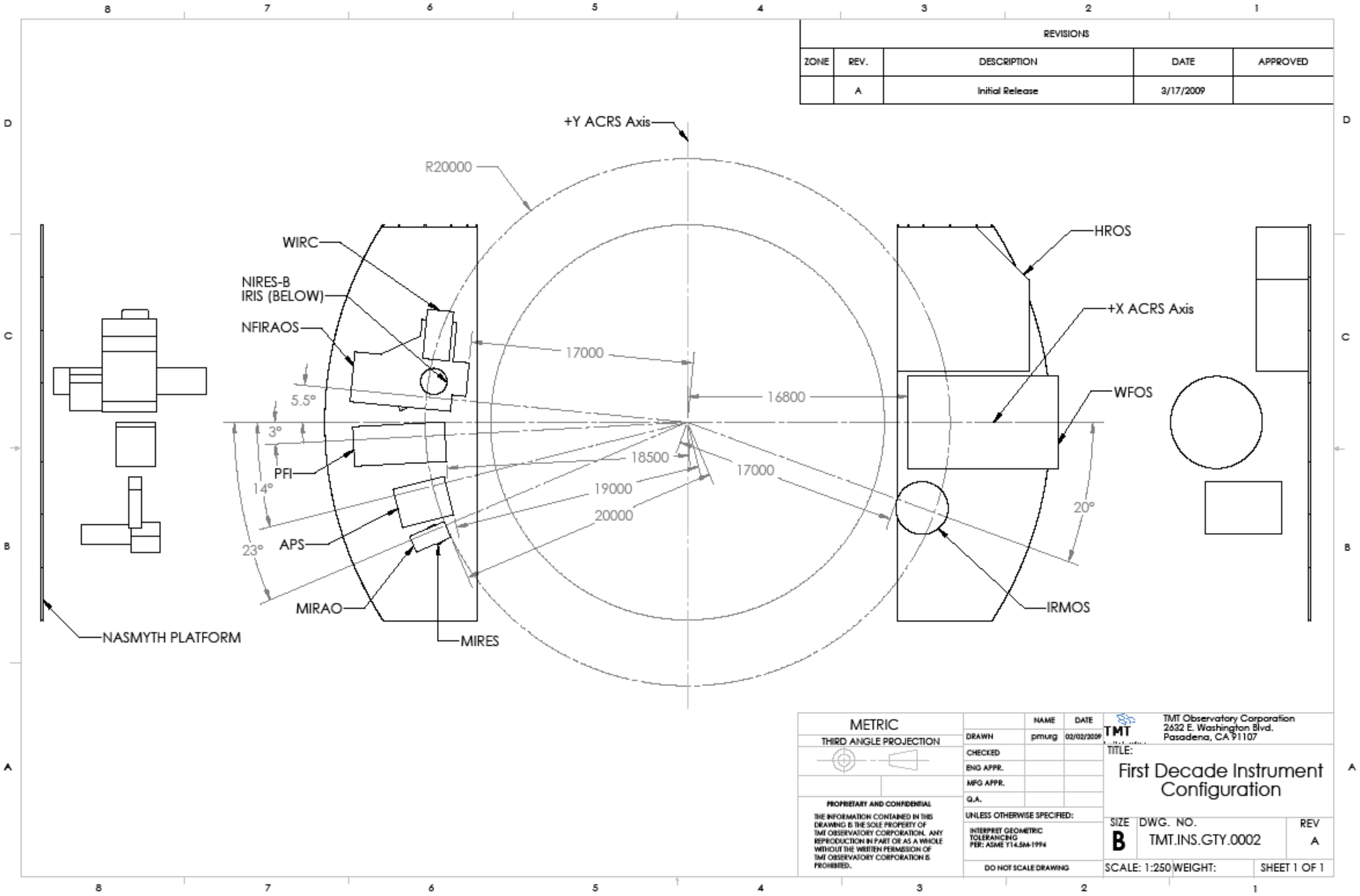

Figure 29 Full SAC Instrument Layout

Discussion:

The –X Nasmyth is configured as follows: NFIRAOS and its associated instruments (any three of IRIS, IRMS, NIRES and WIRC) are located at the 174.5 degree position. PFI is located at the +183 degree position, APS at its desired +194 degree position, and MIRES/MIRAO is at +203 degrees.

The +X Nasmyth is configured as follows: WFOS is oriented horizontally on the elevation axis (0 degrees). HROS is located at the back of this platform, within the trimmed envelope, and is fed by the M3 at +5 degrees. The beam to HROS must be deflected in front of WFOS to reach the instrument. IRMOS is located at the -20 degree location on this platform.

7.5 EXAMPLE MIRROR COATING REFLECTANCE CURVES

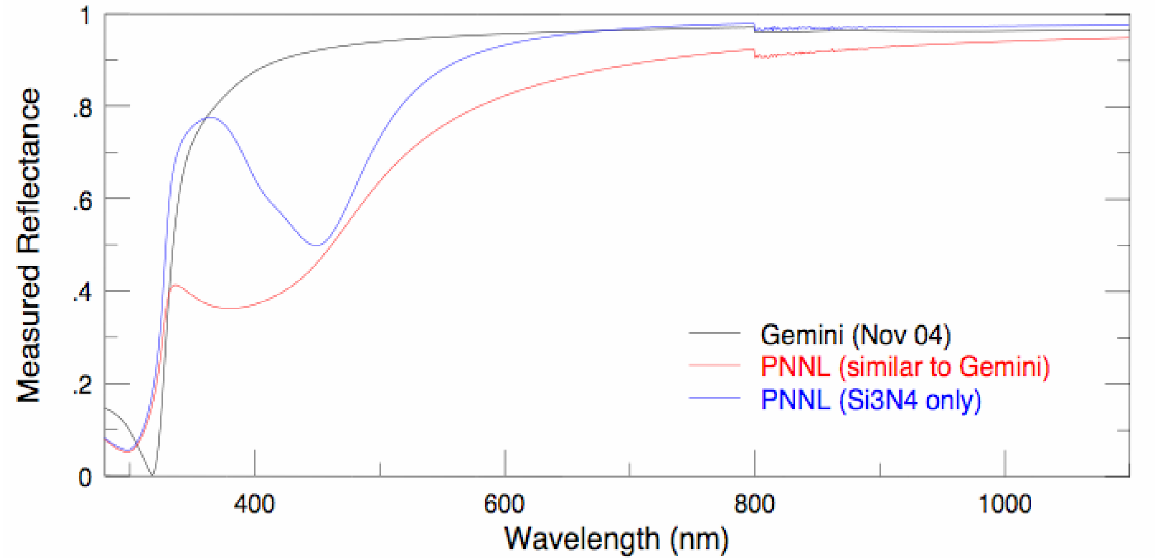

Figure 30 Gemini coating plus other coatings in development. Dip in reflectivity other coatings is caused by surface Plasmon resonances.