OBSERVATORY ARCHITECTURE DOCUMENT

TMT.SEN.DRD.05.002.CCR40

September 29, 2022

SIGNATURE PAGE

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See Document Change Record for change requests incorporated at this time.

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Document Change Record

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CCR39	CR278: Collection-20093, CR299: Collection-23478, CR313: Collection-24819, CR328: Collection-25943, CR341: Collection-26259, CR357: Collection-28650, CR360: Collection-28841, CR362: Collection-29732, CR363: Collection-28923, CR365: Collection-29387, CR366: Collection-29390, CR367: Collection-29391, CR368: Collection-29406, CR372: Collection-29529, CR373: Collection-29556, CR375: Collection-29755, CR379: Collection-29890, CR380: Collection-29956, ADMIN: ADs	G. Trancho, routing #76953	May 24, 2021
CCR38	Released per: CR279: Collection-20094, CR322: Collection-26053, CR324: Collection-25666, CR302: Collection-23830, CR337: Collection-26045, CR321: Collection-25545, CR338: Collection-26133, CR344: Collection-26683, CR352: Collection-28522, CR355: Collection-28559, CR356: Collection-28620, CR361: Collection-28892, ADMIN: Figures and Table numbers, ADs	G. Trancho, routing #68533	October 27, 2020
CCR37	Released per: CR273: Collection-24689, CR282: Collection-24347, CR296: Collection-22983, CR309: Collection-24408, CR318: Collection-25410, CR301: Collection-23669, CR302: Collection-23830, ADMIN	G. Trancho, routing #59136	January 8, 2020

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CCR36	Released per: CR233: Collection-14943, CR243: Collection-19722, CR276: Collection-20085, CR277: Collection-20092, CR287: Collection-23633, CR291: Collection-22522, CR295: Collection-22934, CR298: Collection-23602, CR300: Collection-23480, ADMIN	G. Trancho, routing #48542	March 7, 2019
CCR35	Released per: CR143: Collection-8486, CR232: Collection-14939, CR244: Collection-15785, CR257: Collection-16224, CR259: Collection-16182, CR261: Collection-16318, CR266: Collection-16771, CR268: Collection-19721, CR270: Collection-19843, CR272: Collection-19852, ADMIN: AD/RD updates	S. Roberts, routing #32643	June 18, 2018
CCR34	Released per: CR225: Collection-14719, CR240: Collection-15481 CR242: Collection-15738, ADMIN: Update IRIS, APS, CRYO, M2 envelope ADs	S. Roberts, routing #26275	January 23, 2018
CCR33	Released per: CR218: Collection-13981, CR235: Collection-14957 ADMIN: Update LGSF drawing ADs	S. Roberts, routing # 19749	September 13, 2017
CCR32	Released per: CR161: Collection-9292 (missing from CCR30), CR175: Collection-10859, CR198: Collection-12467, CR203: Collection-12579, CR222: Collection-14558, ADMIN: Update AD/RDs	S. Roberts, routing # 16397	June 5, 2017
CCR31	Released per: CR216: Collection-13852, ADMIN: Update AD/RDs	S. Roberts, routing # 14195	January 30, 2017

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CCR30	Released per: CR130: Collection-8481, CR161: Collection-9292, CR164: Collection-9992, CR166: Collection-10039, CR196: Collection-12344, CR202: Collection-13718, CR209: Collection-13430, CR210: Collection-13447, ADMIN: Administrative fixes (typos, formatting, etc.).	S. Roberts, routing # 12002	November 16, 2016
CCR29	Released per: CR152: Collection-8776, CR157: Collection-9129, CR160: Collection-9254, CR163: Collection-9991, CR172: Collection-10256	See approval page in CCR29	January 12, 2016
CCR28	Released per: CR134: Collection-8419, CR135: Collection-8483, CR139: Collection-8399, CR141: Collection-8422, CR142: Collection-8485, CR150: Collection-8658	See approval page in CCR28	October 13, 2014
CCR27	Released per: CR124: Collection- 7537, CR125: Collection-7538	See approval page in CCR27	December 11, 2013
CCR26	Released per: CR119: Collection-6862, CR117: Collection-6630	See approval page in CCR26	February 5, 2013
CCR25	CR106: Collection-6103 Updates as per Level 1 DRD Change History Document, TMT.SEN.TEC.07.038.REL10	See approval page in CCR25	June 6, 2012
CCR24	Released per: CR050: Collection-4199, CR087: Collection-5447, CR090: Collection-5508, CR093: Collection-5627, Updates as per Level 1 DRD Change History Document, TMT.SEN.TEC.07.038.REL09	See approval page in CCR24	October 12, 2011
CCR23	Released per: CR080: Collection-4913, Updates as per Level 1 DRD Change History Document, TMT.SEN.TEC.07.038.REL08	See approval page in CCR23	December 1, 2010

Revision	Change Request Approval	Release Approval	Date Released
CCR22	Released per: CR062: Collection-4324, CR070: Collection-4529, CR071: Collection-4564, CR072: Collection-4566 Updates as per Level 1 DRD Change History Document, TMT.SEN.TEC.07.038.REL07	See approval page in CCR22	April 27, 2010
CCR21	Released per: CR031: Collection-3926, CR042: Collection-4119, CR057: Collection-4258, CR060: Collection-4309 Updates as per Level 1 DRD Change History Document, TMT.SEN.TEC.07.038.REL06	See approval page in CCR21	December 17, 2009
CCR20	Updates as per Level 1 DRD Change History Document, TMT.SEN.TEC.07.038.REL05	See approval page in CCR20	March 27, 2009
CCR19	Updates as per Level 1 DRD Change History Document, TMT.SEN.TEC.07.038.REL04	See approval page in CCR19	January 28, 2009
CCR18	Updates as per Level 1 DRD Change History Document, TMT.SEN.TEC.07.038.REL03	See approval page in CCR18	September 4, 2008
CCR17	Updates as per Level 1 DRD Change History Document, TMT.SEN.TEC.07.038.REL02	See approval page in CCR17	March 19, 2008
CCR16	Updates as per Level 1 DRD Change History Document, TMT.SEN.TEC.07.038.REL01	See approval page in CCR16	November 14, 2007
CCR15	Updates as per systems engineering watch list document, TMT.SEN.TEC.07.025.REL14	See approval page in CCR15	October 19, 2007
CCR14	Update of Crane System Requirements, Various updates.	See approval page in CCR14	August 14, 2007
CCR13	Updates as per proposed errata and updates as documented in TMT.SEN.TEC.07.025.DRF05	See approval page in CCR13	May 25, 2007

Document Waiver Log

Waiver Approval	Requirements Affected	Approval Date	Approval
RFW009	REQ-1-OAD-1482	September 25, 2019	Routing #55478
RFW012	REQ-1-OAD-1149	February 19, 2020	Routing #60190
RFW013	REQ-1-OAD-5010	February 3, 2020	Routing #59365

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1.1 INTRODUCTION

This is the TMT Observatory Architecture Document (OAD). This document is the project's response to the science requirements encapsulated in the Science Requirements Document (SRD) (RD33) and the Operations Requirement Document (OpsRD) (RD35).

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) (RD33) and Operations Requirement Document (OpsRD) (RD35).

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 APPLICABLE DOCUMENTS

AD1 Deleted

AD2 Deleted

AD3 Deleted

AD4 Deleted
AD5 Deleted
AD6 Deleted
AD7 Deleted
AD8 Deleted
AD9 Deleted
AD10 Deleted
AD11 Deleted
AD12 Deleted
AD13 Deleted
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AD15 TMT Interface N2 Diagram
TMT.SEN.TEC.05.035 CCR42
https://docushare.tmt.org/docushare/dsweb/Get/Version-126124
AD16 TMT M1S Segmentation Database
TMT.OPT.TEC.07.044 CCR17
https://docushare.tmt.org/docushare/dsweb/Get/Version-119022
AD17 Ritchey-Chrétien Baseline Design
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AD26 Deleted
AD27 Deleted
AD28 Deleted
AD29 Deleted
AD30 Deleted
AD31 Deleted
AD32 Deleted
AD33 Deleted
AD34 Deleted
AD35 Deleted
AD36 Deleted
AD37 TMT System Level Hazard Analysis
TMT.SEN.TEC.13.001 REL12
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AD38 Deleted
AD39 Directive 2011/65/EU of the European Parliament and of the Council of 8 June 2011 on

the restriction of the use of certain hazardous substances in electrical and electronic equipment (including CORRIGENDUM)
Directive 2011-65-EU
https://docushare.tmt.org/docushare/dsweb/Get/Version-49518

AD40 Reserved

AD41 Pupil Obscuration Pattern
CAD Drawing No: TMT.TEL.GTY-0001 Rev D
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AD42 STR Keep-In Space Envelope
CAD Drawing No: TMT.TEL.STR-ENV Rev E
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AD52 Nasmyth Platform Instrument Envelope
CAD Drawing No: TMT.INS.GTY.0003 Rev B
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AD70 ENC Stay Out Space Envelope

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AD71 Space Envelope Drawing, Facility Top End
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AD72 Fixed Base Elevator Space Envelope Drawing
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AD73 Light Beams for TMT Instruments
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AD74 Nasmyth Platform Floor Surface Area
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TMT.SEN.DWG.14.005 REL01
https://docushare.tmt.org/docushare/dsweb/Get/Version-47512

AD75 TMT Enclosure - Geometry Drawing
CAD Drawing No: TMT.ENC.GTY-0001 Rev B
TMT.ENC.DWG.10.019 REL03
https://docushare.tmt.org/docushare/dsweb/Get/Version-84171

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AD79 TMT Software Quality Assurance Plan and Software Development Process
TMT.SFT.TEC.14.013 CCR09
https://docushare.tmt.org/docushare/dsweb/Get/Version-125399

AD80 Environmental Safety & Health Hazard/Risk Assessment Processes and Guidelines
TMT.PMO.MGT.10.004 CCR10
https://docushare.tmt.org/docushare/dsweb/Get/Version-120079

AD81 M1 Field Of View Keep Out Volume
CAD Drawing No: TMT.TEL.GTY-0003 Rev A
TMT.SEN.DWG.17.001 REL01
https://docushare.tmt.org/docushare/dsweb/Get/Version-70977

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AD84 Design Requirements Document for Local Safety Controllers
TMT.CTR.DRD.17.001 CCR01
https://docushare.tmt.org/docushare/dsweb/Get/Version-82716

AD85 Observatory Safety System Developers Guide
TMT.CTR.TEC.17.019 REL02
https://docushare.tmt.org/docushare/dsweb/Get/Version-82563

AD86 TMT Software Design Document Software Architecture and Design-Conceptual Design Phase (Vol 1 of 2)
TMT.SFT.TEC.12.014 REL06
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AD87 TMT Software Design Document Technical Architecture/Common Software (Vol 2 of 2)
TMT.SFT.TEC.12.016 REL05
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AD91 Observatory Safety Access Summary
TMT.SEN.TEC.17.065 REL06
https://docushare.tmt.org/docushare/dsweb/Get/Version-113631

AD92 Deleted

AD93 Telescope Work Areas
TMT.STR.DRD.15.003 REL04
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AD94 Deleted

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AD96 Telescope Azimuth and Elevation Wrap Allocations
TMT.SEN.TEC.18.023 REL15
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AD97 Space Envelope, Maximum Component Size
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https://docushare.tmt.org/docushare/dsweb/Get/Version-111447

AD98 First Light Instrument Configuration
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AD99 First Decade Instrument Configuration
CAD Drawing No: TMT.INS.GTY-0002 Rev G
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AD100 TMT Sub-Systems Electronics Space Envelopes
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https://docushare.tmt.org/docushare/dsweb/Get/Version-129368

AD101 Telescope-Mounted Subsystems Space Envelopes
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TMT.SEN.DWG.20.026 REL01
https://docushare.tmt.org/docushare/dsweb/Get/Version-118339

AD102 Safety of machinery -- Emergency stop function -- Principles for design

ISO 13850 Edition 3
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AD103 3F and 4F Floor Cart Path
CAD Drawing No: TMT.SEN.GTY-0013 Rev A
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https://docushare.tmt.org/docushare/dsweb/Get/Version-115929

1.5 Reference Documents

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RD2 Deleted

RD3 TMT Image Size and Wavefront Error Budgets, Report No. 10 (V.11.0), Volume 1 of 3
TMT.OPT.TEC.07.021
https://docushare.tmt.org/docushare/dsweb/Get/Document-8822
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RD4 Analysis of Normalized Point Source Sensitivity as a performance metric for the Thirty Meter Telescope by B-J. Seo et al., SPIE Proceedings (Vol.7017, 2008)
SPIE Conference 10.1117/12.790453 (Volume 7017)
http://proceedings.spiedigitallibrary.org/proceeding.aspx?articleid=790581

RD5 Pupil Stability Error Budget
TMT.SEN.CDD.07.001
https://docushare.tmt.org/docushare/dsweb/Get/Document-8415

RD6 Standard Photometric Systems by Michael S. Bessell (Annual Review Astronomy and Astrophysics, Volume 43:293-336)
DOI:10.1146/annurev.astro.41.082801.100251
http://www.annualreviews.org/doi/abs/10.1146/annurev.astro.41.082801.100251

RD7 A New Software Tool for Computing Earth's Atmospheric Transmission of Near-and Far-Infrared Radiation by Steven D. Lord
NASA-TM-103957
http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19930010877.pdf

RD8 Deleted

RD9 Deleted

RD10 Impact of Observatory Wavefront Errors upon DM Stroke Requirements for NFIRAOS
TMT.AOS.TEC.08.028
https://docushare.tmt.org/docushare/dsweb/Get/Document-10919

RD11 TMT Coordinate Systems and Transforms
TMT.SEN.TEC.07.031
https://docushare.tmt.org/docushare/dsweb/Get/Document-8763

RD12 Seeing-Limited Image Distortion Budget Spreadsheet
TMT.TEL.TEC.09.001
https://docushare.tmt.org/docushare/dsweb/Get/Document-13037

RD13 Deleted

RD14 Deleted

RD15 Normalized point source sensitivity for off-axis optical performance evaluation of the Thirty Meter Telescope by B-J Seo et al., SPIE Proceedings 7738(Vol. 77380G, 2010)
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RD16 URS Final Report - Site-Specific Seismic Hazard Assessment Of Proposed Thirty Meter Telescope Site, Mauna Kea, Hawaii
TMT.STR.TEC.10.001
URS Report 33761857
https://docushare.tmt.org/docushare/dsweb/Get/Document-16229

RD17 Specification and Analysis of TMT Seismic Requirements for STR and STR Mounted Subsystems
TMT.SEN.TEC.12.009
https://docushare.tmt.org/docushare/dsweb/Get/Document-22542

RD18 Overview of the TMT Safety Architecture
TMT.SEN.TEC.14.028
https://docushare.tmt.org/docushare/dsweb/Get/Document-32282

RD19 Image Quality (PSS) Error Budget
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RD20 TMT NFIRAOS LGS MCAO, NGSAO and IRIS Imager Wavefront Error Budget and Current Best Estimate
TMT.AOS.COR.16.062
https://docushare.tmt.org/docushare/dsweb/Get/Document-52202

RD21 Mass Budget for Telescope Mounted Subsystems
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https://docushare.tmt.org/docushare/dsweb/Get/Document-8607

RD22 Vibration Budget
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https://docushare.tmt.org/docushare/dsweb/Get/Document-27582

RD23 Wind Response Report
TMT.SEN.TEC.07.017
https://docushare.tmt.org/docushare/dsweb/Get/Document-8289

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RD29 Servicing Operation: Transferring Large Components into Enclosure and to

Nasmyth Platforms
TMT.SEN.TEC.11.014
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RD30 Deleted

RD31 Deleted

RD32 High Throughput Computing (HTC) - Condor
HTC Condor
https://research.cs.wisc.edu/htcondor/index.html

RD33 Science-Based Requirements Document
TMT.PSC.DRD.05.001
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RD34 Deleted

RD35 Operations Requirements Document
TMT.OPS.DRD.07.002
https://docushare.tmt.org/docushare/dsweb/Get/Document-7842

RD36 TMT Work Breakdown Structure (WBS)
TMT.BUS.SPE.05.003
https://docushare.tmt.org/docushare/dsweb/Get/Document-1810

RD37 TMT Acronyms and Abbreviations
TMT.PMO.MGT.07.013
https://docushare.tmt.org/docushare/dsweb/Get/Document-8283

RD38 Deleted

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RD40 Telescope Optical Feedback System (TOFS) Architecture and Specification
TMT.SEN.SPE.10.001
https://docushare.tmt.org/docushare/dsweb/Get/Document-17969

RD41 TMT NFIRAOS LGS MCAO, NGSAO and IRIS Imager Wavefront Error Budget and Current Best Estimate Description
TMT.AOS.TEC.08.015
https://docushare.tmt.org/docushare/dsweb/Get/Document-10473

RD42 Environmental Safety & Health (ES&H) Hazard/Risk Assessment Processes and Guidelines
TMT.PMO.MGT.10.004
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RD43 TMT Operations Plan
TMT.OPS.TEC.11.099
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RD44 TMT Observation Workflow Concept Document
TMT.AOS.TEC.07.013
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RD45 Observatory Software Operational Concept Definition Document
TMT.SFT.SPE.15.001
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RD46 TMT Functional Safety Management Plan

TMT.CTR.SPE.17.001
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RD47 TMT Reliability Budget Spreadsheet
TMT.SEN.TEC.07.006
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RD48 Acquisition Time Budget
TMT.SEN.TEC.16.029
https://docushare.tmt.org/docushare/dsweb/Get/Document-66286

RD49 High resolution mesopheric sodium properties for adaptive optics applications
A&A 565, A102
https://www.aanda.org/articles/aa/abs/2014/05/aa23460-14/aa23460-14.html

RD50 Deleted

RD51 Deleled

RD52 TMT Top Down Astrometry Error Budget Report
TMT.AOS.TEC.12.039
https://docushare.tmt.org/docushare/dsweb/Get/Document-31383

RD53 TMT Astrometry Error Budget
TMT.AOS.TEC.14.066
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RD54 Point Source Sensitivity Error Budget for NFIRAOS and IRIS Imager
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RD55 Point Source Sensitivity and Pupil Alignment Budget Description fro NFIRAOS and IRIS Imager
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RD56 End to end M1 Pupil Undersizing Budget for IRIS Lyot Mask
TMT.AOS.TEC.17.167
https://docushare.tmt.org/docushare/dsweb/Get/Document-63844

RD57 TMT Reliability Budget and Assumptions for Calculating Downtime
TMT.SEN.TEC.18.048
https://docushare.tmt.org/docushare/dsweb/Get/Document-68658

RD58 Deleted

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RD60 TMT Standards, Codes and Regulations
TMT.SEN.MGT.20.017
https://docushare.tmt.org/docushare/dsweb/Get/Document-83996

RD61 Electromagnetic Interference / Electromagnetic Compatibility Design Guidelines
TMT.SEN.SPE.19.001
https://docushare.tmt.org/docushare/dsweb/Get/Document-76503

RD62 TMT Photometry Error Budget Spreadsheet
TMT.OPT.TEC.20.004
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RD63 TMT Photometry Error Budget Description Report

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RD64 TMT Maintenance Budget
TMT.SEN.TEC.19.009
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RD65 TMT Seeing-Limited Off-Axis Image Budget Rationale
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RD66 TINS Use Cases
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RD67 TMT Pointing Error Budget
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https://docushare.tmt.org/docushare/dsweb/Get/Document-87471

RD68 TMT Data Rates and Storage
TMT.SFT.TEC.12.006
https://docushare.tmt.org/docushare/dsweb/Get/Document-22085

RD69 TMT End-to-End Science Exposure Transfer Latency Budget
TMT.SFT.TEC.22.006
https://docushare.tmt.org/docushare/dsweb/Get/Document-95876/

1.6 ABBREVIATIONS

The abbreviations used in this document are listed in the project acronym list (RD37).

2 SYSTEM DEFINITION

2.1 GENERAL

[REQ-1-OAD-0005] The TMT Observatory shall be located at the 13N site on Mauna Kea, Hawaii, at latitude N 19º 49 ' 57.4", longitude W 155º 28' 53.4" at an altitude of 4012 m.

[REQ-1-OAD-0010] All dimensions contained within this document apply when the sub-systems are at their expected steady state operating temperature during observing and the ambient temperature is equal to the median nighttime temperature for the site (T = 2.3°C).

2.1.1 TMT STANDARDS

The TMT standards, codes and regulations are identified within (RD60), with the purpose of guiding other TMT documentation in the following areas:

- safety in construction and operation processes
- safe work environments
- human safety with regard to operational hazards
- protection from environmental hazards
- equipment safety, reliability and efficiency
- design standards such as design lifetime or material specification
- compatibility between system types and subsystems

Compliance with these standards is generally governed either by SOW or local government permitting and inspection processes. The SE verification process does not apply to standards, unless specific standards are enumerated as requirements in a DRD. The verification of standards, codes and regulation is cover by the PDPD.

2.2 OBSERVATORY SYSTEM DECOMPOSITION

The TMT System decomposition (Table 2-1) identifies WBS (RD36) 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.

The TMT System (PBS) is decomposed into the subsystems as shown in 'Table 2-1: TMT System Decomposition' below.

Table 2-1: TMT System Decomposition (PBS vs WBS)

System (PBS)	Related WBS Element(s)
Facilities	
Enclosure (ENC)	TMT.FAC.ENC
Summit Facilities (SUM)	TMT.FAC.INF.SUM TMT.FAC.INF.ROAD
Observatory Headquarters (HQ)	TMT.FAC.INF.HQ
Telescope	
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
M1 Coating System (M1 COAT)	TMT.TEL.OPT.COAT.M1
M2/M3 Coating System (M2/M3 COAT)	TMT.TEL.OPT.COAT.M2M3
Test Instruments (TINS)	TMT.TEL.OPT.TINS TMT.TEL.CONT.TINC
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
M1 Control System (M1CS)	TMT.TEL.CONT.M1CS
Observatory Safety System (OSS)	TMT.TEL.CONT.OSS
Engineering Sensors (ESEN)	TMT.TEL.CONT.ESEN
Instrumentation	
Narrow Field Near Infrared On-Axis AO System (NFIRAOS)	TMT.INS.AO.NFIRAOS TMT.INS.AO.COMP.VCAM.NFIRAOS TMT.INS.AO.COMP.RTC.NFIRAOS TMT.INS.AO.COMP.WC.NFIRAOS TMT.INS.AO.NFIRAOS.NSCU
Laser Guide Star Facility (LGSF)	TMT.INS.AO.LGSF, TMT.INS.AO.COMP.SLASR
Adaptive Optics Executive Software (AOESW)	TMT.INS.AO.AOESW
Refrigerant Cooling System (REFR)	TMT.INS.COOL.REFR
Cryogenic Cooling System (CRYO)	TMT.INS.COOL.CRYO
InfraRed Imaging Spectrometer (IRIS)	TMT.INS.INST.IRIS TMT.INS.AO.COMP.IRCAM.IRIS
Wide Field Optical Spectrometer (WFOS)	TMT.INS.INST.WFOS
Multi-Object Diffraction-limited High-Resolution Infrared Spectrograph	TMT.INS.INST.MODHIS TMT.INS.AO.COMP.IRCAM.MODHIS
Operations	
Communications and Information Systems (CIS)	TMT.DEOPS.CIS
Common Software (CSW)	TMT.DEOPS.OSW.CSW
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

2.2.1 System Decomposition Element Descriptions

2.2.1.1 FACILITIES

2.2.1.1.1 Enclosure (ENC)

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 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. The cap rotates about an axis perpendicular to the cap/base interface plane. The shutter structure is located inside the cap and consists of an open framework of steel tubing supporting an aluminum 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 servicing and handling of large components inside the enclosure. The enclosure incorporates components to provide adequate safety for the observatory personnel and visitors including local e-stops, sensors and wiring that interface with the observatory safety system. The enclosure also includes the M2 servicing platform and lighting.

The ENC subsystem designs the Enclosure lighting system, including routing and mounting locations for equipment. This lighting system includes emergency lighting.

The Enclosure Control System controls the rotation of the Enclosure base and cap, opening and closing of shutter, deployment of aperture flaps, opening and closing of ventilation doors, operation of cranes, and the deployment of top end servicing platform.

The Enclosure portion of the Engineering Sensors System (ESEN) sensors includes the sensors themselves, the networked data acquisition and control hardware, and software associated with them.

2.2.1.1.2 Summit Facilities (SUM)

The Summit Facilities system decomposition element is defined as follows:

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

The Summit Facilities are the infrastructure located adjacent to the enclosure and telescope that are required to operate TMT. The summit facilities contain the control room; computer room; conference room; office space; visitor viewing gallery; space for hydrostatic bearing equipment; space for facility mechanical equipment such as chillers, pumps, compressors and air handlers; space for cryogenic cooling equipment; an electrical equipment room and space for the main electrical transformers, switchgear, generators and UPS; rooms for mirror stripping, recoating, and storage; an engineering and electronics lab; a machine shop; a shipping and receiving area; a safety equipment room, and spaces for support services such as restrooms, first aid room 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. A facilities management control system will be provided to monitor and control all the facility mechanical and electrical equipment. Safety equipment including local e-stops and sensors and wiring that interface with the observatory safety system will be provided where necessary.

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. Two elevators are provided on the enclosure floor for the transfer of people and equipment to the pier walkway. 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.

The Summit Facilities subsystem is also responsible for providing the end-to-end lighting system, including equipment such as lighting fixtures, lighting management control system and panel. The overall lighting system provides general, task, and emergency lighting, including exit signage lighting. The SUM lighting system interfaces with the STR and ENC lighting systems.

The Summit Facilities also includes the access road between an existing public road and the TMT observatory. 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 road will be unpaved except where necessary to prevent generating dust around existing observatories.

2.2.1.1.3 Observatory Headquarters

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. and will be the normal work location for many of the science, engineering and technical staff. The headquarters building includes offices, reception area, conference rooms, lecture hall, mechanical shop, engineering and electronics laboratory, remote observing/ control room, computer room, mask cutting facility, shipping and receiving area and administrative areas. Also included are mechanical and electrical plant facilities and storage room.

2.2.1.2 TELESCOPE

2.2.1.2.1 Telescope Structure (STR)

The Telescope Structure system decomposition element is defined as follows:

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

The Telescope Structure System includes the: Stationary Structures attached to the Foundation and Pier; Azimuth Structure; Elevation Structure; Hydrostatic Bearing System; Mount Control System; Telescope Structure Utility Services System; Telescope Utility Services system; and alignment fixtures and special tools to support assembly and maintenance, including dummy masses for acceptance testing.

The Stationary Structures include the azimuth track, pintle bearing assembly, a raised service walkway inside the pier, elements of the seismic restraint and a raised azimuth walkway outside the pier.

The Azimuth Structure includes the central structure, Nasmyth platforms, CRYO platforms, instrument support structures, azimuth cable wrap, aerial service platform, elements of the seismic restraint, telescope elevator(s), access walkways, stairways and safety barriers.

The Elevation Structure includes the lower tube structure, elevation journals, mirror cell, elevation cable wrap, M1 segment handling system, M1 cleaning system arms and controls, upper tube structure and walkways to access the LGSF components and mirror cell.

The Hydrostatic Bearing System includes the azimuth, pintle and elevation bearings, the oil supply system including all hoses and pipes between the pumps (located in the Summit Facilities building) and the bearings, and the associated control system.

The Mount Control System includes the servo controller, drive motors and their associated drive electronics, encoders, brakes, rotation limit switches, hard stops and shock absorbers, elevation locking devices and associated control electronics.

The Telescope Structure Utility Services include cable trays and pipe racks throughout the telescope, the utility lines to supply electrical power, chilled water and compressed air to five dedicated distribution centers located on the azimuth and elevation structure and the distribution centers themselves.

The STR (TUS) subsystem designs the telescope lighting system, including routing (including through cable wrap), mounting locations for equipment, and interfaces to the SUM lighting system. The telescope lighting system, including emergency lighting, is designed to provide lighting for the following areas:

- Telescope elevation
- Telescope azimuth
- Telescope fixed structures

The Telescope Utility Services includes the power, chilled water and compressed air lines and mounting hardware between the distribution centers and the telescope structure mounted sub-systems. Not included in the telescope structure or telescope utility services are lines supplying cryogenic or refrigerant coolant to the science instruments (these are part of the Instrumentation Cryogenic Cooling System (CRYO) and the Instrumentation Refrigerant Cooling System (REFR) respectively).

2.2.1.2.2 M1 Optics System (M1S)

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 adjustable attachment points (to the mirror cell), and the spare segments. The segment support assemblies include the segment warping harnesses and their actuators. The M1 Optics System does not 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).

2.2.1.2.3 M2 System (M2S)

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 M2 control system and electronics, and the interfaces to the telescope structure including mechanical positioning hardware and a breakout box for power and other services.

2.2.1.2.4 M3 System (M3S)

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 Blank, the M3 Mirror, the upper portion of the tertiary mirror (M3) system Tower, the M3 Cell Assembly, the M3 Positioner Assembly, the interface hardware between the M3 System and the Telescope Assembly, and support for receiving, assembly, inspection and verification of the M3 System onto the TMT Telescope at the Observatory.

2.2.1.2.5 Optical Cleaning Systems (CLN)

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, fixtures and control systems for cleaning 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 or the robotic M1 cleaning arms or associated control system which are part of the Telescope Structure.

2.2.1.2.6 M2/M3 Coating System (M2/M3 COAT)

The M2/M3 Optical Coating system decomposition element is defined as follows:

Associated WBS element(s): TMT.TEL.OPT.COAT.M2M3

The M2/M3 Coating system includes the M2/M3 coating chambers with their associated equipment (vacuum pumps, magnetrons, etc.), the equipment used to remove the old reflective coating and wash and dry the mirror, coating laboratory instruments or fixtures used to support the mirrors during washing and in the coating chamber, and the lift fixtures to transfer the mirrors from the handling carts to the coating fixtures. It also includes portable clean room equipment for the M2 and M3 coating activities that take place adjacent to the M2/M3 Coating System. It does not include the mirror handling equipment, which is included in Optics Handling Equipment (HNDL). It also does not include the coating laboratory facility equipment (air compressors, cranes, sinks, drains & sumps or fume hoods) or the utilities for the M2/M3 coating chamber, which are included in Summit Facilities. Safety equipment including local e-stops and any sensors and wiring that interface with the Observatory Safety System will be provided.

2.2.1.2.7 M1 Coating System (M1 COAT)

The M1 Optical Coating system decomposition element is defined as follows:

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

The M1 Coating Plant includes the M1 coating chambers with their associated equipment (vacuum pumps, magnetrons, etc.), the equipment used to remove the old reflective coatings and wash and dry the mirror, coating laboratory instruments and fixtures used to support the mirrors during washing and in the coating chamber, and any additional lifting fixtures specific to transfering the mirrors from the handling carts to coating fixtures/equipment. It does not include the mirror handling equipment, which is included in Optics Handling Equipment (HNDL). It also does not include the coating laboratory facility equipment (air compressors, cranes, sinks, drains & sumps or fume hoods) or the utilities supplied to the M1 coating chamber, which are included in Summit Facilities (SUM). Safety equipment including local e-stops and any sensors and wiring that interface with the Observatory Safety System will be provided.

2.2.1.2.8 Test Instruments (TINS)

The Test Instruments system decomposition element is defined as follows:

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

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 telescope mounted surveying instruments in insulated, light-tight enclosures, along with the associated controls and cabling.

It also 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 TINS 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, instruments and reference features on the telescope structure and the fixed base. This data will be used to update the rigid body LUTs for M2 and M3 as well as the mount pointing model and to verify alignment in the event that components are replaced or adjusted. The TINS will provide the electronics and software required to interface the GMS with the Telescope Control System and other observatory sub-systems. It will be possible to utilize GMS measurements in manual and fully automated modes. The GMS will include an expert user GUI.

2.2.1.2.9 Optics Handling Equipment (HNDL)

The Optics Handling system decomposition element is defined as follows:

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

The Optics Handling equipment is used to install, remove, and transport the optical assemblies of the telescope. It includes all of the lifting and handling fixtures 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 Optics Handling equipment also includes the storage cabinets for the spare segments, and segment lifting jack used for raising segments from the M1 for removal. It does not include the cranes which are included in the Enclosure (ENC) or the M1 Segment Handling System which is included in the Telescope Structure (STR). It does not include the crane attachments required for in-situ optics cleaning, which are included in the Optical Cleaning Systems (CLN).

2.2.1.2.10 Alignment and Phasing System (APS)

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 rigid body alignment of the M1, M2 and M3, as well as adjusting the surface figure degrees of freedom for the M1. 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 an optical port where a guider camera and a low order wavefront sensor can be placed in order to test its performance and to validate the active optics control algorithms.

APS will provide an expert user GUI.

2.2.1.2.11 Telescope Control System (TCS)

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 radial order corrections from an instrument WFS 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 M1 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, Structure and Engineering Sensor systems.

The TCS includes an expert user GUI.

2.2.1.2.12 M1 Control System (M1CS)

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 M1CS also controls the M1 warping harness actuators and reads the warping harness strain gauges.

The design and packaging of the electronics mounted on the mirror cell will limit the amount of heat released into the local environment.

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.

2.2.1.2.13 Observatory Safety System (OSS)

The Observatory Safety system decomposition element is defined as follows:

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

The Observatory Safety System (OSS) contributes to the enforcement of safe conditions throughout the summit facility by continuously monitoring the state of connected equipment, systems and sensors and taking appropriate action as soon as an unsafe condition is detected. It is independent from and supplementary to any safety systems and functionality that is contained within individual subsystems. Based on one or more Programmable Logic Controllers (PLCs), it will interface with connected subsystems via a dedicated safety rated fieldbus based on EtherNet/IP; monitor interlock requests and possibly a defined subset of additional signals from all connected subsystems; monitor the emergency stop switches located throughout the summit facility; manage safety interlock enforcement between sub-systems; provide a user interface that provides fault and interlock reporting and reset capabilities: communicate the safety state of all connected subsystems to, at a minimum, the Data Management System (DMS) & Executive Software (ESW).

The OSS includes the Global Safety Controller (GSC), remote I/O modules, the fieldbus network and associated networking components such as switches, a Human-Machine Interface (HMI), racks, enclosures, power supplies, network cabling, emergency stop buttons, and all associated PLC software. The OSS is responsible for mounting hardware and costs associated with mounting and wiring the emergency stops to nearby OSS remote I/O modules. It is also responsible for the laser ON safety light/sign at the entrance of the dome. It does not include the Local Safety Controllers, fire suppression systems, or emergency lighting. These are the responsibility of the individual subsystems.

2.2.1.2.14 Engineering Sensors (ESEN)

The Engineering Sensor system decomposition element is defined as follows:

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

The ESEN system will provide a set of environmental sensors that are located throughout the observatory and are not tightly coupled to any subsystem.

These sensors are generally used for diagnostics but can also be used for quasi real-time control of non-critical systems. Sensors are located on the Telescope Structure, Enclosure,the M1, M2, and M3, the Site Conditioning and Monitoring System, the ground level of the Enclosure and elsewhere throughout the Observatory.

The sensors on the Telescope Structure, the M2 and M3, and the Enclosure use a common data collection and communication architecture and are considered part of the Engineering Sensors (ESEN) System.

The ESEN system encompasses the sensors and the required data acquisition hardware, networking and computing hardware and software necessary to record the sensor measurements.

Baseline sensors included in ESEN include wind speed, air temperature, surface temperature, humidity, dew-point, inclination and acceleration.

The ESEN system will include also the 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.

2.2.1.3 INSTRUMENTATION

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

The NFIRAOS Subsystem decomposition element is defined as follows:

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

NFIRAOS is a Laser Guide Star, Multi-conjugate Adaptive Optics System (NFIRAOS LGS MCAO) 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 34” FOV.

Additional to the LGS MCAO capability, NFIRAOS also includes a Natural Guidestar mode (NGSAO) and a Seeing-Limited mode (NFIRAOS Seeing-Limited), which is a degraded NGSAO mode.

NFIRAOS includes several optical tables, 6 LGS WFS, 1 NGS WFS/TWFS, 2 DMs and a tip/tilt stage (TTS), a source simulator (for natural objects and laser beacons), focal plane mask 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, an acquisition camera, and miscellaneous fixtures), real time computer, local e-stops, any sensors and wiring that interface with the Observatory Safety System.

NFIRAOS also includes the NFIRAOS Science Calibration Unit (NSCU) that provides daytime and nighttime calibrations to NFIRAOS-fed science instruments. Four main sets of calibrations are provided by the NSCU: uniform (flat) illumination for (1) 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: an integrating sphere fed by a set of lamps; a deployment mechanism or mirror to inject light into the beam to NFIRAOS; and a light-tight enclosure with an input shutter. The NSCU is mounted at the front of NFIRAOS.

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.

2.2.1.3.2 Laser Guide Star Facility (LGSF)

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 8 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 (ii) the Beam Transfer Optics and the Laser Launch Telescope System and (iii) the Laser Safety System.

2.2.1.3.3 Adaptive Optics Executive Software (AOESW)

The AOESW system decomposition element is defined as follows:

Associated WBS Element(s): TMT.INS.AO.AOESW

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. The AO Sequencer does not control the instruments themselves (i.e. IRIS, MODHIS, etc.).

2.2.1.3.4 Instrumentation Refrigerant Cooling System (REFR)

This element includes the refrigerant cooling system for TMT telescope-mounted subsystems.

The instrumentation refrigerant cooling system provides phase-change CO2 refrigerant to telescope-mounted instruments and electronics for cooling optical enclosures to sub-zero but non-cryogenic temperatures. This includes all compressors, oil extraction, condensers, heat exchangers and other components in the summit facilities building; the distribution systems (pipes, insulation, valves, connectors, control wiring) located between these components and the instruments/AO systems on the Nasmyth platforms, the LGSF electronic cabinets on the -X Laser Platform, the M2 and LGSF systems located at the Telescope Top End, the M3 system located at the center of the M1 mirror cell, and the M2CS located on the +X Elevation platform; the purging and filling apparatus for servicing and re-charging instrumentation prior to connection with the refrigerant system and the controls system required to operate the system.

The TMT.INS.COOL.REFR WBS element includes all the elements mentioned above, corresponding to the following WBS elements:

- TMT.INS.COOL.REFR.SYS
- TMT.INS.COOL.REFR.COMPR
- TMT.INS.COOL.REFR.PIPES
- TMT.INS.COOL.REFR.CHARGE
- TMT.INS.COOL.REFR.INT

The Instrumentation Refrigerant Cooling System does not include the following:

- Refrigerant expansion valves or evaporation coils within the instruments or insulated panels containing these coils.
- Water/glycol coolant systems. Water/glycol coolant systems required for the instruments and guide star lasers are part of the Observatory chilled water/glycol cooling systems.

2.2.1.3.5 Instrumentation Cryogenic Cooling System (CRYO)

This element includes the cryogenic cooling system for TMT telescope-mounted subsystems.

The instrumentation cryogenic cooling system is the system that provides cryogen to the instrument cryostats for them to maintain their desired temperature. This element includes the helium compressors, cold heads and liquid nitrogen storage dewar, and gaseous nitrogen plant (air compressors, driers, nitrogen generators, purity monitoring equipment) located in the Summit Facilities Utility Room. It includes the distribution system which consists of all pipes, flexible or rigid vacuum jacketed lines with or without bayonet, liquid nitrogen storage dewars on the Nasmyth platforms, gas monitors, valves, connectors, control wiring and any equipment located on the telescope structure required to circulate cryogen for delivery to the instruments. These distribution system components are located between the Summit Facilities Utility Room and the instrumentation on the TMT Nasmyth platforms.

The TMT.INS.COOL.CRYO WBS element includes all the elements mentioned above, corresponding to the following WBS elements:

- TMT.INS.COOL.CRYO.SYS
- TMT.INS.COOL.CRYO.COMPR
- TMT.INS.COOL.CRYO.PIPES
- TMT.INS.COOL.CRYO.INT

The Instrumentation Cryogenic Cooling System does not include the following:

- Cryogenic dewars in the instruments themselves. These are included as part of the individual science instrument systems.
- Water/glycol coolant systems. Water/glycol coolant systems required for the instruments and guide star lasers are part of the Observatory chilled water/glycol cooling systems.

2.2.1.3.6 InfraRed Imaging Spectrometer (IRIS)

The IRIS system decomposition element is defined as follows:

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

2.2.1.3.7 Multi-Objective Diffraction-limited High-resolution Infrared Spectrograph (MODHIS)

The MODHIS system decomposition element is defined as follows:

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

MODHIS is a single mode fiber feed multi-objective spectrograph that receives its Adaptive Optics (AO) corrected light from the TMT facility AO system NFIRAOS (the narrow field infrared adaptive optics system). MODHIS operates in the near-infrared.

TMT.INS.INST.MODHIS includes the effort to design, fabricate and verify the entire science instrument consisting of the instrument rotator and interface structure to NFIRAOS, up-to three low order on-instrument wavefront sensors (OIWFS) and their thermal enclosure, a single fiber injection system and field acquisition and monitoring camera. This WBS also includes the full spectrograph and its enclosure as well as the fiber 'run' system to manage the fibers between the fiber injection system and the spectrograph. This WBS element also includes the Nasmyth mounted equipment and electronics enclosure. It further includes the instrument sequencer and all software required for its component controllers as well as science data reduction and quick-look software capable of real time assessment of data quality, removal of observatory signatures (e.g. mosaic, bias saturation, bad pixel mask and flat fields). Lastly this WBS includes all cabling required to interconnect MODHIS and to relay data, services, etc.

2.2.1.3.8 Wide Field Optical Spectrometer (WFOS)

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 sensor(s) and guide camera, 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.

2.2.1.4 OPERATIONS

2.2.1.4.1 Common Software (CSW)

The CSW system decomposition element is defined as follows:

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

The Common Software (CSW) system includes the software required to integrate the TMT sub-systems and establish the software communication backbone and interfaces necessary for observatory-wide configuration, command, control, status reporting, and data management. The CSW will be layered on top of the IT infrastructure ("network") provided by the Communications and Information sub-system (TMT.DEOPS.OSW.CIS).

2.2.1.4.2 Communications and Information Systems (CIS)

The CIS system decomposition element is defined as follows:

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

Communications and Information Systems (CIS) encompasses the IT hardware, software, and cabling necessary to implement the generalized communications backbones and establish connection to Internet. It also includes the implementation of a distributed time bus system. The network consists of a cable-based (fiber, Cat5/6 Ethernet and CoAX) distribution system out to various network distribution junction boxes located on the telescope structure, and the summit facility control room, laboratory, plant room and site monitoring station. CIS also includes a communications backbone for the Hilo headquarters including computer room, remote control room and offices.

2.2.1.4.3 Data Management System (DMS)

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

2.2.1.4.4 Executive Software (ESW)

The ESW system decomposition element is defined as follows:

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

The ESW provides the core functionality needed to enable classical observing and other future observing modes at the telescope site. The ESW enables synchronized operation of all the TMT sub-systems from user interfaces or other programs. The Observatory Control System (OCS), a sub-component of ESW, is the central engine providing this functionality. Other ESW deliverables include user interfaces for system operators and observers as well as user interfaces for monitoring of system status and overall environmental monitoring. The first light Executive Software is composed of 5 elements:

- The Observatory Control System (TMT.DEOPS.OSW.ESW.OCS),
- The- User Interface Standards (TMT.DEOPS.OSW.ESW.UISTD),
- The High-Level Control and Monitoring system (TMT.DEOPS.OSW.ESW.HCMS),
- The Data Visualization tools (TMT.DEOPS.OSW.ESW.VIZ), and
- The Acquisition Tools (TMT.DEOPS.OSW.ESW.ACQ).

2.2.1.4.5 Science Operations Support Systems (SOSS)

The SOSS decomposition element is defined as follows:

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

Science Operations Support Systems (SOSS) are the software applications used to manage high-level science operations workflow from proposal preparation up to observation execution and data delivery. SOSS includes tools to support: (1) instrument simulators, 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.

2.2.1.4.6 Data Processing System (DPS)

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, and it provides the tools needed to implement a long-term trending data quality assurance process. The DPS has four main components: (1) data processing modules (“recipes”) for removal of atmospheric and instrument signatures, (2) a library for building recipes, (3) infrastructure for automating data processing workflows, and (4) pipelines built on DPS products for data quality assurance.

2.2.1.4.7 Site Conditions Monitoring System (SCMS)

The SCMS system decomposition element is defined as follows:

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

The Site Conditions Monitoring System (i.e. "the weather stations") consists of one external weather station on the TMT site with sensors to measure such parameters as temperature, wind speed, wind direction, free-air seeing, etc. It also includes a MASS/DIMM telescope on top of the summit facilities building. SCMS data is captured and stored in the observatory database. It is displayed in near-real-time to the TMT system operators via their high-level environmental conditions monitor. It is also available to the TMT community at large via a Web interface.

2.2.2 INTERFACES

The interfaces between the subsystems are as defined in the TMT Interface N2 Diagram (AD15).

Utilities such as electrical power, coolants, compressed air, and data and control signals are supplied by some subsytems, physically distributed across other subsystems, and supplied to yet another set of subsystems. To simplify the TMT N^2 diagram, interfaces to the utilities are grouped into "Services" interfaces. These services interface documents describe the interface between all utilities and a given subsystem. These interface documents typically fall into one of two categories. The interface can be for the connections of a subsystem to the supplied utilities for that subsystem or it can be for the routing and distribution of all utilities across a large subsystem like the telescope structure.

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 (RD57).

The allowable downtime budgets for the observatory subsystems are given in 'Table 3-1: Observatory Downtime Allocation (RD47)' below.

Table 3-1: Observatory Downtime Allocation (RD47)

Requirement ID	Subsystem	Allowable Downtime (no backup subsystem)	Allowable Downtime (subsystems with backup available)	Allowable Time Operating in Degraded Mode
[REQ-1-OAD-0311]	TMT Observatory Downtime	3.00%		7.00%
	Facilities			
[REQ-1-OAD-0310]	Enclosure (ENC)	0.40%		1.06%
[REQ-1-OAD-0312]	Summit Facilities (SUM)	0.02%		0.26%
N/A	Observatory Headquarters			0.00%
	Telescope			
[REQ-1-OAD-0314]	Telescope Structure (STR)	0.52%		0.27%
[REQ-1-OAD-0318]	M1 Optics System (M1S)	0.03%		0.16%
[REQ-1-OAD-0320]	M2 Optics System (M2S)	0.17%		0.01%
[REQ-1-OAD-0322]	M3 Optics System (M3S)	0.17%		0.03%
[REQ-1-OAD-0323]	Optical Cleaning Systems (CLN)	0.00%		0.01%
N/A	M1 Coating System (M1 COAT)			
N/A	M2/M3 Coating System (M2/M3 COAT)			
N/A	Test Instruments (TINS)			
N/A	Optics Handling Equipment (HNDL)			
[REQ-1-OAD-0324]	Telescope Control System (TCS)	0.02%		0.00%
[REQ-1-OAD-0328]	M1 Control System (M1CS)	0.24%		4.10%
[REQ-1-OAD-0336]	Alignment and Phasing System (APS)	0.02%		0.01%
[REQ-1-OAD-0340]	Observatory Safety System (OSS)	0.04%		0.00%
[REQ-1-OAD-0341]	Engineering Sensors (ESEN)	0.00%		0.00%
	Instrumentation			
N/A	Science Instruments and AO system	0.99%		
[REQ-1-OAD-0348]	Narrow Field Near Infrared AO System (NFIRAOS)		0.43%	0.70%
[REQ-1-OAD-0350]	Laser Guide Star Facility (LGSF)		0.19%	0.14%
[REQ-1-OAD-0358]	AO Executive Software (AOESW)		0.08%	0.00%
[REQ-1-OAD-0362]	InfraRed Imaging Spectrometer (IRIS)		0.12%	0.14%
[REQ-1-OAD-0364]	Multi-Object Diffraction Limited High Resolution Spectrograph (MODHIS)		0.03%	0.02%
[REQ-1-OAD-0366]	Wide Field Optical Spectrometer (WFOS)		0.15%	0.09%
[REQ-1-OAD-0359]	Refrigerant Cooling System (REFR)	0.10%		0.00%
[REQ-1-OAD-0325]	Cryogenic Cooling System (CRYO)	0.10%		0.00%
	Operations			
[REQ-1-OAD-0370]	Data Management System (DMS)	0.00%		0.00%
[REQ-1-OAD-0372]	Executive Software (ESW)	0.15%		0.00%
[REQ-1-OAD-0380]	Communication and Information Systems (CIS)	0.01%		0.00%
[REQ-1-OAD-0374]	Common Software (CSW)	0.02%		0.00%
N/A	Science Operations Support Systems (SOSS)			
N/A	Data Processing System (DPS)			
[REQ-1-OAD-0375]	Site Conditions Monitoring System (SCMS)	0.00%		0.00%

Discussion: The downtime and degraded mode operation time are defined as percentages of overall annual observing hours for the entire observatory (~3000 per year). ~3000 hours can be used as a reference if level 2 requirements are stated in hours per year rather than as a percentage. The actual number of observing hours is expected to be in the range of 2970 to 3280 per year. The guidelines for calculating downtime and operation in degraded mode are contained in (RD57).

3.2 Heat Dissipation Budgets

Table 3-2: Heat Dissipation Inside Summit Facilities and Dome describes the breakdown of maximum heat dissipated by individual subsystems in the nighttime and daytime to building air.

Table 3-2: Heat Dissipation Inside Summit Facilities and Dome

REQ ID	Item name	C/U	Dissipated heat to building air (kW), average				Notes
			Inside Summit Facilities		Inside Dome		
			Daytime	Nighttime	Daytime	Nighttime	
[REQ-1-OAD-0499]	**Total (First Light)**		**137.3**	**99.6**	**48.0**	**19.3**	
[REQ-1-OAD-0498]	**Total (First Decade)**		**152.0**	**115.3**	**49.4**	**20.7**	
(Level 2 SUM responsibility)	Computer Room + Control Room (First Decade)	C	43.3	54.2	N/A	N/A	(1)
	Utility Room + Support Building (First Decade)	U	108.6	61.2	N/A	N/A	(2)
	Facilities		**69.0**	**22.9**	**11.9**	**0.6**	
[REQ-1-OAD-0501]	ENC	C	0.0	0.0	10.6	0.3	(1)
[REQ-1-OAD-0502]	SUM	U	69.0	22.9	1.3	0.3	
	Telescope		**22.7**	**24.0**	**33.1**	**15.8**	
[REQ-1-OAD-0503]	OSS	C	0.6	0.6	0.1	0.1	(1)
[REQ-1-OAD-0504]	STR	U	3.0	8.0	4.7	2.5	(2)
[REQ-1-OAD-0517]	STR.TUS		0.0	0.0	17.7	2.7	
[REQ-1-OAD-0505]	M1S		0.0	0.0	0.0	0.0	
[REQ-1-OAD-0506]	M2S	C[3]	0.3	1.2	0.0	0.6	(1), (3)
[REQ-1-OAD-0507]	AM2	C	0.4	1.6	0.4	0.7	(1), (3)
[REQ-1-OAD-0508]	M3S	C	0.3	1.2	0.0	0.4	(1)
[REQ-1-OAD-0509]	CLN	C	0.2	0.0	0.6	0.0	(1)
[REQ-1-OAD-0560]	M1 COAT	U	15.4	9.1	0.0	0.0	(2), (4)
[REQ-1-OAD-0510]	M2/M3 COAT	U[4]	15.4	9.1	0.0	0.0	(4), (5)
[REQ-1-OAD-0511]	TINS	C	0.1	0.0	0.5	0.0	(1)
[REQ-1-OAD-0512]	HNDL		0.0	0.0	0.0	0.0	
[REQ-1-OAD-0513]	APS	C	0.5	0.2	0.1	0.3	(1)
[REQ-1-OAD-0514]	TCS	C	0.5	0.5	0.0	0.0	(1)
[REQ-1-OAD-0515]	M1CS	C	1.2	2.4	8.5	8.5	(1)
[REQ-1-OAD-0516]	ESEN	C	0.4	0.4	0.6	0.6	(1)
	Instrumentation		**36.2**	**39.4**	**3.9**	**3.8**	
	First Light		**33.8**	**35.9**	**2.6**	**2.6**	
[REQ-1-OAD-0518]	NFIRAOS	C	2.7	4.0	0.3	0.3	(1)
[REQ-1-OAD-0520]	LGSF	C	1.5	2.3	1.1	1.1	(1)
[REQ-1-OAD-0521]	AOESW	C	5.3	5.3	0.0	0.0	(1)
[REQ-1-OAD-0522]	CRYO	U	16.3	16.3	0.2	0.1	(2)
[REQ-1-OAD-0523]	REFR	U	4.9	4.9	0.5	0.5	(2)
[REQ-1-OAD-0524]	IRIS	C	1.8	1.8	0.3	0.3	(1)
[REQ-1-OAD-0527]	WFOS	C	0.6	0.6	0.2	0.2	(1)
[REQ-1-OAD-0528]	MODHIS	C	0.6	0.6	0.1	0.1	(1)
	First Decade		**2.4**	**3.5**	**1.3**	**1.3**	
[REQ-1-OAD-0529]	HROS	C	0.2	0.4	0.3	0.3	(1)
[REQ-1-OAD-0530]	IRMOS	C	0.5	0.7	0.3	0.3	(1)
[REQ-1-OAD-0531]	PFI	C	0.5	0.7	0.3	0.3	(1)
[REQ-1-OAD-0532]	MIRAO	C	0.5	0.6	0.1	0.1	(1)
[REQ-1-OAD-0533]	MIRES	C	0.2	0.4	0.1	0.1	(1)
[REQ-1-OAD-0535]	NIRES-R	C	0.5	0.7	0.2	0.2	(1)
	Operations		**24.1**	**29.0**	**0.5**	**0.5**	
[REQ-1-OAD-0537]	CIS	C	5.0	5.0	0.5	0.5	(1)
[REQ-1-OAD-0539]	CSW	C	4.9	6.2	0.0	0.0	(1)
[REQ-1-OAD-0540]	DMS	C	7.3	7.3	0.0	0.0	(1)
[REQ-1-OAD-0541]	ESW	C	3.7	7.4	0.0	0.0	(1)
[REQ-1-OAD-0542]	SOSS	C	0.8	0.8	0.0	0.0	(1)
[REQ-1-OAD-0543]	DPS	C	1.2	1.2	0.0	0.0	(1)
[REQ-1-OAD-0544]	SCMS	C	1.2	1.2	0.0	0.0	(1)

Notes:

(1) Heat dissipation requirements are not imposed on subsystems for equipment in the Computer & Control Rooms (i.e. no flowdown to Level 2, and no verification is required). The Systems Engineering (SE) team has performed a conservative analysis of the Computer & Control Room heat dissipation estimates to inform the SUM cooling design. SUM is responsible for air cooling the various rooms in the Summit Facilities according to the budgets presented here. The subsystems are bound to their power allocations in the Computer & Control Rooms, which SE uses to estimate the heat dissipation. Thus, while SE is not imposing heat dissipation requirements in these areas, there is still control of the estimates via the power budgets. SE will work with the subsystems to refine the Computer & Control Room heat dissipation estimates according to various use cases of the observatory.

(2) As mentioned in note (1), SUM is responsible for air cooling the various rooms in the Summit Facilities. For subsystems with equipment in other areas of the Summit Facilities (e.g. Utility Room, Coating areas), heat dissipation requirements are imposed on those subsystems as noted by (2) in the table.

(3) AM2 & M2S are non-concurrent. Total considers AM2 as the worst case.

(4) M1 COAT & M2/M3 COAT are non-current. Total considers M1 COAT as the worst case.

(5) M2/M3 COAT is only used during shutdown (while no observations are scheduled). As such, no requirement flowdown is imposed.

3.3 Image Quality Budget for Natural Seeing Operations

3.3.1 On-Axis Budget

The following error budget provides image jitter and image blur allocations for the telescope (excluding instruments) at the following conditions:

- On-axis images delivered to any instrument location
- Telescope pointing to a 30 degree zenith angle.
- Median site wind speed
- r0 = 0.2 m
- The median observing temperature (REQ-1-OAD-0010), or at a temperature difference of 2.5K from the APS alignment temperature.

The budget doesn't include effects of image rotators and atmospheric dispersion compensators, or other effects associated with the instruments.

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).

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_N is in (RD4).

The error categories of the budget in Table 3-4: Telescope Image Quality Error Budget (RD19) are explained in the Appendix, Section 6.2.

Observatory performance is a function of the actual environmental and operational conditions and parameters. The PSS image quality error budget (RD19) is defined under the following conditions:

- The optical wavelength is 0.5 µm.
- Image quality is defined on-axis, i.e. at the center of the focal surface.
- The budgeted values are the means over all environmental and operational conditions.
- The atmospheric Fried parameter is 20cm in zenith direction (approx. median seeing for 60 meters above ground).

Table 3-3: Telescope Image Quality Error Budget (RD19)

Requirement ID	Description	Error Allocation					Wavefront Error Allocation after AO (NFIRAOS) Correction [nm RMS]					Notes
[REQ-1-OAD-0400]	**Observatory (up to the Nasmyth Focus)**	0.8500					62.0					
[REQ-1-OAD-0402]	**Thermal (mirror and dome) seeing**		0.9650					34.0				TS
	Optical surface shapes		0.8880					35.1				
[REQ-1-OAD-0406]	**M1 shape**			0.9346					26.1			
	M1 shape M1 system				0.9546					22.9		
	Segment residual figure error					0.9595					21.8	SRFE
	Segment thermal distortion					0.9998					2.3	STD
	Segment support print through - M1 effects					0.9955					6.2	SSPT-M1S
	Segment drift errors					0.9999					0.5	SDE
	Segment in-plane displacement					0.9997					1.7	SIPD
	M1 gravity, thermal, installation errors					1.0000					1.0	SIPD-M1
	M1 shape M1CS effects				0.9790					15.4		
	Segment support print through - M1CS effects					0.9970					1.5	SSPT-M1CS
	Segment out-of-plane residual					0.9918					6.1	SOPD
	Segment dynamic displacement residual					0.9901					14.1	SDDR
	M1 shape STR effects				0.9998					1.7		
	STR gravity, thermal, installation errors					0.9998					1.7	SIPD-STR
[REQ-1-OAD-0422]	**M2 shape**			0.9822					11.5			
	M2 residual figure error				0.9851					11.2		M2RFE
	M2 thermal distortion				0.9984					0.9		M2TD
	M2 shape drift errors				0.9999					0.5		M2SDE
	M2 support print through				0.9991					2.1		M2SPT
	M2 dynamic shape residual				0.9997					0.6		M2DSR
[REQ-1-OAD-0434]	**M3 shape**			0.9903					8.9			
	M3 residual figure error				0.9921					8.8		M3RFE
	M3 thermal distortion				0.9997					0.9		M3TD
	M3 shape drift errors				0.9999					0.5		M3SDE
	M3 support print through				0.9986					0.8		M3SPT
	M3 dynamic shape residual				1.0000					0.0		M3DSR
[REQ-1-OAD-0460]	**Wavefront Sensing**			0.9768					15.9			
	M1 warping harness wavefront measurement error				0.9896					11.7		WFSWH
	M1 segment phasing wavefront measurement error				0.9970					5.8		WFSSP
	Low order wavefront measurement error (APS and Instrument)				0.9992					0.9		WFSLO
	M1 segment tip/tilt wavefront measurement error				0.9908					9.0		WFSTT
	Optical alignment		0.9926					38.0				
[REQ-1-OAD-0448]	**Telescope collimation errors**			0.9997					0.0			COLL
[REQ-1-OAD-0454]	**Image jitter (control noise)**			0.9947					17.0			CN
	Guider Noise (Instrument)				0.9990					0.0		CN-INS
	Mount Control Noise				0.9980					9.0		CN-STR
	M2 jitter				0.9978					5.4		CN-M2
	M3 jitter				0.9999					13.4		CN-M3
[REQ-1-OAD-0480]	**Wind jitter residual**			0.9986					16.1			WJ
	STR wind residual				0.9986					16.0		WJ-STR
	M2 wind residual				1.0000					1.0		WJ-M2
	M3 wind residual				1.0000					1.0		WJ-M3
[REQ-1-OAD-0486]	**Vibration jitter residual**			0.9995					30.0			VJ
[REQ-1-OAD-0488]	**Dynamic blur residual**			1.0000					0.0			DBLUR
	Contingency		0.9994					3.3				

3.3.2 OFF-AXIS BUDGET

The seeing limited PSS_N at the Nasmyth focus is allowed to linearly degrade up to 5% with increasing telescope field angle*. A*t the edge of the 20 arcminute diameter field, at 0.5μm wavelength and r_0 = 20cm in zenith direction, the allowed off-axis normalized (RD15) PSS_N is 0.8075 (0.85 on-axis allocation times 0.95).

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 an on-axis normalized 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 at the edge of the FOV is a PSS_N of 0.5620 normalized to the on-axis image. 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 leads to a total PSS_N of 0.5339 at 10 arcmin normalized to the on-axis image. This on-axis normalized PSS_N allocation is - by definition - the product of the on-axis normalized PSS_N corresponding to the design aberration (0.6612) and the off-axis normalized allocation (0.8075).

The budget applies to the delivered focal surface at any image point at a 10 arcminute field radius, but does not include any instrument aberrations. The budget applies at a zenith angle of 30 degrees and operating temperature of 2 degrees C. It assumes that all optics are aligned on axis using the alignment and phasing system and that a wavefront sensor is employed close to the science field to measure and control low order wavefront errors.

The metric used for the off axis budget is $PSSN_F$. $PSSN_F$ is defined as:

$$PSSN_F = \frac{\int_\infty \left| PSF_{t+a+e,\emptyset}(\overrightarrow{\theta}) \right|^2 d\vec{\theta}}{\int_\infty \left| PSF_{t+a,\emptyset}(\overrightarrow{\theta}) \right|^2 d\vec{\theta}}$$

Where $PSF_{t+a+e,\varphi}$ is combined point spread function of atmosphere, ideal telescope and aberration at field angle φ and $PSF_{t+a,\varphi}$ is the PSF of the atmosphere and ideal telescope at field angle φ, and θ represents the 2 dimensional coordinates of the PSF. Overall science loss is given by $PSSN_F$/PSSN for the equivalent on axis allocation

Table 3-4: Telescope Off Axis Image Quality Error Budget (PSSNF)

Requirement ID	Description	Off Axis Image Quality ($PSSN_F$)	Additional Science Loss due to Off Axis Effects $PSSN_F$/PSSN
[REQ-1-OAD-0500]	TMT Additional science loss due Off-axis effects	0.9339	0.9500
[REQ-1-OAD-0490]	M2 Shape	0.9496	0.9649
	M2 Polishing Errors	0.9750	0.9897
	M2 Support Print Through	0.9741	0.9750
	M2 Prescription Tolerances	0.9998	0.9999
[REQ-1-OAD-0492]	M3 Shape	0.9850	1.0000
	M3 Polishing Errors	0.9864	1.0000
	M3 Support Print Through	0.9986	1.0000
[REQ-1-OAD-0495]	Alignment	0.9995	0.9995
[REQ-1-OAD-0496]	Wavefront Sensing	0.9990	0.9998
	Contingency		0.9853

3.3.3 Elevation Angle Dependence of the Budget

[REQ-1-OAD-0525] The TMT shall achieve the PSSn in [REQ-1-OAD-0400] at any observing zenith angle with r0 = 20 cm (at zA = 0) and at median wind speed and median observing temperature [REQ-1-OAD-0010].

Discussion: The normalized Point Source Sensitivity metric is normalized to the actual atmospheric seeing and therefore accounts for atmospheric conditions, including seeing degradation due to increasing zenith angle. Note that some individual terms may exceed their PSSn allocation at some zenith angles.

3.4 TMT Image Quality for Adaptive Optics Operations

3.4.1 Adaptive Optics Wavefront Error Budget

The RMS wavefront error budgets (RD20) define the following allocations:

- NGSAO Observing Mode: at the center of the corrected field for magnitudes 8 and 12
- LGS MCAO Observing Mode: at the center of the corrected field, and over a 34” x 34” FoV.

TMT AO Error Budget and CBE Description (RD41) defines all the error terms and their rationales used in (RD20), summarized in Table 3-6: NFIRAOS LGS MCAO and IRIS RMS wavefront error budget and Table 3-5: NFIRAOS NGSAO and IRIS RMS wavefront error budget.

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.

Table 3-6: NFIRAOS LGS MCAO and IRIS RMS wavefront error budget and Table 3-5: NFIRAOS NGSAO and IRIS RMS wavefront error budget below therefore impose requirements upon both the Facility AO system and the other observatory subsystems introducing these disturbances.

The overall requirement applies to one band at a time due to the chromaticity of windows in NFIRAOS.

Table 3-5: NFIRAOS NGSAO MCAO and IRIS RMS wavefront error budget (RD20)

		mR=8 GS REQ				mR=12 GS REQ				
REQ #	Terms	L0	L1	L1	L2	L0	L1	L1	L2	
	NFIRAOS NGSAO and IRIS/MODHIS Total WFE	156				190				TMT.AOS.TEC.08.015
REQ-1-OAD-0196	High Order Modes		143				151			Section 3.1
	Telescope									Section 3.1.1
REQ-1-OAD-0251	TCS			6				6		Section 3.1.1.1
	Pupil misregistration (Control)				6				6	Section 3.1.1.1.1
REQ-1-OAD-0252	M1S			29				29		Section 3.1.1.2
	M1 static shape				29				29	
REQ-1-OAD-0253	M1CS			14				14		Section 3.1.1.3
	Segment dynamic misalignment				14				14	
REQ-1-OAD-0254	M2S			13				13		Section 3.1.1.4
	M2 Static Shape				11				11	
	Focal Plane Tilt				0				0	
	Pupil misregistration (M2 actuators)				6				6	
REQ-1-OAD-0255	M3S			11				11		Section 3.1.1.5
	M3 Static Shape				9				9	
	Pupil misregistration (M3 actuators)				6				6	
REQ-1-OAD-0256	APS			16				16		Section 3.1.1.6
	M1 shape calibration				16				16	
	Facilities									Section 3.1.2
REQ-1-OAD-0257	ENC			30				30		Section 3.1.2.1
	Dome Seeing				22				22	
	Mirror Seeing				20				20	
	Instrumentation									Section 3.1.3
REQ-1-OAD-0273	NFIRAOS SYSTEM			128				136		Section 3.1.3.1
REQ-1-OAD-0264	IRIS/MODHIS			40				40		Section 3.1.3.3
REQ-1-OAD-0198	Low Order Modes (Tip/Tilt and Focus)		39				39			Section 3.2
	Telescope									Section 3.2.1
REQ-1-OAD-0278	STR, M1, M2 and M3			35				35		Section 3.2.1.1
	Windshake tip/tilt error				2				2	
	Telescope structure vibration				30				30	
	Telescope tracking jitter				17				17	
	Instrumentation									Section 3.2.2
REQ-1-OAD-0279	NFIRAOS + IRIS/MODHIS System			10				10		Section 3.2.2.1
REQ-1-OAD-0272	IRIS/MODHIS			16				16		Section 3.2.2.2
	Contingency		48				109			

Table 3-6: NFIRAOS LGS MCAO and IRIS/MODHIS RMS wavefront error budget (60 x 60 actuators, on axis and 34"34") in nm (RD20)

		On axis-REQ				34"x34" REQ				
REQ #	Terms	L0	L1	L1	L2	L0	L1	L1	L2	
	NFIRAOS LGS MCAO and IRIS Total WFE	193				207				TMT.AOS.TEC.08.015
REQ-1-OAD-0199	High Order Modes		171				188			Section 2.1
	Telescope									Section 2.1.1
REQ-1-OAD-0251	TCS			6				6		Section 2.1.1.1
	Pupil misregistration (Control)				6				6	Section 2.1.1.1.1
REQ-1-OAD-0252	M1S			29				29		Section 2.1.1.2
	M1 static shape				29				29	
REQ-1-OAD-0253	M1CS			14				14		Section 2.1.1.3
	Segment dynamic misalignment				14				14	
REQ-1-OAD-0254	M2S			13				18		Section 2.1.1.4
	M2 Static Shape				11				11	
	Focal Plane Tilt				0				13	
	Pupil misregistration (M2 actuators)				6				6	
REQ-1-OAD-0255	M3S			11				11		Section 2.1.1.5
	M3 Static Shape				9				9	
	Pupil misregistration (M3 actuators)				6				6	
REQ-1-OAD-0256	APS			16				16		Section 2.1.1.6
	M1 shape calibration				16				16	
	Facilities									Section 2.1.2
REQ-1-OAD-0257	ENC			30				30		Section 2.1.2.1
	Dome Seeing				22				22	
	Mirror Seeing				20				20	
	Instrumentation									Section 2.1.3
REQ-1-OAD-0258	NFIRAOS SYSTEM			155				173		Section 2.1.3.1
REQ-1-OAD-0264	IRIS/MODHIS			40				40		Section 2.1.3.2
REQ-1-OAD-0265	LGSF			34				34		Section 2.1.3.3
	High order aberration				30				30	
	Low order aberration				15				15	
REQ-1-OAD-0201	Low order Modes (Tip/tilt, Focus and Plate Scale)		83				83			Section 2.2
	Telescope									Section 2.2.1
REQ-1-OAD-0266	STR, M1, M2 and M3			35				35		Section 2.2.1.1
	Windshake tip/tilt error				2				2	
	Windshake plate scale error				5				5	
	Telescope structure vibration				30				30	
	Telescope tracking jitter				17				17	
	Instrumentation									Section 2.2.2
REQ-1-OAD-0267	NFIRAOS + IRIS/MODHIS System			74				74		Section 2.2.2.1
REQ-1-OAD-0272	IRIS/MODHIS			16				16		Section 2.2.2.2
	Contingency		35				24			

Discussion: The Residual T/T tracking jitter is 0.4 mas on the sky after correction by the NFIRAOS tip/tilt rejection transfer function modeled as an integrator with 400 Hz sampling frequency (F_S), 0.4 ms delay (τ) from last photon on OIWFS to last DM actuator commanded by DME, and a gain (g) of 0.63 (See Figure: AO Rejection Transfer Function). This rejection transfer function is described by:

$$H(s) = \frac{s^2}{s^2 + gF_s^2\left(1 - e^{-s/F_s}\right)e^{-\tau s}}$$

$$s = 2\pi i f$$

Discussion: The intent is to provide this model NFIRAOS Tip/Tilt rejection transfer function and require that the telescope jitter shall have an acceptably small RMS residual, when convolved with this function, which is derived for median frame rates at 50% sky coverage.

Jitter includes the residuals from local disturbances caused by telescope subsystems, e.g. motor cogging and cable wrap drag; and sensor and actuator noise causing: M1 jitter (relative to the sky), M2 tilt jitter (relative to M1), M2 decenter jitter (relative to M1), M3 tilt and rotate jitter (relative to M1), M3 piston jitter (relative to M1).

It does not include observatory vibration (generated externally to these subsystems) transmitted by a cable wrap, nor vibration caused by fluid turbulence within cable wraps. It does not include other observatory vibration, nor windshake.

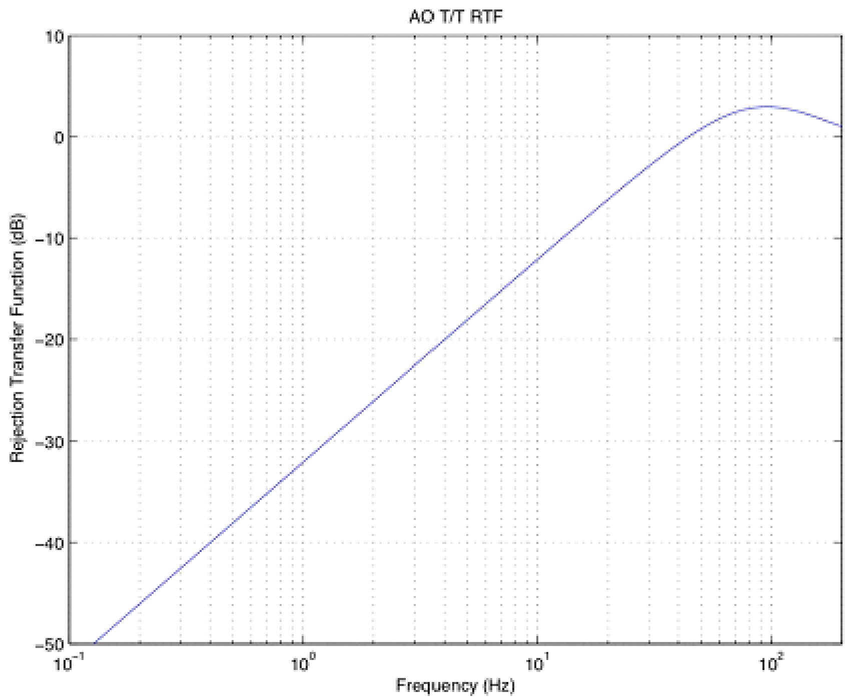

Figure 3-1: AO Rejection Transfer Function

[REQ-1-OAD-0284] TMT Observatory, in NFIRAOS Seeing Limited mode, shall deliver a K Band enclosed energy of at least 40% for a 160 mas slit, at the edge of the 2 arcmin unvignetted field of view under median conditions, using using a guide star magnitude of J < 21.

[REQ-1-OAD-0285] TMT Observatory, in NFIRAOS Seeing Limited mode, shall deliver a J Band enclosed energy of at least 30% for a 160 mas slit, at the edge of the 2 arcmin unvignetted field of view under median conditions, using using a guide star magnitude of J < 21.

[REQ-1-OAD-2745] The TMT observatory LGS MCAO capability shall be upgradeable to a High Order RMS WFE of 120 nm on axis and 133 nm over a 30 arcsec diameter FOV by an idealized 120 x 120 deformable mirror with infinite temporal bandwidth.

3.4.2 Elevation Angle Dependence of the Budget

[REQ-1-OAD-0595] TMT Observatory WFE degradation with zenith angle shall be less than or equal to (secz)^1/2 relative to the requirement at zenith.

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

3.4.3 OPD Wavefront Corrector Stroke Allocation

The higher-order wavefront errors induced by telescope aberrations, instrument aberrations, and dome/mirror seeing must be correctable to the error budget allocations using a total wavefront correction. The budgeted optical path difference allocation between these sources is shown in Table 3-7.

Table 3-7: OPD budget for the correction of Observatory wavefront error source (RD10)

Requirements ID	Item	OPD budget WFE (µm)
[REQ-1-OAD-0612]	**Overall Observatory**	2.000
[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

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 (RD10).

3.4.4 NFIRAOS PSSN

Discussion: This budget (RD54) is for background-limited imaging of unresolved point sources. Numbers in the PSSN budget in Table below multiply together. A description about terms is in RD55. If each item in the PSSN budget were perfect, it would be equal 1.0. However, the various terms in the second column of the Table below together result in PSSN = 0.157 for K, meaning that it takes approximately 7x more exposure time to detect a point source than for a TMT built to its nominal design, with 100% throughput and perfect AO correction. Items in the second column are themselves the products of terms in the third column.

Table 3-8: PSSN NFIRAOS LGS MCAO and NGSAO and IRIS Imager

		On Axis MCAO PSSN Budget									34" x 34" MCAO PSSN Budget								
Requirements ID	Item	J			H			K			J			H			K		
	PSSN MCAO NFIRAOS + IRIS Imager	0.051			0.106			0.157			0.039			0.092			0.145		
REQ-0-SRD-0805	Wavefront Error (PSS ∝ S^2)		0.182			0.376			0.577			0.141			0.325			0.531	
REQ-1-OAD-0199	High Order WFE in nm -> S^2			0.217			0.416			0.610			0.168			0.359			0.562
REQ-1-OAD-0201	Lo Order WFE broadening PSF -> S			0.840			0.905			0.945			0.840			0.905			0.945
	Throughput (PSS ∝ η)		0.328			0.328			0.328			0.328			0.328			0.328	
REQ-1-OAD-1600	Telescope Requirement			0.910			0.910			0.910			0.910			0.910			0.910
REQ-1-OAD-2811	NFIRAOS Requirement			0.800			0.800			0.800			0.800			0.800			0.800
REQ-1-OAD-3089	IRIS Imager Requirement			0.450			0.450			0.450			0.450			0.450			0.450
REQ-1-OAD-0716	Pupil Shift (0.4% Undersized Lyot)		0.875			0.875			0.875			0.875			0.875			0.875	
	Undersized IRIS Lyot mask vignetting			0.955			0.955			0.955			0.955			0.955			0.955
	Undersized Lyot mask PSF broadening			0.917			0.917			0.917			0.917			0.917			0.917
REQ-1-OAD-0705, REQ-1-OAD-3092	Background [PSS ∝ $(1+I_b/I_o)^{-1}$]		0.997			0.997			0.958			0.997			0.997			0.958	
	Thermal Background			0.999			0.999			0.960			0.999			0.999			0.960
	Scattered Light			0.999			0.999			0.999			0.999			0.999			0.999
	Out of focus ghosts			0.999			0.999			0.999			0.999			0.999			0.999
REQ-1-OAD-0723	Image Smearing (PSS ∝ S)		0.992			0.995			0.997			0.992			0.995			0.997	
	Image derotator																		
	Offset b/w OIWFS/IRIS Focal plane																		
	ADC errors																		
	Amplitude non-uniformities		0.988			0.991			0.994			0.988			0.991			0.994	
	Atmospheric scintillation			0.988			0.991			0.994			0.988			0.991			0.994
REQ-1-OAD-0727	M1 segments T.P variation			0.9998			0.9998			0.9998			0.9998			0.9998			0.9998
REQ-1-OAD-0725	Ghosting (PSS ∝ 1-2ε)		1.000			1.000			1.000			1.000			1.000			1.000	
	Static focused ghost			0.9995			0.9995			0.9995			0.9995			0.9995			0.9995

		NGSAO PSSN Budget mR=8 guide star									NGSAO PSSN Budget mR=12 guide star								
Requirements ID	Item	J			H			K			J			H			K		
	PSSN NGSAO NFIRAOS + IRIS Imager	0.079			0.136			0.181			0.043			0.097			0.149		
REQ-0-SRD-880,881	Wavefront Error (PSS ∝ S^2)		0.281			0.483			0.664			0.155			0.343			0.548	
REQ-1-OAD-0196	High Order WFE in nm -> S^2			0.292			0.494			0.672			0.161			0.351			0.555
REQ-1-OAD-0198	Lo Order WFE broadening PSF -> S			0.962			0.978			0.988			0.962			0.978			0.988
	Throughput (PSS ∝ η)		0.328			0.328			0.328			0.328			0.328			0.328	
REQ-1-OAD-1600	Telescope Requirement			0.910			0.910			0.910			0.910			0.910			0.910
REQ-1-OAD-2811	NFIRAOS Requirement			0.800			0.800			0.800			0.800			0.800			0.800
REQ-1-OAD-3089	IRIS Imager Requirement			0.450			0.450			0.450			0.450			0.450			0.450
REQ-1-OAD-0716	Pupil Shift (0.4% Undersized Lyot)		0.875			0.875			0.875			0.875			0.875			0.875	
	Undersized IRIS Lyot mask vignetting			0.955			0.955			0.955			0.955			0.955			0.955
	Undersized Lyot mask PSF broadening			0.917			0.917			0.917			0.917			0.917			0.917
REQ-1-OAD-0705, REQ-1-OAD-3092	Background [PSS ∝ $(1+I_b/I_o)^{-1}$]		0.997			0.997			0.958			0.997			0.997			0.958	
	Thermal Background			0.999			0.999			0.960			0.999			0.999			0.960
	Scattered Light			0.999			0.999			0.999			0.999			0.999			0.999
	Out of focus ghosts			0.999			0.999			0.999			0.999			0.999			0.999
REQ-1-OAD-0723	Image Smearing		0.992			0.995			0.997			0.992			0.995			0.997	
	Image derotator																		
	Offset b/w OIWFS/IRIS Focal plane																		
	ADC errors																		
	Amplitude non-uniformities		0.988			0.991			0.994			0.988			0.991			0.994	
	Atmospheric scintillation			0.988			0.991			0.994			0.988			0.991			0.994
REQ-1-OAD-0727	M1 segments T.P variation			0.9998			0.9998			0.9998			0.9998			0.9998			0.9998
REQ-1-OAD-0725	Ghosting (PSS ∝ 1-2ε)		1.000			1.000			1.000			1.000			1.000			1.000	
	Static focused ghost			0.9995			0.9995			0.9995			0.9995			0.9995			0.9995

Note: Requirements with dark grey background indicate requirements defined in other budgets and/or other units in this document.

Discussion: During adaptive optics mode guiding, image smearing in [REQ-1-OAD-0723] is less than 0.0005 arcsec RMS after AO correction, anywhere in the field of view of a given instrument.

3.5 POINTING ERROR BUDGET

Pointing is the operation when the telescope initially settles on 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 TMT Pointing Budget [RD67] allocates allowable residual errors to the alignment tolerances to the key elements of the Observatory. 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.

[REQ-1-OAD-0661] The Telescope shall point to a sky coordinate with an RMS accuracy of less than 1.0 arcsec for all instrument locations.

Discussion: [REQ-1-OAD-0661] is measured on-axis for any instrument location and includes any global instrument location errors. However, it excludes any instrument internal specific errors. It is expected that each instrument location requires unique calibration for M3. This requirement also excludes thermal induced errors and temporal errors. Refer to [RD67] for further information. This requirement is measured using the results of a calibration run with an update of the pointing model at a nominal wavelength of 1.0um.

[REQ-1-OAD-0662] Goal: The Telescope pointing performance should not degrade by more than 1.3" RMS over a year, prior to re-calibration.

Discussion: [REQ-1-OAD-0662] allows the pointing performance of the Telescope to degrade by an additional 1.3" RMS. It is applied in RSS to [REQ-1-OAD-0661] such that prior to the calibration, the overall Telescope pointing performance may degrade up to 1.6" RMS. This requirement includes temporal errors. The dominant temporal error is settling of the pier and foundations. This requirement also includes errors induced by thermal changes which causes variation from night to night. Refer to [RD67] for further information.

Table 3-9: Pointing Error Budget in arcsec RMS

Requirement #	Error Terms	Arcsec RMS
	Telescope Pointing	**1.64**
[REQ-1-OAD-0661]	**Telescope pointing after Pointing Test**	**1.00**
[REQ-1-OAD-0660]	Residual Astrometry & Atmospheric	0.10
[REQ-1-OAD-0666]	Structure & M1S	0.60
[REQ-1-OAD-0669]	M2S	0.40
[REQ-1-OAD-0672]	M3S & Instrument Position	0.40
	Contingency	0.55
[REQ-1-OAD-0662]	**Telescope Pointing over a year, prior to re-calibration**	**1.30**
[REQ-1-OAD-0667]	Thermal	0.40
[REQ-1-OAD-0668]	Temporal	1.20
	Contingency	0.30

3.6 TMT Pupil Shift Budget

3.6.1 TMT Pupil Shift Budget - No AO Feedback

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 3-10: Pupil Shift Budget in RMS, assuming a Gaussian distribution with RMS = 1 sigma (RD5)

Requirement ID	Item	Pupil Shift RMS (% of pupil diameter)
[REQ-1-OAD-0702]	**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

3.6.2 TMT Pupil Shift Budget - with AO Feedback

Table 3-11: End to End Undersizing Budget for IRIS Lyot Mask contains the bottoms up budget (RD56) for the residual misalignment of the pupil on to IRIS' Lyot stop. Blurring of the Pupil on IRIS Lyot stop due to IRIS optical design is a systematic error that has been analyzed in Zemax at 0.2% and is the largest single item in the budget. Mechanical design guidelines for IRIS random errors are to use 2-sigma tolerances for a total of two times the RMS pupil misalignment, so the top line of the budget is the systematic errors plus double the second line which is the quadrature sum of the random errors in the lines below and to the right. A more detailed description of these terms is in RD55.

Table 3-11: End to End Undersizing Budget for IRIS Lyot Mask

Requirement ID	Item	Undersizing IRIS Lyot Mask (%)			
[REQ-1-OAD-0716]	**Mask Undersize (Systematic + 2 * random)**	0.40%			
	Systematic errors		0.20%		
[REQ-1-OAD-0717]	**IRIS Optical Blurring of Pupil (systematic)**			0.20%	
	Random errors RMS sum (1 sigma)		0.10%		
[REQ-1-OAD-0718]	**NFIRAOS**			0.05%	
	Pupil mirror in PWFS - accuracy				0.030%
	Pointing model errors for PWFS				0.030%
	Pupil image centroiding				0.010%
	M1 segment non-uniformity				0.005%
	NFIRAOS exit pupil magnification				0.006%
	Axial Tolerance of Exit pupil				0.025%
[REQ-1-OAD-0476]	**Telescope (M3)**			0.002%	
[REQ-1-OAD-0719]	**RSS of IRIS random terms**			0.050%	
	Rotating Offset center of mass of cryostat/OIWFS				0.028%
	Accuracy of XY stage for Lyot stop				0.026%
	Fabrication accuracy of Lyot stop				0.005%
	Position error of the Lyot stop in Z direction				0.001%
	NFIRAOS Simulator Pupil position error in Z direction				0.012%
	DM11 poke pattern meas. error				0.017%
	Centroiding Mask on PV vs poke pattern				0.010%
	Adjustment error of the tilt ring				0.022%
	High frequency rotator bearing runout				0.006%
	Contingency			0.070%	

Note: Requirements with Double Underline indicate requirements defined in other budgets and/or other units in this document.

3.7 PLATE SCALE STABILITY BUDGET

This budget controls the stability of positions in the telescope field of view. This budget is elaborated in more detail in (RD12).

Table 3-12: Telescope budget for stability of plate scale, specified in terms of maximum image motion of any point in the full 20 arcmin diameter field relative to the center of the field.

Requirement ID	Item	Maximum Image Motion (mas)
[REQ-1-OAD-0721]	**Telescope Plate Scale Stability**	60
[REQ-1-OAD-0720]	M1 Curvature change	8
[REQ-1-OAD-0722]	M2 quadratic figure errors	20
[REQ-1-OAD-0724]	M3 quadratic figure errors	40
[REQ-1-OAD-0726]	Change in back focal distance	26
[REQ-1-OAD-0728]	Uncompensated defocus	3
[REQ-1-OAD-0730]	Focal surface tilt relative to instrument	20
[REQ-1-OAD-0732]	Decentration of optical axis in FoV	20
[REQ-1-OAD-0734]	Other factors	10

3.8 MASS BUDGET

Table 3-13: Mass Budget for Telescope Mounted Subsystems (RD21)

Requirement	Subsystem Decomposition		Mass (not to exceed)		
	Abbreviation	Description	Subsystem Total (tonnes)	Elevation (tonnes)	Azimuth (tonnes)
[REQ-1-OAD-0739]	TEL+Payload	**Telescope + Payload***	2650	1298	1351
[REQ-1-OAD-0740]	STR	Telescope Structure	2200	1100	1100
		Elev. Structure		1077.5	
		Az. Structure			964.4
		Inst. Support Structures			45.6
		Utility Services Lines and Junctions (STR, TUS-2, TUS-3)		22.5	96.7
[REQ-1-OAD-0742]	M1S	M1 System	130.0	130.0	
[REQ-1-OAD-0744]	M2S	M2 System	6.8		
		M2S ASSY Top end		6.5	
		M2S EE and Cables		0.3	
[REQ-1-OAD-0745]	AM2	Adaptive Secondary Mirror System*	8.8		
		AM2 ASSY Top end		8.5	
		AM2 EE and Cables		0.3	
[REQ-1-OAD-0746]	M3S	M3 System	12.5	12.5	
[REQ-1-OAD-0748]	TINS	Test Instruments	0.3		
		GMS		0.1	0.1
		PFC*		0.1	
[REQ-1-OAD-0754]	M1CS	M1 Control System	29.1	29.1	
[REQ-1-OAD-0758]	OSS	Observatory Safety System	0.1	0.05	0.05
[REQ-1-OAD-0760]	ESEN	Engineering Sensors	0.4	0.3	0.1
[REQ-1-OAD-0769]	CLN	Optical Cleaning System	11.2		
		DPT Cleaning Arms Equiment		1.0	
		CO2 Bulk Delivery Equipment +X			5.1
		CO2 Bulk Delivery Equipment -X			5.1
[REQ-1-OAD-0766]	LGSF	Laser guide star facility	14.4		
		LGSF laser system		9.3	
		LGSF BTO Optical Path		3	
		LGSF Top End		2.1	
[REQ-1-OAD-0781]	CRYO	Cryogenic Coolant System	11.5		
		CRYO Equipment on TEL NAS -X			4.80
		CRYO Equipment on TEL NAS +X			4.80
		CRYO Lines and Junctions on Telescope			1.90
[REQ-1-OAD-0783]	REFR	Refrigerant Cooling System	3.1		
		REFR Lines and Junctions on Telescope		0.7	2.4
[REQ-1-OAD-0787]	CIS	CIS	2.5		
		CIS Lines and Junctions on Telescope		1.2	1.3

Table 3-13 cont.					
[REQ-1-OAD-0750]	APS	Alignment and Phasing System	6.0		
		Instrument (early light)			5.6
		APS EE (early light)			0.4
		Instrument (first decade)*			5.6
		APS EE (first decade)*			0.4
[REQ-1-OAD-0764]	NFIRAOS	NFIRAOS	52.6		
		Instrument			46.3
		NFIRAOS EE			6.3
[REQ-1-OAD-0768]	IRIS	IRIS	10.4		
		Instrument			6.8
		Cable Wrap			2.8
		IRIS EE			0.8
[REQ-1-OAD-0770]	MODHIS	MODHIS	6.8		
		Instrument			5.8
		MODHIS EE			1.0
[REQ-1-OAD-0772]	MIRES	MIRES + MIRAO	6.9		
		Instrument (MIRAO)			2.4
		Instrument (MIRES)			3.5
		MIRAO+MIRES EE			1.0
[REQ-1-OAD-0774]	PFI	PFI	5.3		
		Instrument			4.1
		PFI EE			1.2
[REQ-1-OAD-0776]	NIRES-R	NIRES-R	6.9		
		Instrument			5.9
		NIRES-R EE			1.0
[REQ-1-OAD-0780]	WFOS	WFOS	42.0		
		Instrument			41.0
		WFOS EE			1.0
[REQ-1-OAD-0782]	HROS	HROS	43.6		
		Instrument			41.4
		HROS EE			2.2
[REQ-1-OAD-0784]	IRMOS	IRMOS	18.6		
		Instrument			16.1
		IRMOS EE			2.5
[REQ-1-OAD-0786]	Misc. Nasmyth	Misc. Nasmyth	20.0		
		+X Side			10.0
		-X Side			10.0

3.9 VIBRATION BUDGET

An analysis has been performed to estimate allowable force contributions at various locations on the telescope that in combination would meet the allowable NFIRAOS-corrected wavefront error allocated to vibration in [REQ-1-OAD-0253 (M1 contribution) and [REQ-1-OAD-0278] (Image Jitter contribution).

This results in the following allocations of vibration contributions to system AO WFE among subsystems in '*Table 3-14: Vibration Budget* (RD22)' below. The allocations are separated into contributions in three locations, on the telescope, within the enclosure and in the summit facilities. Each line of the table with a requirement number should be interpreted as follows: vibration sources within the designated subsystem shall contribute less than the number of nm specified in the table to NFIRAOS-corrected RMS WFE.

Table 3-14: Vibration Budget (RD22)

Requirement ID	First Light/ First Decade		Subsystem	Location	Subsystem allowable AO WFE impact (nm)	Estimated allowable force (N rms)	Estimated sensitivity value (nm/N)
[REQ-1-OAD-1118]	First Light	-	Observatory Vibrations Total	-	30.0		
		-	Contingency		13.3		
		-		Inside Support Building	6.0		
		-		Within Enclosure	22.2		
		-		On Telescope	13.9		
[REQ-1-OAD-1119]	First Light/First Decade	-	Observatory Vibrations Total	-	30.0		
		-	Contingency		13.1		
		-		Inside Support Building	6.0		
		-		Within Enclosure	22.2		
		-		On Telescope	14.1		
[REQ-1-OAD-1177]	First Light	AOESW	Adaptive Optics Executive Software	Inside Support Building	0.4	10.0	0.04
[REQ-1-OAD-1168]	First Light	APS	Alignment and Phasing System	Inside Support Building	0.2	5.0	0.04
[REQ-1-OAD-1127]	First Light	APS	Alignment and Phasing System	On Telescope	0.0	0.0	2.4
[REQ-1-OAD-1190]	First Light	CIS	Communications and Information Systems	Inside Support Building	0.2	5.0	0.04
[REQ-1-OAD-1159]	First Light	CIS	Communications and Information Systems	Within Enclosure	0.1	1.0	0.08
[REQ-1-OAD-1136]	First Light	CIS	Communications and Information Systems	On Telescope	1.0	0.5	1.9
[REQ-1-OAD-1164]	First Light	CLN	Optical Cleaning Systems	Inside Support Building	0.0	0.0	0.04
[REQ-1-OAD-1124]	First Light	CLN	Optical Cleaning Systems	On Telescope	0.0	0.0	
[REQ-1-OAD-1152]	First Light	CLN	Optical Cleaning Systems	Within Enclosure	0.0	0.0	0.08
[REQ-1-OAD-1165]	First Light	M1 COAT	M1 Optical Coating System	Inside Support Building	0.8	20.0	0.04
[REQ-1-OAD-1153]	First Light	M2/M3 COAT	M2/M3 Optical Coating System	Within Enclosure	0.0	0.0	0.08
[REQ-1-OAD-1178]	First Light	CRYO	Instrumentation Cryogenic Cooling	Inside Support Building	1.3	30.0	0.04
[REQ-1-OAD-1137]	First Light	CRYO	Instrumentation Cryogenic Cooling	On Telescope	1.9	1.0	1.9
[REQ-1-OAD-1191]	First Light	CSW	Common Software	Inside Support Building	0.2	5.0	0.04
[REQ-1-OAD-1192]	First Light	DMS	Data Management Systems	Inside Support Building	0.2	5.0	0.04
[REQ-1-OAD-1195]	First Light	DPS	Data Processing System	Inside Support Building	0.2	5.0	0.04
[REQ-1-OAD-1149]	First Light	ENC	Enclosure	Within Enclosure	21.8	260.0	0.08
[REQ-1-OAD-1173]	First Light	ESEN	Engineering Sensors	Inside Support Building	0.0	0.0	0.04
[REQ-1-OAD-1132]	First Light	ESEN	Engineering Sensors	On Telescope	0.0	0.0	10.9
[REQ-1-OAD-1158]	First Light	ESEN	Engineering Sensors	Within Enclosure	0.0	0.0	0.08
[REQ-1-OAD-1193]	First Light	ESW	Executive Software	Inside Support Building	0.2	5.0	0.04
[REQ-1-OAD-1167]	First Light	HNDL	Optics Handling Equipment	Inside Support Building	0.0	0.0	0.04
[REQ-1-OAD-1126]	First Light	HNDL	Optics Handling Equipment	On Telescope	0.0	0.0	
[REQ-1-OAD-1155]	First Light	HNDL	Optics Handling Equipment	Within Enclosure	0.0	0.0	0.08
[REQ-1-OAD-1179]	First Light	IRIS	Infrared Imaging Spectrometer	Inside Support Building	0.2	5.0	0.04
[REQ-1-OAD-1138]	First Light	IRIS	Infrared Imaging Spectrometer	On Telescope	1.0	0.5	1.9
[REQ-1-OAD-1176]	First Light	LGSF	Laser Guide Star Facility	Inside Support Building	0.4	10.0	0.04
[REQ-1-OAD-1135]	First Light	LGSF	Laser Guide Star Facility	On Telescope	4.1		
	First Light	LGSF	BTO	On Telescope	0.8	0.5	1.6
	First Light	LGSF	Laser electronics	On Telescope	3.3	0.5	6.6
	First Light	LGSF	Lasers	On Telescope	0.8	0.5	1.6
	First Light	LGSF	Top-end	On Telescope	2.2	0.2	10.9
[REQ-1-OAD-1170]	First Light	M1CS	M1 Control System	Inside Support Building	0.2	5.0	0.04
[REQ-1-OAD-1129]	First Light	M1CS	M1 Control System	On Telescope	1.5	0.5	3.0
[REQ-1-OAD-1121]	First Light	M1S	M1 Optics System	On Telescope	0.0	0.0	
[REQ-1-OAD-1162]	First Light	M2S	M2 System	Inside Support Building	0.0	0.0	0.04
[REQ-1-OAD-1122]	First Light	M2S	M2 System	On Telescope	3.8		
	First Light	M2S	M2 electronics	On Telescope	1.6	0.5	3.2
	First Light	M2S	M2CA	On Telescope	1.1	0.1	10.9
	First Light	M2S	M2PA	On Telescope	3.3	0.3	10.9

Requirement ID	First Light/ First Decade		Subsystem	Location	Subsystem allowable AO WFE impact (nm)	Estimated allowable force (N rms)	Estimated sensitivity value (nm/N)
[REQ-1-OAD-1163]	First Light	M3S	M3 System	Inside Support Building	0.0	0.0	0.04
[REQ-1-OAD-1123]	First Light	M3S	M3 System	On Telescope	1.1	1.0	1.1
[REQ-1-OAD-1181]	First Light	MODHIS	MODHIS	Inside Support Building	0.2	5.0	0.04
[REQ-1-OAD-1140]	First Light	MODHIS	MODHIS	On Telescope	1.0	0.5	1.9
[REQ-1-OAD-1133]	First Light	NFIRAOS	Narrow Field Near Infrared AO System	On Telescope	1.9	1.1	1.7
[REQ-1-OAD-1174]	First Light	NFIRAOS	Narrow Field Near Infrared AO System	Inside Support Building	0.2	5.1	0.04
[REQ-1-OAD-1172]	First Light	OSS	Observatory Safety System	Inside Support Building	0.2	5.0	0.04
[REQ-1-OAD-1131]	First Light	OSS	Observatory Safety System	On Telescope	0.0	0.0	
[REQ-1-OAD-1157]	First Light	OSS	Observatory Safety System	Within Enclosure	0.1	1.0	0.08
[REQ-1-OAD-1198]	First Light	REFR	Instrumentation Refrigerant Cooling	Inside Support Building	1.3	30.0	0.04
[REQ-1-OAD-1197]	First Light	REFR	Instrumentation Refrigerant Cooling	On Telescope	1.9	1.0	1.9
[REQ-1-OAD-1196]	First Light	SCMS	Site Conditions Monitoring System	Inside Support Building/Tower	0.2	5.0	0.04
[REQ-1-OAD-1194]	First Light	SOSS	Science Operations Support Systems	Inside Support Building	0.2	5.0	0.04
[REQ-1-OAD-1151]	First Light	STR	Telescope structure	Within Enclosure	1.5	10.0	0.15
[REQ-1-OAD-1161]	First Light	STR	Telescope Structure	Inside Support Building	3.7	50.0	0.07
[REQ-1-OAD-1120]	First Light	STR	Telescope Structure	On Telescope	12.0		
	First Light	STR	Telescope Utility Services	On Telescope	10.7	1.4	7.6
	First Light	STR	Azimuth cable wrap	On Telescope	0.5	1.0	0.5
	First Light	STR	Azimuth drives cooling	On Telescope	0.7	1.0	0.7
	First Light	STR	Elevation cable wrap	On Telescope	1.3	1.0	1.3
	First Light	STR	Elevation drives cooling	On Telescope	1.9	1.0	1.9
	First Light	STR	HBS oil distribution	On Telescope	0.7	1.0	0.7
	First Light	STR	Other	On Telescope	4.7	1.0	4.7
[REQ-1-OAD-1160]	First Light	SUM	Summit Facilities	Inside Support Building	4.2	100.0	0.04
[REQ-1-OAD-1150]	First Light	SUM	Summit Facilities	Within Enclosure	4.2	10.0	0.42
[REQ-1-OAD-1169]	First Light	TCS	Telescope Control System	Inside Support Building	0.2	5.0	0.04
[REQ-1-OAD-1128]	First Light	TCS	Telescope Control System	On Telescope	0.0	0.0	
[REQ-1-OAD-1166]	First Light	TINS	Test Instruments	Inside Support Building	0.0	0.0	0.04
[REQ-1-OAD-1125]	First Light	TINS	Test Instruments	On Telescope	0.0	0.0	
[REQ-1-OAD-1154]	First Light	TINS	Test Instruments	Within Enclosure	0.0	0.0	0.08
[REQ-1-OAD-1180]	First Light	WFOS	Wide Field Optical Spectrometer	Inside Support Building	0.2	5.0	0.04
[REQ-1-OAD-1139]	First Light	WFOS	Wide Field Optical Spectrometer	On Telescope	1.2	0.8	1.4
[REQ-1-OAD-1182	First Decade	HROS	High Resolution Optical Spectrometer	Inside Support Building	0.2	5.0	0.04
[REQ-1-OAD-1141]	First Decade	HROS	High Resolution Optical Spectrometer	On Telescope	1.0	0.5	1.9
[REQ-1-OAD-1183]	First Decade	IRMOS	Near-Infrared Multi-Object Sectrometer	Inside Support Building	0.2	5.0	0.04
[REQ-1-OAD-1142]	First Decade	IRMOS	Near-Infrared Multi-Object Sectrometer	On Telescope	1.0	0.5	1.9
[REQ-1-OAD-1185]	First Decade	MIRAO	Mid-Infrared AO System	Inside Support Building	0.2	5.0	0.04
[REQ-1-OAD-1144]	First Decade	MIRAO	Mid-Infrared AO System	On Telescope	1.0	0.5	1.9
[REQ-1-OAD-1186]	First Decade	MIRES	Mid-Infrared Echelle Spectrometer	Inside Support Building	0.2	5.0	0.04
[REQ-1-OAD-1145]	First Decade	MIRES	Mid-Infrared Echelle Spectrometer	On Telescope	1.0	0.5	1.9
[REQ-1-OAD-1188]	First Decade	NIRES-R	Near Infrared Echelle Spectrometer	Inside Support Building	0.2	5.0	0.04
[REQ-1-OAD-1147]	First Decade	NIRES-R	Near Infrared Echelle Spectrometer	On Telescope	1.0	0.5	1.9
[REQ-1-OAD-1184]	First Decade	PFI	Planet Formation Instrument	Inside Support Building	0.2	5.0	0.04
[REQ-1-OAD-1143]	First Decade	PFI	Planet Formation Instrument	On Telescope	1.0	0.5	1.9

Discussion: It is understood that the AO WFE due to vibration for either image jitter or M1 segment dynamics cannot be readily calculated for most subsystems. The purpose of the "Estimated allowable force" and "sensitivity" columns are to provide an interpretation of these requirements that is considered acceptable to TMT for the flow-down to each subsystem for these requirements. These force values are to be interpreted as follows: the root-sum-square (RSS) of forces from a given subsystem in one of the three locations shall be less than the specified number of Newtons after passing through a filter that has unit magnitude over the frequency band f > 5 Hz to f < 20 Hz, decreasing with 1/f^2 below 5Hz and f^2 above 20 Hz (allowing more force if the source is at lower or higher frequency).

In cases where a subsystem has been given an allocation based on a distribution between subcomponents at varying sensitivities, the subsystem may re-allocate the forces between locations provided the aggregate allowable WFE value is met.

3.10 M1S/M1CS Actuator/Stroke Budgets

3.10.1 M1CS Actuator Range of Travel Budget

The range of travel of the M1CS position actuators is budgeted to accommodate the factors listed in '*Table 3-15: M1CS Actuator Range of Travel Budget*' below.

Table 3-15: M1CS Actuator Range of Travel Budget.

Requirement Number	Component	Actuator Travel Allowance (mm)
REQ-1-OAD-0808	M1CS Actuator Travel	5
REQ-1-OAD-0800	Gravity Deflection of Telescope Elevation Structure and M1 Optics System	1.8
REQ-1-OAD-0802	Thermal Deflection of Telescope Elevation Structure and M1 Optics System	0.42
REQ-1-OAD-0804	M1 Subcell installation errors	0.4
REQ-1-OAD-0806	Diagnostics	0.25
REQ-1-OAD-0807	End of Travel Margin	0.2
REQ-1-OAD-0809	Mounted Segment Assembly Tolerances	0.7
REQ-1-OAD-0810	M1 Radius of Curvature Uncertainty	0.3
	Margin	0.93

3.10.2 M1S Warping Harness Stroke Budget

The following table sets limits for what percentage of warping harness stroke can be used to correct errors present on the M1 segments, M2 and M3 mirrors. The requirements are expressed as % stroke used and should be evaluated as the maximum error used on any one of the 21 warping harness actuators on any individual segment.

Table 3-16: M1S Warping Harness Stroke Budget

Requirement ID	Effect	% Warping Harness Stroke Allocated
[REQ-1-OAD-1979]	**Warping Harness Stroke**	63
[REQ-1-OAD-1980]	**M1S Warping Harness Stroke**	45
	M1 segment polishing	20
	M1 segment installation errors	5
	M1 segment surface change due to coating stress	3
	M1 segment thermal distortion	2
	M1 segment assembly and manufacturing tolerances and errors	10
	M1 segment thermal clocking and translation errors	2
	M1 Small Terms	3
[REQ-1-OAD-1986]	**M2S Warping Harness Stroke**	17
	M2 shape tolerances	7
	M2 low and mid frequency polishing errors	5
	M2 support print through	5
[REQ-1-OAD-1988]	**M3S Warping Harness Stroke**	1
	M3 polishing errors	1

3.11 Maintenance Budgets

The Maintenance requirements in this section ensure that there is sufficient time and personnel available to perform all maintenance activities. The TMT Maintenance Budget and requirements are broken down into three major categories. These are:

- Shutdown Maintenance Activities: Maintenance tasks for major items where it is not possible (without prohibitive expense) to conduct the maintenance within a day and therefore observing time is lost.
- System Level Maintenance Activities: Maintenance tasks that involve multiple subsystems.
- Subsystem Level Maintenance Activities: Maintenance tasks that are largely within the control (and therefore the design) of the subsystems.

The TMT Maintenance Budget assumes the Observatory is in steady-state operations.

3.11.1 Shutdown Maintenance

[REQ-1-OAD-0815] TMT Observatory Scheduled Maintenance activities shall not exceed 6 elapsed hours on any given day, with exception of the shutdown activities defined in Table-3-17 and Table 3-18, and certain system level maintenance activities as defined in Table 3-19.

Discussion: This is intended to limit the maximum duration of a Scheduled Maintenance task such that the Observatory can be ready for Observing that night. Scheduled Maintenance tasks may be split across multiple days if the subsystems can return to a full operational state at the end of each day.

Certain System Level Maintenance activities may exceed this requirement, but can still be completed in time for night time operations. These cases require approval by TMT and may involve two different shifts of personnel to complete the activity.

The TMT Maintenance Budget (RD64) allocates time to subsystems for Observatory Shutdown Maintenance activities as shown in Table 3-17 and Instrumentation Shutdown Maintenance as shown in Table 3-18.

Table 3-17: Observatory Shutdown Maintenance Budget (for activities that prevent nighttime observations)

Requirement Number	Shutdown Activity	Subsystems Involved	Time (days*)	Frequency
REQ-1-OAD-0817	TMT Shutdown Activties - Yearly		5	
REQ-1-OAD-0820	M2S Recoating / In-situ Wet Washing (alternating)	M2, M2/M3 COAT, HNDL, CLN	5	Every year
REQ-1-OAD-0822	M3S Recoating / In-situ Wet Washing (alternating)	M3, M2/M3 COAT, HNDL, CLN	5	Every year
REQ-1-OAD-0825	Flexible Transfer lines Servicing/Replacement	CRYO, REFR (alternating)	5	Every year
REQ-1-OAD-0829	SCMS	SCMS	5	Every year
REQ-1-OAD-0818	TMT Shutdown Activities - Every 25 years		10	
REQ-1-OAD-0824	STR Replacement of Wraps	STR	10	Every 25 years

*includes day and night

Discussion: M2 and M3 reoating and in-situ wet-washing happen in alternate years such that M2 is recoated while M3 is wet-washed, and M3 is recoated while M2 is wet-washed.

Table 3-18: Instrumentation Shutdown Budget (for activities that limit nighttime observations)

Requirement Number	Shutdown Activity	Time (days*)	Frequency
[REQ-1-OAD-0835]	TMT Instruments Shutdown	60	
[REQ-1-OAD-0827]	NFIRAOS Shutdown	10	Every year*
[REQ-1-OAD-0828]	IRIS Shutdown	60	Every 10 years**
[REQ-1-OAD-0830]	WFOS Shutdown	60	Every 10 years**
[REQ-1-OAD-0831]	MODHIS Shutdown	60	Every 10 years**
[REQ-1-OAD-0832]	First Decade Instruments Shutdown	60	Every 10 years**

* Can overlap with annual Observatory Shutdown

**Only one instrument shutdown activity occurs each year

3.11.2 System Level Maintenance

The TMT Maintenance Budget (RD64) allocates time to perform the System Level Maintenance activities defined in Table 3-19. The allocations are based on the duration and frequency of an activity, and the number of personnel needed for the activity.

Table 3-19: System Level Maintenance Budget

Requirement Number	Maintenance Activity	Subsystems Involved	Time (hours)	Frequency	Activity Hours / Year	Personnel	Personnel Hours / Year
[REQ-1-OAD-0838]	System Level Maintenance Activities						12,398
[REQ-1-OAD-0840]	M1 Segment Exchange	STR, M1S, HNDL	10	Every 2 weeks	260	8	2,080
[REQ-1-OAD-0841]	M1 Coating	M1S, HNDL, M1 COAT	8	5 days/week	2,040	4	8,160
[REQ-1-OAD-0842]	M1 CO2 Cleaning	M1S, STR, CLN	8	Every 2 weeks	208	4	832
[REQ-1-OAD-0843]	M2 CO2 Cleaning	M2S, STR, CLN	4	Every 2 weeks	104	3	312
[REQ-1-OAD-0844]	M3 CO2 Cleaning	M3S, STR, CLN	4	Every 2 weeks	104	3	312

3.11.3 SUBSYSTEM MAINTENANCE

The TMT Maintenance Budget (RD64) allocates time to perform an Environmental Event Inspection and Scheduled Maintenance activities to each subsystem, as shown in Table 3-20.

An Environmental Event Inspection is an inspection that occurs after a 10-year earthquake or after a survival weather event. This inspection is of the full observatory to ensure no significant damage has occurred and subsystems are in a safe condition to allow astronomical observations or regular maintenance operations to take place.

Table 3-20: Subsystem Maintenance Budget

Requirement	Subsystem	Maintenance Time Allocation		Additional Shutdown Maintenance?	Additional System Level Maintenance?
		Environmental Event Inspection (person hrs/event in 1 day)	Scheduled Maintenance (person hrs/year)		
[REQ-1-OAD-0849]	Available Subsystem Preventive Maintenance Time	144	9,234		
[REQ-1-OAD-0850]	Enclosure (ENC)	12	2,200	Y	N
[REQ-1-OAD-0851]	Summit Facilities (SUM)	3	650	N	N
N/A	Headquarters (HQ)	0	0	N	N
[REQ-1-OAD-0852]	Telescope Structure (STR)	12	1,096	N	Y
[REQ-1-OAD-0890]	Telescope Utility Services (STR.TUS)	4	250	N	N
[REQ-1-OAD-0853]	M1 System (M1S)	25	800	N	Y
[REQ-1-OAD-0854]	M2 System (M2S)	2	200	Y	Y
[REQ-1-OAD-0856]	M3 System (M3S)	2	200	Y	Y
[REQ-1-OAD-0857]	Optical Cleaning (CLN)	2	100	N	Y
[REQ-1-OAD-0858]	M1 Optical Coating (M1CP)	3	50	N	Y
[REQ-1-OAD-0889]	M2/M3 Optical Coating (M2M3CP)	3	50	N	N
[REQ-1-OAD-0859]	Test Instruments (TINS)	1	50	N	N
[REQ-1-OAD-0860]	Optics Handling (HNDL)	2	75	N	Y
[REQ-1-OAD-0861]	Alignment & Phasing (APS)	2	80	Y	N
[REQ-1-OAD-0862]	Telescope Control (TCS)	0.25	12	N	N
[REQ-1-OAD-0863]	M1 Control (M1CS)	6	800	N	N
[REQ-1-OAD-0864]	Engineering Sensors (ESEN)	4	100	N	N
[REQ-1-OAD-0865]	Observatory Safety System (OSS)	1	100	N	N
[REQ-1-OAD-0866]	Narrow Field InfraRed AO System (NFIRAOS)	6	80	Y	N
[REQ-1-OAD-0867]	Laser Guide Star Facility (LGSF)	12	330	N	N
[REQ-1-OAD-0868]	AO Executive Software (AOESW)	0.25	12	N	N
[REQ-1-OAD-0872	Cryogenic Cooling (CRYO)	4	100	Y	N
[REQ-1-OAD-0873]	Instrument Refrigeration (REFR)	4	100	Y	N
[REQ-1-OAD-0875]	Communications and Information System (CIS)	1	100	N	N
[REQ-1-OAD-0876]	Common Software (CSW)	0.25	12	N	N
[REQ-1-OAD-0877]	Data Management System (DMS)	0.25	12	N	N
[REQ-1-OAD-0878]	Executive Software (ESW)	0.25	12	N	N
[REQ-1-OAD-0879]	Science Ops Support (SOSS)	0.25	12	N	N
[REQ-1-OAD-0880]	Data Processing (DPS)	0.25	12	N	N
[REQ-1-OAD-0881]	Site Conditions Monitoring System (SCMS)	4	40	Y	N
	First Light Instruments				
[REQ-1-OAD-0869]	IRIS	2	80	Y	N
[REQ-1-OAD-0870]	MODHIS	2	80	Y	N
[REQ-1-OAD-0871]	WFOS	6	160	Y	N
[REQ-1-OAD-0882]	First Decade Instruments	2	80	Y	N

3.12 Astrometry and Photometry Budgets

3.12.1 AO Astrometry Error Budget

The TMT AO Astrometry Error Budget (RD52) below allocates the differential astrometry components, where one-dimensional time-dependent RMS astrometric positional uncertainties, after fitting distortion measured with field stars, and over a 34 arcsecond field of view, in the H band for a 100 s integration time. These errors should fall as $t^{-1/2}$.

The TMT AO Astrometry Description (RD53) defines all the error terms and their rationales used in (RD52). The key observations input parameters are: Science Case DR3, with Nsci = 1, NField = 100, Nref = 7, N(NGS) = 3 and SNRsci = 200.

Table 3-21: AO Astrometry Accuracy Budget Allocations

	REQ-1-OAD-0848	REQ-1-OAD-0894	REQ-1-OAD-0895	REQ-1-OAD-0896	REQ-1-OAD-0897	REQ-1-OAD-0898	
	σ[µas]	M1/M2	M3	NFIRAOS	IRIS	SOSS (GS Catalogs)	Fundamental
Astrometric accuracy	**50.0**	**0.0**	**5.0**	**15.5**	**13.3**	**12.7**	**38.8**
Astrometric precision	44.1	0.0	5.0	15.5	13.3	0.0	38.8
Focal-plane measurement errors	39.1	0.0	0.0	0.0	6.9	0.0	38.5
Opto-mechanical errors	14.5	0.0	5.0	9.4	8.4	0.0	5.0
Atmospheric refraction errors	7.7	0.0	0.0	0.0	7.7	0.0	0.0
Residual turbulence errors	12.3	0.0	0.0	12.3	0.0	0.0	0.0
Total plate scale error	12.7	0.0	0.0	0.0	0.0	12.7	0.0
Contingency	19.7						

[REQ-1-OAD-0845] Differential astrometry systematic one-dimensional RMS position uncertainties shall be less than 10 µas.

3.12.2 AO PHOTOMETRY ERROR BUDGET

The TMT AO Photometry Error Budget Spreadsheet (RD62) allocates the AO differential photometry components for point sources with SNR=100 and not fainter than magnitude 24 (Vega) in J band over a 34x34 arcsec field of view. It is assumed that at least one reference star is in each image and that the image is moderately crowded as defined in the TMTAO Photometry Error Budget Description Report (RD63). The error budget applies to imaging of point sources and assumes photometric conditions. RD63 defines all the error terms, assumptions and their rationales. Errors are reported as percentages.

This error budget applies to AO photometry only, and the values in it are specific to the NFIRAOS/IRIS combination. Absolute photometry here is to be understood as measuring the flux in absolute on-sky units. Measurements are still taken relative to one or several reference stars. The OAD error budget includes all error terms, unlike the SRD which specifies the requirement to apply only to errors due to PSF residual spatial variability.

Table 3-22: Differential and Absolute AO Photometry Error Budget Allocations

	[REQ-1-OAD-0891]	[REQ-1-OAD-0892]	[REQ-1-OAD-0893]	[REQ-1-OAD-0899]	[REQ-1-OAD-0989]	[REQ-1-OAD-0855]		
	Differential Photometry Total Error (%)	Absolute Photometry Total Error(%)	M3 (%)	NFIRAOS (%)	IRIS (%)	AOESW.PSF-R (%)	Fundamental (%)	Total Calibration Star Error (%)
Photometry Errors (%)	**2.00**	**5.00**	**0.17**	**0.44**	**0.30**	**1.41**	**1.10**	**1.88**
Astronomical source errors	0.46	0.65	0.00	0.00	0.00	0.00	0.46	0.46
Detector errors	0.33	0.47	0.00	0.30	0.14	0.00	0.00	0.33
Residual atmospheric turbulence errors	0.25	0.35	0.00	0.25	0.00	0.00	0.00	0.25
Atmospheric refraction errors	0.10	0.14	0.00	0.00	0.10	0.00	0.00	0.10
Optomechanical errors	0.36	0.48	0.17	0.20	0.24	0.00	0.00	0.36
Data reduction errors	1.73	2.45	0.00	0.00	0.00	1.41	1.00	1.73
Margin	0.69	4.24						

3.13 TMT DATA STORAGE BUDGET

The Data Rates and Storage document (RD68) defines requirements to ensure that there is sufficient disk space available to store key engineering and science data.

Table 3-23: TMT DMS Data Storage Requirements

Requirement ID	Subsystem	TMT Science DMS (GB/night) (c) (d)	US-ELTP Science Archive (GB/night) (c) (d) (e)	TMT Engineering DMS (MB/night) (a) (b) (d)	Notes
[REQ-1-OAD-9600]	**Total TMT DMS Data Storage (Early Operations)** (Total Data Storage calculation was made with the more demanding case scenario First Light as defined on Science Yearly Rates Sheet)	1158	4659	481600	(a) Included under TCS (b) Included under SUM.FMCS (c) includes raw and process data (d) includes ancillary files (e) includes raw readouts data
[REQ-1-OAD-9601]	**Total TMT DMS Data Storage (Steady-State)** (Total Data Storage calculation was made with steady state operations instrument usage as defined Science Yearly Rates Sheet)	628	4154	514778	
	Facilities				
[REQ-1-OAD-9602]	Enclosure (ENC)			(a)	
[REQ-1-OAD-9603]	Summit Facilities (SUM, FMCS)(b)			7.0	
N/A	Sea Level Facilities (SLF)			N/A	
	Telescope				
[REQ-1-OAD-9604]	Telescope Structure (STR)			(a)	
[REQ-1-OAD-9605]	M1 Optics System (M1S)			(a)	
[REQ-1-OAD-9606]	M2 Optics System (M2S)			(a)	
[REQ-1-OAD-9607]	M3 Optics System (M3S)			(a)	
[REQ-1-OAD-9608]	Optical Cleaning Systems (CLN)			1.0	
[REQ-1-OAD-9609]	M1 Coating System (M1 COAT)			(b)	
[REQ-1-OAD-9610]	M2/M3 Coating System (M2/M3 COAT)			(b)	
[REQ-1-OAD-9611]	Test Instruments (TINS)			2.0	
[REQ-1-OAD-9612]	Optics Handling Equipment (HNDL)			N/A	
[REQ-1-OAD-9613]	Telescope Control System (TCS)(a)			3545.0	
[REQ-1-OAD-9614]	M1 Control System (M1CS)			14781.6	
[REQ-1-OAD-9615]	Alignment and Phasing System (APS)			136420.1	
[REQ-1-OAD-9616]	Observatory Safety System (OSS)			329.6	
[REQ-1-OAD-9617]	Engineering Sensors (ESEN)			78625.8	
	Instrumentation				
N/A	First Light Instruments and AO system				
[REQ-1-OAD-9618]	Narrow Field Near Infrared AO System (NFIRAOS)			64192.9	
[REQ-1-OAD-9619]	Laser Guide Star Facility (LGSF)			1406.3	
[REQ-1-OAD-9620]	AO Executive Software (AOESW)	142.00	142.00	59.6	
[REQ-1-OAD-9621]	InfraRed Imaging Spectrometer (IRIS)	917.95	4565.47	5529.6	
[REQ-1-OAD-9622]	Multi-Object Diffraction Limited High Resolution Spectrograph (MODHIS)	118.11	1936.65	1363.5	
[REQ-1-OAD-9623]	Wide Field Optical Spectrometer (WFOS)	32.33	32.33	5529.6	
N/A	First Decade Instruments and AO system			0.0	
N/A	PSI	61.95	2234.55	5529.6	
N/A	NIRES-R	61.95	2234.55	5529.6	
N/A	IRMOS	123.91	4469.11	5529.6	
N/A	HROS	15.73	15.73	5529.6	
N/A	MICHI	1.06	30376.06	5529.6	
[REQ-1-OAD-9628]	Refrigerant Cooling System (REFR)			1.0	
[REQ-1-OAD-9629]	Cryogenic Cooling System (CRYO)			1.0	
	Operations				
[REQ-1-OAD-9631]	Data Management System (DMS)	1.00	1.00	0.5	
[REQ-1-OAD-9632]	Executive Software (ESW)	1.00	1.00	0.5	
[REQ-1-OAD-9631]	Communication and Information Systems (CIS)				
[REQ-1-OAD-9632]	Common Software (CSW)				
[REQ-1-OAD-9631]	Science Operations Support Systems (SOSS)	1.00	1.00	0.5	**TBC as pending Noirlab updates
[REQ-1-OAD-9632]	Data Processing System (DPS)			0.1	**TBC as pending Noirlab updates
[REQ-1-OAD-9631]	Site Conditions Monitoring System (SCMS)	115.29	115.29	77629.4	

3.14 End-to-End Science Exposure Transfer Latency Budget

The TMT End-to-End Science Exposure Transfer Latency Budget (RD69) in Table 3-24 establishes latency requirements to ensure files are available for PIs in the US-ELTP Science Archive in a timely manner.

Table 3-24: TMT End-to-End Science Exposure Transfer Latency Budget

TMT ID	End-to-End Science Exposure Transfer Latency Budget	ms (99%)	Notes
[REQ-1-OAD-9705]	Instrument to US-ELTP File Available Latency	300,000	Maximum time for a file to be available for access in the US-ELTP Archive, starting from when the exposure ends.
[REQ-1-OAD-9706]	Instrument to Summit File Available Latency	2,300	Maximum time for a file to be available for access in the DMS Summit Storage, starting from when the exposure ends.
	Instrument Image Construction to DMS Transfer Start	1,300	Maximum time an instrument can take to prepare an exposure and submit it to the DMS. Starts when exposure ends and ends when transfer of file to DMS is started.
	Instrument to DMS Copy Latency	750	Maximum time to transfer the file from instrument to DMS (network latency), based on a 650 MB file.
	DMS Summit File Availability Latency	150	Maximum time DMS can take to make the FITS file available for retrieval after the transfer from an instrument is complete.
	Margin	100	
[REQ-1-OAD-9707]	Summit to HQ File Available Latency	10,000	Maximum time for an exposure to be available in the HQ Storage, starting from when it is available in the Summit Storage. This value is largely dependent on the polling period, network speed between summit and headquarters, and degradation of network performance because network between summit and HQ is shared with all observatories.
	DMS Headquarters New File Polling Period	5,000	Maximum time between requests for new files at the Summit Storage from HQ DMS.
	Summit File Access Time	100	Maximum time for DMS to locate a file in Summit Storage and start transfer, starting from when the request is received.
	CIS Summit to HQ Transfer Latency	1,000	Maximum time to transfer the file from TMT Summit to HQ (network latency), based on a 650 MB file. Includes network degradation due to shared network between Summit and HQ.
	DMS Ingest Exposure at Headquarters	750	Maximum time DMS can take to make the FITS file available for retrieval after the transfer from the Summit is complete.
	Margin	3150	
[REQ-1-OAD-9708]	HQ to US-ELTP File Available Latency	250,400	Maximum time for an exposure to be available in the US-ELTP Archive, starting from when it is available in the HQ Storage. Largely dependent on polling period and network speed to TMT. Assumes CIS must determine/fund network connections to archive with USELTP. We cannot assume the commercial internet to transfer our large amount of data.
	US-ELTP New File Polling Period	240,000	Recommended time between requests for new files at the HQ Storage from US-ELTP.
	HQ File External Access Time	500	Maximum time for DMS to authenticate a request, locate a file in HQ Storage, and start transfer, starting from when the request is received.
	DMS HQ to USELTP Transfer Latency	2,000	Maximum time to transfer the file from HQ to US-ELTP (network latency), based on a 650 MB file.
	US-ELTP Time to Ingest File	1,000	Maximum time US-ELTP can take to make the FITS file available for retrieval after the transfer from the HQ is complete.
	Margin	6,900	
	Margin	37,300	

4 SYSTEM SPECIFICATION

4.1 GENERAL SYSTEM REQUIREMENTS

4.1.1 ENVIRONMENTAL AND LIFETIME REQUIREMENTS

The following definitions are used in this section to define the level of performance that must be achieved when equipment is exposed to the listed environmental conditions:

- Observing Performance Conditions- sub-systems must meet all requirements necessary whilst observing (in either seeing limited or adaptive optics mode) over this range of conditions. These include functional requirements, performance requirements and lifetime requirements.
- Facility Performance - the summit facilities, enclosure and any sub-systems that are used for servicing or maintenance must perform these functions and meet all related requirements over this range of conditions. These include functional requirements, performance requirements and lifetime requirements.
- Component Functional Conditions - any mechanical, electrical, or electromechanical components of a sub-system must be capable of functioning over this range of conditions.
- Survival Conditions - All sub-systems must survive repeated exposure to these conditions without damage or degradation, or need for servicing, part replacement, alignment etc. Equipment may be powered on or powered off under these conditions, but does not need to operate. Equipment must be able to resume operations after a 6-hour inspection period and without replacing any parts.

4.1.1.1 ENVIRONMENTAL REQUIREMENTS APPLYING TO ALL SUB-SYSTEMS

4.1.1.1.1 PRESSURE

[REQ-1-OAD-1201] All sub-systems shall meet their Observing and Facility Performance requirements over the ambient air pressure range 600-618hPa.

[REQ-1-OAD-1202] All sub-systems shall meet their Component Functional requirements over the ambient air pressure range 600-1015hPa.

[REQ-1-OAD-1203] All sub-systems shall meet their Survival requirements over the ambient air pressure range 590 -1025hPa.

[REQ-1-OAD-4440] All sub-systems shall meet their Survival requirements when in an unpowered state.

Discussion: Survival Conditions are detailed throughout Section 4.1.1.

4.1.1.1.2 OZONE

[REQ-1-OAD-1204] All sub-systems shall meet their Observing and Facility Performance requirements when equipment is continually exposed to ozone concentrations of 50 parts per billion.

4.1.1.2 ENVIRONMENTAL CONDITIONS FOR ENCLOSURE AND OTHER UNPROTECTED EQUIPMENT

"Unprotected equipment" refers to any equipment (such as the Summit Facilities, the Site Conditions Monitoring System, and the Engineering Sensors) that are not protected from external environmental conditions when the enclosure is closed. Some parts of the enclosure may be exempt from the requirements in this section if it can be shown that they are protected or insulated from the outside conditions. Equipment in this category will be subject to the requirements in section 'Environmental Conditions for Equipment Inside Enclosure'.

4.1.1.2.1 TEMPERATURE

[REQ-1-OAD-1206] The enclosure and unprotected equipment shall meet its observing performance requirements over the range -5 to +9°C.

[REQ-1-OAD-1207] The enclosure and unprotected equipment shall meet its facility performance requirements over the range -10 to +13°C.

[REQ-1-OAD-1208] The enclosure and unprotected equipment shall meet its component functional requirements over the range -13 to +25°C.

[REQ-1-OAD-1209] The enclosure and unprotected equipment shall meet its survival requirements over the range -16 to +30°C.

4.1.1.2.2 Temperature Gradients

[REQ-1-OAD-1211] The enclosure and unprotected equipment shall meet Observing Performance, Facility Performance, and Component Functional requirements when the absolute temperature variation is within the 99.9% values defined in Table: Temporal Temperature Gradients Inside and Outside Enclosure.

[REQ-1-OAD-1212] The enclosure and unprotected equipment shall meet Survival requirements at temperature gradients up to the maximum level stated in Table: Temporal Temperature Gradients Inside and Outside Enclosure.

4.1.1.2.3 Humidity

[REQ-1-OAD-1213] The enclosure and unprotected equipment shall meet its Observing Performance requirements when relative humidity is between 0 and 95% at temperatures between -5 to +9°C.

[REQ-1-OAD-1214] The enclosure and unprotected equipment shall meet its Facility Performance, Component Functional, and Survival requirements over the relative humidity range 0-100% (condensing conditions) at temperatures between -10 and +13°C.

4.1.1.2.4 Wind Speed

[REQ-1-OAD-1216] The enclosure and unprotected equipment shall meet its Observing Performance requirements at wind speeds up to 18m/s (1 minute average velocity at 20m elevation).

[REQ-1-OAD-1217] The enclosure and unprotected equipment shall meet its Facility Performance requirements at wind speeds up to 30m/s (3s gust at 20m elevation).

[REQ-1-OAD-1218] The enclosure and unprotected equipment shall meet its Survival requirements at external wind speeds up to 83.7m/s (3s gust at 20m elevation).

Discussion: For equipment not covered by (RD60: ASCE 7-98), wind speeds should be considered using the air density resulting from the lowest temperature and lowest pressure for the conditions.

4.1.1.2.5 Rainfall

[REQ-1-OAD-1219] The enclosure and unprotected equipment shall meet its Facility Performance and Survival requirements in the presence of external rainfall up to 0.04m/hour.

[REQ-1-OAD-1273] The summit facility and enclosure shall provide protection that allows the observatory to meet its facility performance requirements in the presence of snow, hail, and rainfall.

4.1.1.2.6 Lightning

[REQ-1-OAD-1221] The enclosure and summit facilities shall provide lightning protection per NFPA 780.

4.1.1.2.7 Snow and Ice

4.1.1.2.7.1 Snow and Ice Operational Requirements

[REQ-1-OAD-1222] The Summit Facilities and Enclosure shall be fully operational with up to 150 kg/m2 snow and ice load (vertical projection) after removal of ice and snow from critical areas.

4.1.1.2.7.2 Snow and Ice Survival Requirements

[REQ-1-OAD-1223] The Summit Facilities and Enclosure shall be able to support snow loads up to 150kg/m2.

[REQ-1-OAD-1224] The Summit Facilities and Enclosure shall be able to support ice loads up to 68kg/m^2.

Discussion: The snow and ice loads can act concurrently.

4.1.1.2.8 Dust

[REQ-1-OAD-1226] The Enclosure and unprotected equipment shall meet its Observing and Facility Performance requirements when equipment is continually exposed to dust concentrations as defined in Table: Median dust levels at Mauna Kea site below REQ-1-OAD-1241.

4.1.1.3 Environmental Conditions for Equipment Inside Enclosure

Discussion: "Equipment inside the enclosure" refers to any sub-systems inside the enclosure that are protected from external environmental conditions.

4.1.1.3.1 Temperature

[REQ-1-OAD-1227] Any equipment inside the enclosure shall meet its Observing Performance requirements over a temperature range from -5°C to +9°C.

[REQ-1-OAD-1228] Any equipment inside the enclosure shall meet its Facility Performance requirements over a temperature range from -10°C to +13°C.

[REQ-1-OAD-1229] Any equipment inside the enclosure shall meet its Component Functional requirements over a temperature range from -13°C to +25°C.

[REQ-1-OAD-1231] Any equipment inside the enclosure shall meet its Survival Requirements over a temperature range from -16°C to +30°C.

4.1.1.3.2 Temperature Gradients (Short Term)

[REQ-1-OAD-1232] Any equipment inside the enclosure shall meet Observing Performance, Facility Performance, and Component Functional requirements when the absolute temperature variation is within the 99.9% night-time values defined in Table 4-1: Temporal Temperature Gradients Inside and Outside Enclosure.

[REQ-1-OAD-1233] Any equipment inside the enclosure shall meet Survival requirements at temperature gradients up to the 99.9% values for all data as stated in Table 4-1: Temporal Temperature Gradients Inside and Outside Enclosure.

Table 4-1: Temporal Temperature Gradients Inside and Outside Enclosure

Integration time (minutes)	99.9% night-time (°C/h)	99.9% all data (°C/h)
Instantaneous (Thermal Shock)	N/A	17
1 (2-min sampling)	26.8	52.1
4	15.6	23.6
8	9.5	11.4
16	5.7	6.3
32	3.4	3.8
60	2.2	2.6

Discussion: These temperature gradients apply to the air temperature and not any presumed structure or equipment rates of change.

4.1.1.3.3 Temperature Variation (Long Term)

[REQ-1-OAD-1234] The TMT Optics systems (M1, M2, M3, M1CS) shall meet their requirements for overall image quality at a temperature difference of 2°C from the most recent APS alignment.

Discussion: APS alignment can take place at any temperature within the operational temperature range (see requirement REQ-1-OAD-1227). In the two weeks following an APS alignment, the mean nighttime temperature is expected to be about 1.6°C different from the temperature at which the alignment is performed.

4.1.1.3.4 Wind Speed

[REQ-1-OAD-1237] The sub-systems inside the enclosure shall meet their Observing Performance, Facility Performance, and Survival requirements under the conditions defined in Table 4-2: Wind speeds inside enclosure.

Table 4-2: Wind speeds inside enclosure

Environmental Conditions	Observatory Floor (m/s)	Nasmyth Platform, M1, M3 (m/s)	Top end, M2 (m/s)
Observing Performance (nominal)	N/A	2.6	1.3
Observing Performance (peak)	7.2	8.2	9.7
Facility Performance	15	10	20.5
Survival (long duration, <10 min exposure)	15	10	20.5
Survival (short duration, <30s exposure)	18	12	24.6

Discussion: The above values are maximum values taken from each of the three locations under corresponding external wind speeds. The model used to generate them did not include detailed features such as the M1 mirror cell structure and therefore local values in protected areas may be significantly reduced. If lower requirements are used, these must be agreed on a case by case basis.

Discussion: Wind speeds should be considered using the air density resulting from the lowest temperature and lowest pressure for the conditions.

4.1.1.3.5 Humidity

[REQ-1-OAD-1238] The sub-systems inside the enclosure shall meet their Observing and Facility Performance requirements when relative humidity is between 0 and 95% at their respective temperature ranges.

[REQ-1-OAD-1242] The sub-systems inside the enclosure shall meet their Component Functional requirements when relative humidity is between 0 and 95% at temperatures between -10 to +13°C.

Discussion: The temperature range of -10 to +13°C is used because humidity data from MK shows that 100% humidity conditions occur between -10 and +10°C, and an additional 3° margin has been included in the upper limit. Relative humidity of 0-95% over the entire component functional temperature range is not required as component functional conditions relate to a lab environment, where we wouldn't expect to see high humidity levels.

[REQ-1-OAD-1239] The sub-systems inside the enclosure shall meet their Survival requirements when humidity is between 0 and 100% (condensing conditions) at temperatures between -10 to +13°C.

Discussion: Compliance with the humidity requirements can be demonstrated in one of several ways:

- *Dedicated test based on the above conditions*

- *Selection of appropriate rated connectors and electrical enclosures (minimum IP moisture resistance rating of 4 or NEMA enclosures type 3)*
- *Inspection of designs and materials used in designs*

Discussion: The temperature range of -10 to +13°C is used because humidity data from MK shows that 100% humidity conditions occur between - 10 and +10°C, and an additional 3° margin has been included in the upper limit.

4.1.1.3.6 DUST

[REQ-1-OAD-1241] The sub-systems inside the enclosure shall meet Observing and Facility Performance requirements when equipment is continually exposed to dust concentrations as defined in Table 4-3: Median dust levels at Mauna Kea Site.

Table 4-3: Median dust levels at Mauna Kea site

Particle Sizes (µm)	0.3-0.5	0.5-1.0	1.0 – 2.0	2.0 – 5.0	>5.0	Total number > 0.5um
No. of particles/foot^3	26×10^3	4.5×10^3	912	417	54	5.8×10^3
No. of particles/m^3	918×10^3	159×10^3	32×10^3	14.7×10^3	1.9×10^3	207×10^3

4.1.1.4 ENVIRONMENTAL REQUIREMENTS INSIDE UTILITY ROOM

[REQ-1-OAD-1251] The Summit Facilities Utility Room temperature shall be maintained between 0°C and 25°C at any time that equipment inside it is expected to operate.

[REQ-1-OAD-1252] The Summit Facilities Utility Room relative humidity shall be maintained between 0 and 95% at any time that equipment inside it is expected to operate.

[REQ-1-OAD-1253] All equipment located in the Summit Facilities Utility Room shall survive exposure to temperatures in the range 0-35°C. In the range 0 to -16°C, equipment can be assumed to be non-operational, in the range 0-35°C the equipment may be operational.

[REQ-1-OAD-1254] All equipment in the Summit Facilities Utility Room shall survive exposure to relative humidity levels up to 100% (condensing conditions). Equipment may be assumed to be non-operational at relative humidity levels >95%.

4.1.1.5 ENVIRONMENTAL REQUIREMENTS INSIDE COMPUTER ROOM

[REQ-1-OAD-1261] The Summit Facilities Computer Room temperature shall be maintained between 15-22°C at all times that equipment inside it is expected to operate.

[REQ-1-OAD-1262] The Summit Facilities Computer Room temperature rate of change shall not exceed 20°C/hour at any time that equipment within it is expected to operate.

[REQ-1-OAD-1263] The Summit Facilities Computer Room humidity level shall be maintained between 20-80% RH with a maximum dew point of 17°C at all times that equipment inside it is expected to operate.

Discussion: Requirements REQ-1-OAD-1261 to 1263 define how well the conditions inside the computer room have to be controlled at any time that equipment located there is expected to be operational.

[REQ-1-OAD-1264] Computer Room equipment, in its power off state, shall survive exposure to temperatures in the range -16 to 45°C.

[REQ-1-OAD-1266] Computer Room equipment, in its power off state, shall survive exposure to humidity in the range 8-80% RH with a maximum dew point of 27°C.

Discussion: Requirements REQ-1-OAD-1264 and 1266 define the conditions that equipment must sustain in the event that power is lost to the observatory and the air conditioning systems for the computer room are inoperable.

4.1.1.6 Duty Cycle

[REQ-1-OAD-1271] The observatory shall be designed to support the following duty cycle over its 50-year lifespan:

- 20 slewing moves per night
- 20 slewing moves per day
- Average azimuth slewing distance: 60°
- Average elevation slewing distance: 15°
- Average nighttime zenith angle: 32.5°

4.1.1.7 Electromagnetic Interference/Electromagnetic Compatibility

[REQ-1-OAD-1276] TMT subsystems shall not emit, nor be susceptible to, electromagnetic radiation or electromagnetic conduction at any frequency that significantly interferes with the operation of itself, any other TMT subsystems, or any other astronomical facilities.

Discussion: This requirement may be verified-by-design if the design follows the EMI/EMC Design Guidelines (RD61).

[REQ-1-OAD-1278] To prevent electromagnetic interference with the operation of the M1CS edge sensors, subsystems/equipment with drive system motors and variable speed motor drives operating at nighttime within the enclosure shall not operate at frequencies between 35-100 kHz, and use fixed frequency chopping if such equipment operates at frequencies below 35 kHz.

4.1.2 Other General Requirements

Discussion: This section contains requirements that apply to multiple sub-systems.

[REQ-1-OAD-1272] Any equipment with exposed surfaces that are expected to be below the dew point in normal operation shall be equipped with drip trays, drains or other devices to prevent condensation forming on these surfaces dripping onto other equipment.

[REQ-1-OAD-1274] During night time, the TMT Observatory shall not generate detectable light pollution at visible or near-infrared wavelengths (except when the laser is in use at 589nm) during scientific observations.

Discussion: i.e., no LEDs, lasers or other light sources are allowed unless sealed inside light-tight enclosures, or remotely controlled.

[REQ-1-OAD-1100] The system shall operate with segments missing from the primary mirror or segments removed from the overall control loop.

Discussion: [REQ-1-OAD-2110] defines the requirement for positioning segments removed from overall control loop.

[REQ-1-OAD-1106] All fasteners and other hardware that could fall and damage M1 or other optics during servicing or removal/installation activities shall be designed to be captive.

4.2 Telescope

[REQ-1-OAD-1001] TMT Observatory Telescope Subsystems defined in OAD Section 2.2.1.2 shall operate and meet all requirements for at least 50 years with preventive maintenance.

Discussion: Preventive maintenance means servicing, repairing, and replacing components and subsystems based on their expected lifetime, as opposed to their failure.

4.2.1 Optical Design

Discussion: The optical design is documented in (AD17).

[REQ-1-OAD-1000] The telescope optical design shall be a Ritchey Chrétien (R-C) configuration (AD17).

[REQ-1-OAD-1005] The entrance pupil of the system shall be the primary mirror with circumscribing circle at least 30 m diameter.

[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 nominal back focal distance of the system shall be 16.5 m with a tolerance of +/-0.02m.

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 by a baffle around M2 and M3 and in the instrument designs. The size of the M2 and M3 baffles shall, at minimum, equal the size of a beam from the telescope exit pupil to a 20 arcmin diameter field-of-view at an instrument located on the elevation axis.

[REQ-1-OAD-1027] Any structures that cause blockage of the telescope pupil shall be designed to minimize scattered or glancing incidence light falling within the field of view of the telescope.

[REQ-1-OAD-1030] The TMT Observatory entrance pupil shall have a maximum of 4% obscuration due to the shadow of the secondary mirror and its support structure and follow the pattern shown in (AD41).

Table 4-4: Summary of the optical design

Requirement ID	Parameter	Nominal Value	Tolerance
[REQ-1-OAD-1050]	Final focal length and plate scale[D]	450 m	+/-2.6m
		0.458366 arcsec/mm	+/-0.0026arcsec/mm
[REQ-1-OAD-1052]	Primary mirror vertex radius of curvature[P]	+60.000000 m	+/-0.032m
[REQ-1-OAD-1054]	Primary mirror conic constant (K_1)[P]	-1.00095348	0
[REQ-1-OAD-1056]	Primary to secondary mirror separation (d)[P]	27.0937500 m	+/-0.026m
[REQ-1-OAD-1058]	Secondary mirror vertex radius of curvature (k_2)[P]	- 6.22767857 m	+/-0.021m
[REQ-1-OAD-1060]	Secondary mirror conic constant[P]	-1.31822813	0.054dk_2+/-0.00047
[REQ-1-OAD-1062]	Tertiary mirror curvature (1/radius of curvature)[P]	$0 m^{-1}$	+/-$34x10^{-6} m^{-1}$
REQ-1-OAD-1064]	Medial Field curvature (concave towards the sky)[P]	3.00923	+/-0.01m
[REQ-1-OAD-1066]	Unobstructed field of view delivered to foci	20 arcmin	N/A
[REQ-1-OAD-1068]	Unvignetted field of view (FOV) based on clear apertures of M2 and M3	15 arcmin	N/A

Notes: P indicates that this is a primary dimension and that tolerances apply to the fabricated parts. D indicates a derived parameter and that the value may fall in this range depending on the as manufactured primary dimensions.

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.

*Discussion: *No tolerance is specified for the M1 conic constant as it should be used as a basic dimension in the individual segment prescriptions **The M2 conic constant tolerance depends on the achieved tolerance on the M2 radius of curvature, dk_2. ***Clear apertures should maintain 15 arcminutes unvignetted field of view under all tolerance conditions.*

4.2.2 AEROTHERMAL CONSIDERATIONS

The transverse cross sectional area of the telescope above a plane perpendicular to the optical axis and 14.4m above the elevation axis are less than the values defined in the table below. The allocations to M2 and LGSF apply from any direction perpendicular to the optical axis. The STR allocations are defined relative to the optical axis but from the +X and +Y ECRS directions.

Table 4-5: Maximum Allowable Cross Sectional Area of Telescope Top End

<table>
<tr><th>Requirement ID</th><th>Sub-System</th><th colspan="2">Maximum Transverse Cross Sectrional Area (m²)</th></tr>
<tr><td>[REQ-1-OAD-1090]</td><td>M2S</td><td colspan="2">4.0</td></tr>
<tr><td>[REQ-1-OAD-1092]</td><td>LGSF Top End</td><td colspan="2">4.0</td></tr>
<tr><td>[REQ-1-OAD-1094]</td><td>LGSF Beam Transfer Tube</td><td colspan="2">6.0</td></tr>
<tr><td rowspan="2">[REQ-1-OAD-1096]</td><td rowspan="2">Telescope Structure</td><td>Area projected onto ECRS XZ plane</td><td>Area projected onto ECRS YZ plane</td></tr>
<tr><td>45.0</td><td>70.0</td></tr>
</table>

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.

4.2.3 Telescope Structure

4.2.3.1 General

The telescope structure provides 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-1220] It shall be possible to position the telescope elevation axis at any zenith angle between 0° and 90°, with an observing range between 1° and 65°.

Discussion: The telescope needs to maintain horizon and zenith pointing position for prolonged time periods and:

- *The telescope mount axes intersect at a single point.*
- *The telescope elevation axis is above the primary mirror.*
- *The intersection of the elevation and azimuth axes are coincident with the center of the enclosure radius.*
- *The observatory floor is at the level of the external grade.*

[REQ-1-OAD-1245] At all elevation and azimuth angles, no point on the telescope elevation and azimuth structure shall extend beyond the volume defined in drawing TMT.TEL.STR-ENV (AD42).

Discussion: The height of:

- *elevation axis above the azimuth journal is 19.5 meters.*
- *elevation axis above the primary mirror vertex is 3.5 meters.*
- *azimuth journal above ground is 3.5 meters.*

A fixed walkway with outside radius not exceeding 20.4m is provided around the perimeter of the telescope pier.

[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 at an azimuth angle of 0 degrees in TCRS coordinates (pointing South).

Discussion: It may be desirable to vary this azimuth position slightly (+/-5 degrees) from one day to the next to avoid causing any degradation to the azimuth track or pier by repeatedly loading exactly the same area for prolonged periods.

[REQ-1-OAD-1282] The external surfaces of the telescope structure shall have an emissivity < 0.4.

Discussion: Note that some surfaces may require different surface properties as a result of stray light analysis.

[REQ-1-OAD-1286] The telescope structure shall provide space, structural support, and access/servicing provisions for the instruments/EE listed in TMT.INS.GTY-0001 (AD98), TMT.INS.GTY-0002 (AD99) and TMT.SE.GTY-0001 (AD100) without violating any space envelopes.

[REQ-1-OAD-1243] The telescope structure shall provide space, structural support, and access/servicing provisions for the M1S as defined in TMT.SEN.GTY-0006 (AD101) without violating any space envelopes.

[REQ-1-OAD-1244] The telescope structure shall provide space, structural support, and access/servicing provisions for the M2S as defined in TMT.SEN.GTY-0006 (AD101) and the M2S electronics as defined in TMT.SEN.GTY-0001 (AD100) without violating any space envelopes.

[REQ-1-OAD-1246] The telescope structure shall provide space, structural support, and access/servicing provisions for the M3S as defined in TMT.SEN.GTY-0006 (AD101) and the M3S electronics as defined in TMT.SEN.GTY-0001 (AD100) without violating any space envelopes.

[REQ-1-OAD-1247] The telescope structure shall provide space, structural support, and access/servicing provisions for the TINS as defined in TMT.SEN.GTY-0006 (AD101) without violating any space envelopes.

[REQ-1-OAD-1248] The telescope structure shall provide space, structural support, and access/servicing provisions for the CRYO as defined in TMT.SEN.GTY-0006 (AD101) without violating any space envelopes.

[REQ-1-OAD-1249] The telescope structure shall provide space, structural support, and access/servicing provisions for the M1CS without violating any space envelopes TMT.SEN.GTY-0001 (AD101).

[REQ-1-OAD-1256] The telescope structure shall provide space, structural support, and access/servicing provisions for the LGSF as defined in TMT.SEN.GTY-0006 (AD101) without violating any space envelopes.

4.2.3.1.1 Seismic Accelerations

[REQ-1-OAD-1284] Under all operating conditions and configurations, the STR shall withstand the representative time series of site-specific seismic accelerations as described in (RD16) such that:

- After a 10-year return period earthquake, the STR can resume normal operations after inspection by the normal operations staff.
- After a 200-year earthquake, the STR can resume normal operations within two weeks after the observatory staff has resumed regular duty.
- After a 1000-year return period earthquake, STR components do not damage the telescope optics or present worse than a marginal hazard to personnel in the event of their failure.

Discussion: A marginal hazard is defined in the ES&H Hazard/Risk Assessment Processes and Guidelines (AD80).

[REQ-1-OAD-1287] Under all operating conditions and configurations, subsystems which are mounted on the telescope structure shall withstand the seismic accelerations defined in 'Table 4-6: Seismic limits for telescope-mounted subsystems' such that:

- After a 10-year return period earthquake, the subsystems can resume normal operations after inspection by the normal operations staff.
- After a 200-year earthquake, the subsystems can resume normal operations within two weeks after the observatory staff has resumed regular duty.
- After a 1000-year return period earthquake, components do not damage the telescope optics or present worse than a marginal hazard to personnel in the event of their failure.

Table 4-6: Seismic Limits on Telescope Structure Mounted Subsystems

Subsystems	Maximum Acceleration (g)		
	10-year return period	200-year return period	1000-year return period
M1 System, LGSF Lasers, and equipment in the mirror cell	0.84	1.8	3.0
M2 System, LGSF Top End Equipment	1.4	3.0	5.0
M3 System	0.84	1.8	3.0
Science Instruments, NFIRAOS, APS, and equipment on the Nasmyth Platform	1.12	2.5	4.0

Discussion: The limits in this table apply to the maximum acceleration at the center of mass of the mounted subsystem, in any direction. If seven or more time histories are analyzed, the maximum acceleration shall be interpreted as the average of the maximum accelerations from all of the seismic time histories from (RD16). The above accelerations are purely seismic accelerations and do not include 1g gravity loads.

Discussion: This requirement is intended to set a general requirement on the telescope structure that can be used for verification of the seismic performance. It is possible that large subsystems may not withstand these upper bounds on acceleration. In those cases, more detailed requirements for specific seismic loading of telescope mounted subsystems will be contained in the appropriate interface control document. The process for specifying and assessing the seismic loading of telescope mounted sub-systems is contained in 'Specification and Analysis of TMT Seismic Requirements' (RD17). Input acceleration time histories are provided by (RD16).

Discussion: A factor of 0.28 is applied to the 1000-year return period accelerations to calculate 10-year return period earthquake accelerations. This factor can also be applied to any time series seismic data resulting from analysis of the 1000-year return period earthquake. The levels of a 1000-year return period earthquake have a 5% probability of being exceeded in a 50-year period. A marginal hazard is defined in the ES&H Hazard/Risk Assessment Processes and Guidelines (AD80).

[REQ-1-OAD-1289] Sub-systems shall meet the respective criteria for 10-, 200-, and 1000-year return period earthquakes over the following temperature ranges:

- 10 year: -16° to +30°C
- 200 year: -5° to +13°C
- 1000 year: -5° to +13°C

[REQ-1-OAD-1291] Derating of seismic loading for 200- or 1000-year return period earthquakes for equipment in temporary configurations whose failure can damage the M1, M2, M3 or present worse than a marginal hazard to personnel shall use the acceleration scaling factors in Table 4-7: Seismic Acceleration Scaling Factors for Temporary Configurations - Personnel/Optics Safety.

Table 4-7: Seismic Acceleration Scaling Factors for Temporary Configurations-Personnel/Optics Safety

Annual Exposure	Total exposure (years)	Acceleration Scaling Factor
1 week	0.959	0.49
2 weeks	1.918	0.6
1 month	4.17	0.76
2 months	8.33	0.94
73 days	10	1

Discussion: This table can only be applied in the absence of more specific seismic loading requirements for particular temporary configurations. When a subsystem team believes that a derating is appropriate, and the duty cycle is not clearly defined in requirements, there should be agreement reached between the TMTPO (including Systems Engineering) and the team. Once agreed, this duty cycle can be carried through the design / analysis documentation and recorded in the verification of the requirement.

Discussion: Where no specific exposure value is provided, the derating for the next highest exposure value must be used. Exposure values larger than the last value in the table must not use any derating.

The derating provided by this requirement is intended as relief for subsystems in temporary configurations and is based on an assumed linearity of the response to seismic input accelerations. Deviations from this theoretical response caused by non-linear seismic dampers in the telescope structure are not considered in this probabilistic derating factor. No requirement is implied on the telescope structure to ensure that this derating factor is achieved.

[REQ-1-OAD-1294] Derating of seismic loading for 200- or 1000-year return period earthquakes for equipment in temporary configurations not covered by [REQ-1-OAD-1291] shall use the acceleration scaling factors in Table 4-8: Seismic Acceleration Scaling Factors for Temporary Configurations.

Table 4-8: Seismic Acceleration Scaling Factors for Temporary Configurations

Annual Exposure	Total exposure (years)	Acceleration Scaling Factor
1 week	0.959	0.3
1 month	4.17	0.47
3 months	12.5	0.65
146 days	20	0.75
6 months	25	0.81
1 year	50	1

Discussion: This table can only be applied in the absence of more specific seismic loading requirements for particular temporary configurations. When a subsystem team believes that a derating is appropriate, and the duty cycle is not clearly defined in requirements, there should be agreement reached between the TMTPO (including Systems Engineering) and the team. Once agreed, this duty cycle can be carried through the design / analysis documentation and recorded in the verification of the requirement.

Discussion: Where no specific exposure value is provided, the derating for the next highest exposure value must be used. Exposure values larger than the last value in the table must not use any derating. The derating provided by this requirement is intended as relief for subsystems in temporary configurations and is based on an assumed linearity of the response to seismic input accelerations. Deviations from this theoretical response caused by non-linear seismic dampers in the telescope structure are not considered in this probabilistic derating factor. No requirement is implied on the telescope structure to ensure that this derating factor is achieved.

4.2.3.2 TELESCOPE AZIMUTH STRUCTURE

[REQ-1-OAD-1285] The telescope azimuth axis shall operate over an angle of 500 degrees without unwrapping.

Discussion: This requirement is intended to set the telescope motion range as well as minimum requirements on the range of cable wraps etc.

[REQ-1-OAD-1288] The azimuth range shall be -330° to +170° relative to the TCRS Coordinate System.

Discussion: The definition of Azimuth angle is given in Table 6-1: Coordinate systems for the ideal, undisturbed telescope. The center of the azimuth rotation range is oriented with the telescope facing 10 degrees south of east, which is at an azimuth angle of -80 degrees in the TCRS Coordinate System.

[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-1297] A man lift shall be mounted on the azimuth structure to enable personnel to access to the M3 mirror during M3 removal or installation (with the telescope horizon pointing).

4.2.3.3 TELESCOPE ELEVATION STRUCTURE

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

[REQ-1-OAD-1314] The design of the telescope elevation structure shall allow the M3 system to be removed from the telescope using the enclosure shutter mounted hoist (as defined in [REQ-1-OAD-6216] when the telescope is in a horizon pointing position.

Discussion: The maximum deflections of the interface planes between the telescope and the M2S and LGSF laser launch telescope are not to exceed the values given in 'Table 4-9: Maximum allowable deflection of the telescope top end". These limits apply at any observing temperature combined with any elevation angle between 0 and 65º.

Table 4-9: Maximum allowable deflection of the telescope top end

Requirement ID	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 about M2CRS x axis	+/-2.5mrad
[REQ-1-OAD-1326]	Tile relative to the M1 optical axis about the M2CRS Y axis	+/-0.5mrad
[REQ-1-OAD-1324]	Translation perpendicular to the M1 optical axis	+/-15mm

4.2.3.4 TELESCOPE PIER

The telescope pier structure supports all load combinations of the telescope and other components supported by the telescope under all operating conditions. The telescope pier design incorporates vibration mitigation to minimize the generation and transmission of vibrations to the telescope, instruments, adaptive optics, alignment & phasing, and calibration subsystems (as shown in Table 3-14).

[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.

[REQ-1-OAD-1336] A section of the fixed walkway extending approximately 45 degrees clockwise from the centre of the main entrance to the fixed enclosure shall be designed to be removable.

Discussion: A removable section of walkway may facilitate the transfer of large items into the enclosure (AD97).

4.2.3.5 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-1345] The cable wraps shall accommodate the distribution of all utilities, VTCW, HBS, power and grounding, CIS, CRYO, REFR, lighting, fire alarm, FCA, and safety network to the telescope structure as defined in (AD96).

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

[REQ-1-OAD-1350] Each cable wrap assembly (Azimuth turning, Azimuth hanging, Elevation +X and Elevation -X) shall include spare capacity to carry an additional 25% of the total number of lines selected for that wrap, including at least one additional line of any type planned for that particular wrap.

[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-1365] The utilities and cables running through the cable wrap system, shall not be damaged from failures of either the cable wrap and 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.

4.2.3.6 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 4-1: Bound on mount control torque rejection with respect to open-loop' below.

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.*

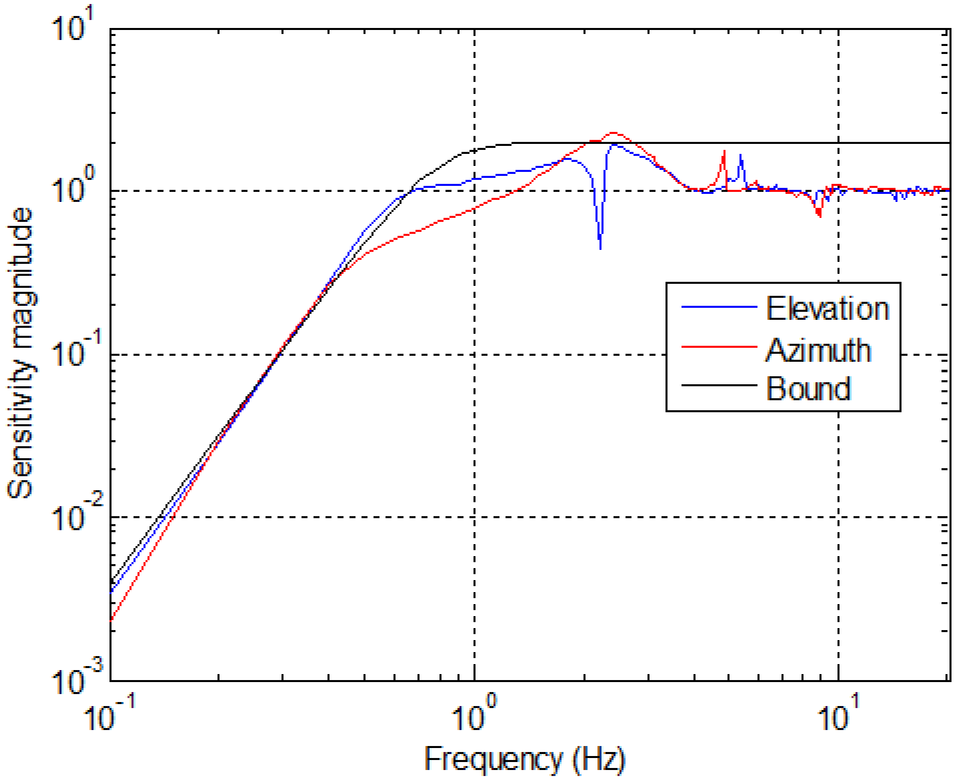

Figure 4-1: Bound on mount control torque rejection with respect to open-loop. The mount control rejection achieved with the current design is shown for comparison.

4.2.3.6.1 Telescope Azimuth Axis Slewing

[REQ-1-OAD-1376] The telescope shall be capable of making all azimuth axis moves rapidly, such that they can be completed, including smooth ramping profiles and settling time, faster than an equivalent move with a trapezoidal velocity profile with acceleration and deceleration rate of 0.13 degrees/s^2 and a maximum velocity of 2.5 degrees/sec.

Discussion: This requirement is in addition to the short move requirements. It does not imply that a trapezoidal velocity profile must be used, and is not intended to prescribe actual design accelerations or maximum velocities.

[REQ-1-OAD-1377] The maximum slewing rate of the telescope azimuth axis shall not exceed 2.5 degrees/sec.

4.2.3.6.2 Telescope Elevation Axis Slewing

[REQ-1-OAD-1378] The telescope shall be capable of making all elevation axis moves rapidly, such that they can be completed, including smooth ramping profiles and settling time, faster than an equivalent move with a trapezoidal velocity profile with acceleration and deceleration rate of 0.1 degrees/s^2 and a maximum velocity of 1 degrees/sec.

Discussion: This requirement is in addition to the short move requirements. It does not imply that a trapezoidal velocity profile must be used, and is not intended to prescribe actual design accelerations or maximum velocities.

[REQ-1-OAD-1379] The maximum slewing rate of the telescope elevation axis shall not exceed 2.0 degrees/sec.

4.2.3.6.3 Telescope Short Move Time & Accuracy for Seeing Limited (SL) & AO

4.2.3.6.3.1 Accuracy Allocation

During telescope moves including AO and seeing-limited guider offsets, nods and dithers, the telescope accuracy shall be partitioned to subsystems as per the following table. The seeing-limited requirements are intended to support meeting the AO guider offset accuracy requirements. Assumption: M3 does not have to move for offsets of less that 10 arc-seconds on the sky, therefore the allocation is zero.

Table 4-10: Sub-allocation of accuracy requirements for Seeing Limited Acquisition and Guider Offsets

Requirement ID	Move Distance	Mode	Telescope Accuracy (arcsec RMS)	M3 Allocation (arcsec RMS)	STR Azimuth Allocation (arcsec RMS)	STR Elevation Allocation (arcsec RMS)
[REQ-1-OAD-1113]	< 10 arcseconds	Guider	0.05	0.0 (0% in RSS)	0.041 (2/3 in RSS)	0.029 (1/3 in RSS)
[REQ-1-OAD-1101]	>= 10, <=30 arcseconds	Guider	0.05	0.035 (50% in RSS)	0.027 (30% in RSS)	0.022 (20% in RSS)
[REQ-1-OAD-1099]	> 30, <=300 arcseconds	Guider	0.05	0.035 (50% in RSS)	0.027 (30% in RSS)	0.022 (20% in RSS)
[REQ-1-OAD-1114]	Up to 0.1 degree	Offset (no Guider)	0.5	0.354 (1/2 in RSS)	0.289 (1/3 in RSS)	0.204 (1/6 in RSS)
[REQ-1-OAD-1103]	Up to 1.0 degree	Offset (no Guider)	0.5	0.354 (1/2 in RSS)	0.289 (1/3 in RSS)	0.204 (1/6 in RSS)

Discussion: The following requirements are for AO guider offsets. Assumption: Motion control at the diffraction limit will be achieved by use of the AO tip-tilt optics and the AO wavefront sensor.

[REQ-1-OAD-1104] AO guider offsets of up to 30 arcseconds on the sky shall be accurate to 0.002 arcseconds RMS.

[REQ-1-OAD-1112] The TCS shall not send move commands to the M3 mirror during offsets of 10 arc-seconds or less on the sky.

4.2.3.6.3.2 Time to Move

The following requirements define time and accuracy for telescope seeing limited (SL) and adaptive optics (AO) guider offsets, nods and dithers, and acquisition offsets.

Table 4-11: Time to move requirements for nodding, dithering; seeing-limited (SL) and adaptive optics (AO) guider offsets; and acquisition offsets

Requirement ID	Operation and Distance on Sky	Time to Move (seconds)
[REQ-1-OAD-1105]	1 arcsec Nod, Dither; or SL or AO Guider Offset	< 2
[REQ-1-OAD-1115]	5 arcsec Nod, Dither; or SL or AO Guider Offset	< 2.5
[REQ-1-OAD-1107]	10 arcsec Nod, Dither; or SL or AO Guider Offset	< 4
[REQ-1-OAD-1108]	30 arcsec Nod, Dither; or SL or AO Guider Offset	< 5
[REQ-1-OAD-1109]	1 arcmin SL Guider Offset	< 5
[REQ-1-OAD-1110]	0.1 degree Acquisition Offset (without guider feedback)	< 7
[REQ-1-OAD-1111]	1 degree Acquisition Offset (without guider feedback)	< 11.3

Discussion: TMT spends at least 80% of the period at the dwell points of nodding and dithering.

[REQ-1-OAD-1199] The observatory shall support a pattern of non-redundant dithers extending over a period of 4 hours with a time interval between two consecutive dithers (T_A in Figure 4-2 below) as short as 20 seconds with an RMS accuracy given in [REQ-1-OAD-1104] and Table 4-1.

Discussion: Accuracy is defined with respect to the mean of all the dither positions in the pattern. This assumes all dither end points are contained in a box of up to 30 arcsec square for AO guiding, and 1 arcmin for seeing limited dithers. Non-redundant in this requirement means that each point *in the dither pattern sequence is used only once. An example of a non-redundant dither is shown in Figure 4-1.1.*

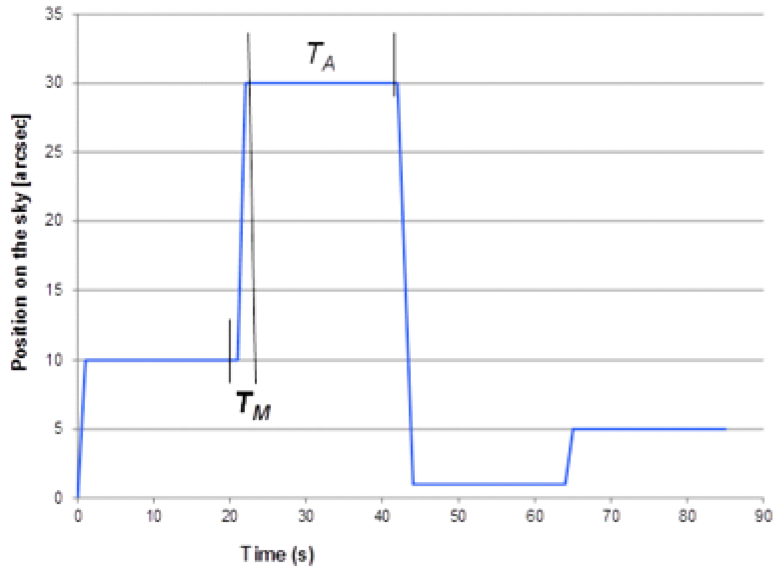

Figure 4-2: Example of non-redundant dither. TA is the time between dither moves as per REQ-1-OAD-1199, i.e., the open shutter/dwell time (TA ≥ 20 s), TM is move time or dither loss.

4.2.3.6.4 Open Loop Tracking

[REQ-1-OAD-1240] The Telescope (STR, M1CS, M2 & M3) shall have an average tracking accuracy of less than 0.21 arc-seconds RMS over a 5 minute time period.

Discussion: Prior to the start of the tracking period, all pointing and offsetting errors are set to zero. The requirement is for the average of many 5 minute trajectories over the full azimuth and elevation range of the Telescope.

4.2.3.7 Nasmyth Platforms and Instrumentation Support

4.2.3.7.1 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 4-3: Allowable image jitter as seen by an instrument mounted on the Nasmyth Platform' below.

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.

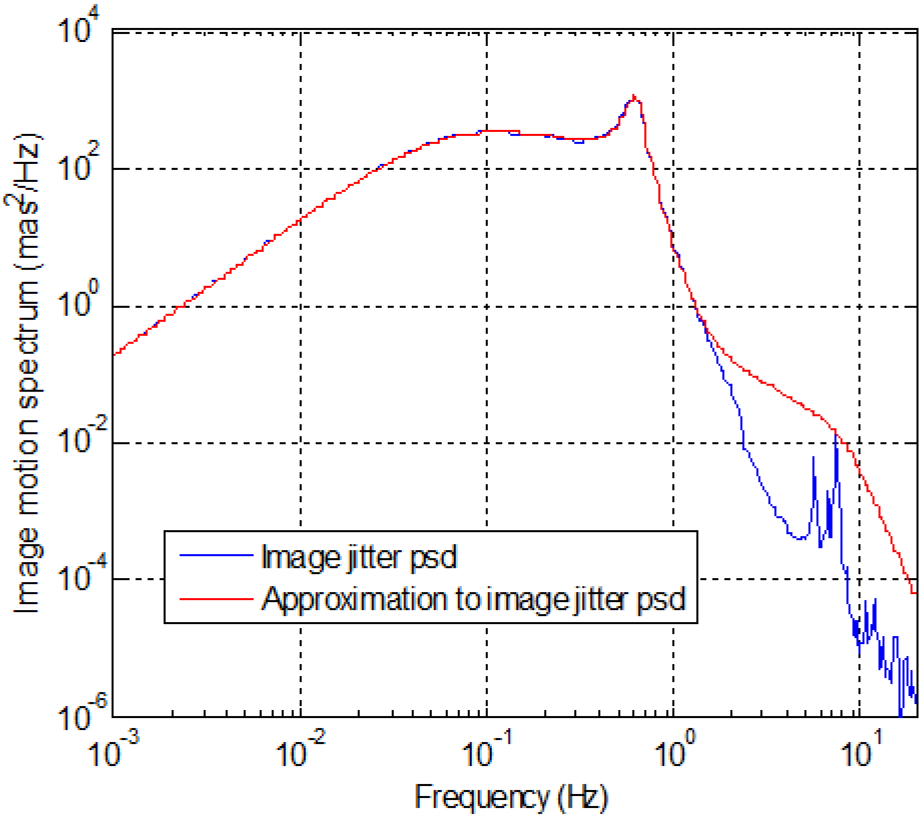

Figure 4-3: Allowable image jitter as seen by an instrument mounted on the Nasmyth Platform

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 (RD23). 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

$$k \frac{(f^2)}{\left|1 + 2\zeta_0 if/f_0 - (f/f_0)^2\right|^2 \cdot \left|1 + 2\zeta_1 if/f_1 - (f/f_1)^2\right|^2} \cdot \frac{\left|1 + 2\zeta_2 if/f_2 - (f/f_2)^2\right|^2}{\left|1 + 2\zeta_3 if/f_3 - (f/f_3)^2\right|^2}$$

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 ζ_0 = 1.25, ζ_1 = 0.1, ζ_2 = 0.5, ζ_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 90 mas respectively.

4.2.3.7.2 Configuration

[REQ-1-OAD-1390] The Nasmyth platforms, instruments and their support structures must not extend outside the volume defined in TMT.INS.GTY.0003 (AD52).

[REQ-1-OAD-1395] The Nasmyth platforms shall provide a permanent platform covering the area defined in TMT.INS.GTY-0004 (AD74) at an elevation of 7 m below the elevation axis. All structure above this level shall be reconfigurable.

[REQ-1-OAD-1397] No part of the telescope structure shall obscure the light path to the science instruments as defined in (AD73) or the incoming light to the primary mirror as defined in (AD81), over the full range of observing zenith angles.

Discussion: AD81 does not apply to the M3 support tower or the top end support, which is included in (AD41).

[REQ-1-OAD-1398] The STR, excluding the Instrument Support Structures, shall be compatible with delivering the following FoVs to the instruments:

+X Nasmyth Platform:

1. For Nasmyth foci locations between -26.5º and -21º, the unobscured FOV can decrease linearly from 20 arcmin diameter at -21º to 5 arcmin diameter at -26.5º.

2. For Nasmyth foci locations from -21º to 0º, a full FOV of 20 arcmin diameter is required, without obscuration by the telescope structure.

3. For Nasmyth foci locations between 0º and +5.5º, the unobscured FOV can decrease linearly from 20 arcmin diameter at 0º to 5 arcmin diameter at +5.5º.

-X Nasmyth Platform:

1. For Nasmyth foci locations between +174.5º and +180º, the unobscured FOV can decrease linearly from 20 arcmin diameter at +180º to 5 arcmin at +174.5º.

2. For Nasmyth foci locations from +180º to 201º, a full FOV of 20 arcmin diameter is required, without obscuration by the telescope structure.

3. For Nasmyth foci locations between +201º and +206.5º, the unobscured FOV can decrease linearly from 20 arcmin diameter at +201º to 5 arcmin diameter at +206.5º.

Discussion: The unobscured field diameter is allowed to decrease at Nasmyth foci locations off the elevation axis as long as the complete Science instrument suite in (AD98) and (AD99) can be housed on the Nasmyth platforms such that the field required by each instrument is not further infringed upon.

Discussion: If an instrument provides their own support structure, they must adhere to this requirement to ensure the instrument support structure does not interfere with the FoV.

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

Discussion: In the first light configuration, the APS system is moveable between the on and off axis positions without reconfiguration of any first light instruments.

[REQ-1-OAD-1410] At First Light, the Nasmyth Platforms shall provide support for the following instruments, each at their own foci: NFIRAOS with the NSCU, feeding IRIS and MODHIS, 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.

Discussion: The Nasmyth sides are designated -X and +X corresponding to directions in the Azimuth Coordinate Reference System. The foci locations are designated by their angular position, where 0 degrees is on the +X platform aligned with the telescope elevation axis, increasing counterclockwise 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 upgradeable to support the following First Decade instruments, each at their own foci and with their required field of view: IRMOS, MIRES, PFI, NIRES, HROS.

Discussion: The instrument locations for the full SAC instrument suite are shown in AD98 (First Light) and AD99 (First Decade).

Discussions: Instruments are not to exceed the volumes listed in requirements [REQ-1-OAD-1416] to [REQ-1-OAD-1429] and [REQ-1-OAD-1431]. Allocations for future instrumentation are notional layouts and are not binding on the TEL STR.

Discussion: These volumes and focal plane positions are required to meet the instrument arrangement as shown in (AD98) and (AD99).

[REQ-1-OAD-1416] The APS shall stay within the volumes, and meet the focal plane position requirements, defined in drawings TMT.INS.GTY-0001 (AD98), TMT.INS.GTY-0002 (AD99), and TMT.SEN.GTY-0001 (AD100).

[REQ-1-OAD-1417] HROS shall stay within the volumes, and meet the focal plane position requirements, defined in drawings TMT.INS.GTY-0002 (AD99) and TMT.SEN.GTY-0001 (AD100).

[REQ-1-OAD-1418] IRIS shall stay within the volumes, and meet the focal plane position requirements, defined in drawings TMT.INS.GTY-0001 (AD98) and TMT.SEN.GTY-0001 (AD100).

[REQ-1-OAD-1419] MODHIS shall stay within the volumes, and meet the focal plane position requirements, defined in drawings TMT.INS.GTY-0001 (AD98) and TMT.SEN.GTY-0001 (AD100).

[REQ-1-OAD-1420] IRMOS shall stay within the volumes, and meet the focal plane position requirements, defined in drawings TMT.INS.GTY-0002 (AD99) and TMT.SEN.GTY-0001 (AD100).

[REQ-1-OAD-1421] MIRAO shall stay within the volumes, and meet the focal plane position requirements, defined in drawings TMT.INS.GTY-0002 (AD99) and TMT.SEN.GTY-0001 (AD100).

[REQ-1-OAD-1422] MIRES shall stay within the volumes, and meet the focal plane position requirements, defined in drawings TMT.INS.GTY-0002 (AD99) and TMT.SEN.GTY-0001 (AD100).

[REQ-1-OAD-1423] NFIRAOS shall stay within the volumes, and meet the focal plane position requirements, defined in drawings TMT.INS.GTY-0001 (AD98) and TMT.SEN.GTY-0001 (AD100).

[REQ-1-OAD-1426] NIRES-R shall stay within the volumes, and meet the focal plane position requirements, defined in drawings TMT.INS.GTY-0002 (AD99) and TMT.SEN.GTY-0001 (AD100).

[REQ-1-OAD-1428] PFI shall stay within the volumes, and meet the focal plane position requirements, defined in drawing TMT.INS.GTY-0002 (AD99) and TMT.SEN.GTY-0001 (AD100).

[REQ-1-OAD-1429] WFOS shall stay within the volumes, and meet the focal plane position requirements, defined in drawings TMT.INS.GTY-0001 (AD98) and TMT.SEN.GTY-0001 (AD100).

4.2.3.7.3 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-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.

4.2.3.7.4 SERVICES

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

4.2.3.7.5 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 personnel are transiting to and from the Nasmyth areas.

[REQ-1-OAD-1465] The Telescope Structure shall provide the capability to lift equipment up to 1.5 x 1.5 x 1.5 m and 500 kg from the Observatory Floor to the Nasmyth Platforms.

[REQ-1-OAD-1467] Elevator access to and from the Nasmyth areas shall be possible at any telescope azimuth position.

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 4.6.1 of the OAD.

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

[REQ-1-OAD-1482] All instruments shall not block the pathways on the 4F Nasmyth platforms (per AD103) used 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.

4.2.3.7.6 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.

4.2.3.7.7 Access between Platforms

[REQ-1-OAD-1490] Walkway access shall be provided between the -X and +X Nasmyth platforms and accesible at all telescope elevation angles.

[REQ-1-OAD-1492] The walkways between the +X and -X Nasmyth areas shall not be blocked as per (AD103).

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.

Discussion: The intent is to have a >1.5 m wide pathway between the +X and -X Nasmyth areas.

4.2.3.7.8 Instrument Handling, Installation and Removal

[REQ-1-OAD-1515] A lay down area for staging and assembly of equipment with a footprint of at least 5 x 7 m, and 5 m high, shall be provided on both Nasmyth platforms.

Discussion: This area will be used for unpacking and assembly of instrument components prior to lifting them into place at the instrument location. The area is sufficiently high so that a temporary clean room can be assembled to create environmental conditions suitable for handling precision mechanisms and optics. As a goal, this area can be equipped as permanent instrument lab where entire instruments can be assembled and then lifted to their final location.

[REQ-1-OAD-1517] The telescope STR design shall provide sufficient clearance between it and the enclosure fixed base and rotating base to allow a component of the size shown in (AD97) to be lifted from the floor to the Nasmyth platforms.

[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.

Discussion: The Nasmyth platforms are in close proximity to the primary mirror, which will not have a protective mirror cover.

[REQ-1-OAD-1525] All Nasmyth instrument handling, installation and removal activities shall be compatible with the requirements of the operating observatory environment.

Discussion: Activities such as in situ welding, cutting and grinding are considered incompatible with this environment, they must ne avoid and it will required TIO approval. Activities will be planned, and equipment will 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.

4.2.3.7.9 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.

4.2.3.7.10 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-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.

4.2.3.7.11 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-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.

[REQ-1-OAD-1605] Components of the observatory wide fire system shall be mounted on the telescope structure to:

- allow personnel in this area to initiate a fire alarm
- ensure fire alarms are audible and visible to personnel working on the telescope structure
- detect smoke and heat caused by a fire on the telescope or telescope.

4.2.3.8 Segment Handling Crane

[REQ-1-OAD-1610] The STR Segment Handling System (STR SHS) is an integrated system that consists of: (1) a Segment Lifting Fixture (SLF) that interfaces to the Mounted Segment Assembly (MSA); (2) a positioning system that moves the SLF to install or remove the segments in the primary mirror array; and (3) a crane or other means to raise segments from the observing floor to the mirror cell and lower them back to the observing floor.

Discussion: When a MSA is to be installed into the primary mirror, the MSA is positioned by the STR SHS (with SLF) and held in a prescribed orientation above the mirror array as the shaft of the Segment Lifting Jack is extended from the segment subcell to first engage with the segment, and then extend further to transfer the MSA weight from the SLF to the Jack, at which time, the SLF Talons are opened and the MSA is lowered into position. The SLF will then retract, permitting movement to another location. Removal of a MSA follows the reverse of this process.

[REQ-1-OAD-1612] The STR SHS shall be mounted on the telescope structure.

[REQ-1-OAD-1614] Installation and removal of primary mirror segments shall be accomplished with the telescope locked in a zenith-pointing orientation.

[REQ-1-OAD-1616] The STR SHS shall enable the installation and removal of any 10 primary mirror segments per 10-hour day.

Discussion: The STR SHS is not the only subsystem and hardware used in a segment exchange, but it is critical to the activity of exchange. Hence the STR SHS is designed to not be the limiting factor in performing 10 segment exchanges in one 10-hr day.

[REQ-1-OAD-1618] The STR SHS duty cycle shall permit:

- 2000 installation or removal operations during construction,
- 10 routine segment exchanges during a single 10-hour day, once every two weeks for fifty years (13,000 segment exchanges),
- a proof test (at two times rated load) every six months for 50 years.

[REQ-1-OAD-1620] The STR SHS shall be able to access, install and remove any of the 492 segments in the primary mirror.

[REQ-1-OAD-1622] The STR SHS shall be placed in a stowed position when the telescope is used for observing. In its stowed position, no component of the STR SHS shall vignette the field of view of any of the science instruments.

[REQ-1-OAD-1630] The STR SHS shall enable MSAs to be raised and lowered directly to a segment handling cart on the observatory floor.

Discussion: This requirement does not prevent the use of a Segment Exchange Frame (SHC.SEF) being raised to the Segment Handling Platform (SHP) in order to interface the MSA to HNDL Segment Handling Cart (SHC). The SHC.SEF provides a safer (and non-critical) interface to the MSA with which to perform handling.

[REQ-1-OAD-1632] The STR SHS shall have six motorized degrees of freedom (Tx, Ty, Tz, Rx, Ry, Rz, defined in a convenient orthogonal coordinate system).

[REQ-1-OAD-1634] The STR SHS shall level the segment (Tip = Tilt = 0) prior to installing/removing the segment onto the handling cart.

Discussion: To minimize risk to the segments, the number of transfers of the MSA from one piece of handling equipment to another should be minimized - hence the levelling of segments is done *on the STR SHS without need of extra equipment. This allows the segment to be lowered directly onto any of the Segment Handling Carts.*

[REQ-1-OAD-1636] If the STR SHS is stowed when an earthquake up to the level of a very infrequent earthquake occurs, the STR SHS shall not damage any telescope mirror or any science instrument.

[REQ-1-OAD-1638] If the STR SHS is in use when an earthquake, up to the level of an infrequent earthquake occurs, the STR SHS shall not damage any telescope mirror systems, including M1 and M3, or any science instrument.

[REQ-1-OAD-1639] If the STR SHS is raising or lowering a segment from/to the observing floor when an earthquake up to the level of a frequent earthquake occurs, the STR SHS shall not allow damage to the MSA being moved.

[REQ-1-OAD-1640] The STR SHS shall strictly minimize any contaminants which might be deposited onto the surface of the primary mirror or tertiary mirror, including dust, debris, grease, oil or other fluids.

Discussion: It is not possible to absolutely not deposit dust on M1 from a system that is tipping with M1 and will be operating and stored in a dusty environment.

[REQ-1-OAD-1641] In its stowed position, the STR SHS shall not significantly interfere with the free flow of air across the surface of the primary mirror.

[REQ-1-OAD-1642] No elements of the STR SHS (including any payload) shall be able to contact the primary mirror under any combination of environmental, seismic and operational conditions or during loss of power. The STR SHS should minimize the potential damage to the segment which is in the process of being engaged during a seismic condition or operational failure.

Discussion: "being engaged" refers to the capture of the segment for the purpose of removal using the Segment Lifting Fixture.

4.2.4 TELESCOPE MIRROR OPTICAL COATING REQUIREMENTS

[REQ-1-OAD-1615] The M1 or M2/M3 Coating Systems shall allow application of coating recipes other than the baseline coating, including coatings of different materials and number of layers.

Discussion: It is assumed that a maximum of six magnetrons total could be used for future advanced mirror coatings. A five material design is the current maximum for UV enhanced coatings.

Discussion: 'Table 4-12: Requirements for M1, M2 and M3 Optical Coatings' lists the requirements for the optical coatings on each of the M1, M2 and M3 mirror surfaces.

Table 4-12: Requirements for M1, M2 and M3 Optical Coatings.

Requirement ID	Description	Wavelength Range (µm)	Requirement	Goal
[REQ-1-OAD-1600]	Minimum Reflectivity per Surface	0.31 - 0.34	N/A	0.8
		0.34 - 0.36	0.56 →0.72	0.9
		0.36 - 0.40	0.72 → 0.84	0.9 → 0.95
		0.4 - 0.5	0.84 → 0.93	0.95 → 0.98
		0.5 - 0.7	0.93 → 0.97	0.98
		0.7 - 28	0.97	0.98
[REQ-1-OAD-1603]	Maximum Emissivity per Surface	0.7 - 28	0.015	0.013
[REQ-1-OAD-1606]	ΔR / Wavelength	0.31 - 28	< 0.003 / nm	

Discussion: Thermal radiation collected at the focal surface, in the FOV of the system, from the primary, secondary, and tertiary mirror assemblies together are not to exceed 10% of the radiation of a 273 K black body, assuming that a cold stop is used to mask out the telescope top end obstructions.

[REQ-1-OAD-1609] The M1, M2, and M3 Optical Coatings shall have a lifetime of at least 2 years while meeting performance requirements.

Discussion: This assumes a cleaning frequency as defined in The TMT Maintenance Budget (RD64).

Discussion: 'Table 4-13: Mirror Reflectivity After In-Situ Cleaning' lists the requirements for the in-situ cleaning mirror reflectivity on each of the M1, M2 and M3 mirror surfaces

Table 4-13: Mirror Reflectivity After In-Situ Cleaning

Requirement ID	Wavelength Range (µm)	Requirement	Goal
[REQ-1-OAD-1608]	0.31 - 0.34	N/A	0.5
	0.34 - 0.36	0.53 → 0.69	0.73
	0.36 - 0.40	0.69 → 0.81	0.73 → 0.86
	0.4 - 0.5	0.81 → 0.9	0.86 → 0.94
	0.5 - 0.7	0.9 → 0.93	0.94
	0.7 - 28	0.93	0.94

Discussion: Where a range is given, it applies linearly over the wavelength range. This requirement is the reflectivity for each mirror measured individually. It is not designed to preclude wet washing by use of the phrase 'in-situ'.

4.2.5 M1 Optics System

4.2.5.1 General

[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.

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

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-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-1685] The segment and the portions of the SSA that will stay with it in the coating chamber shall be compatible with the vacuum and coating environment, and shall not show any degradation after 30 re-coating cycles.

[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 SOPD Segment Out of Plane Displacement [REQ-1-OAD-0406] for periods of at least 30 days without updates from the APS.

[REQ-1-OAD-1692] The STR shall provide access to 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.

4.2.5.2 Segmentation

[REQ-1-OAD-1700] The primary mirror of the system shall be segmented as shown in '*Figure 4-4: Layout of the segmented primary mirror, as projected on the X-Y plane of the Elevation Coordinate System (ECRS)*' below; it contains 492 segments.

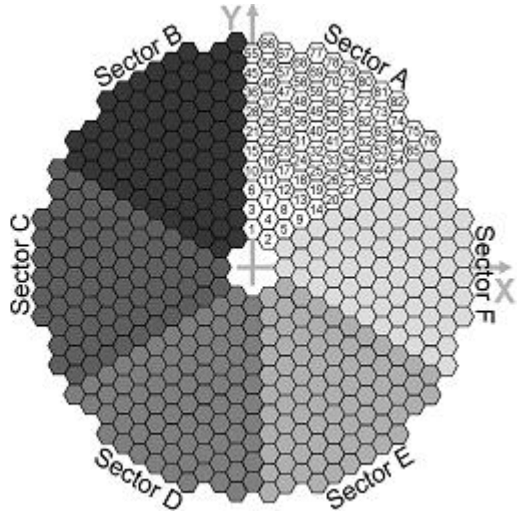

Figure 4-4: Layout of the segmented primary mirror, as projected on the X-Y plane of the Elevation Coordinate System (ECRS). The capital letters denote identical sectors rotated by 60 degrees relative to each other.

[REQ-1-OAD-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 is 2.5mm, and each segment has a 0.5mm bevel. Therefore the optical gap between segments is 3.5mm. For the 1386 gaps between segments, the total pupil obscuration is 0.56%.

[REQ-1-OAD-1730] The segment support assembly must accommodate, without damage, the maximum tilt that can be imposed by the M1CS actuators.

[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 results in a segment gap change of less than 0.54 mm under all Observing Performance conditions, and less than 1.0 mm under all Facility Performance conditions.

Discussion: The gap due to gravity is limited to 0.44mm over the 0-90° zenith range. The ΔT for Observing Conditions is -7°C and the ΔT for Facility Performance Conditions is -12°C. This results in a gap closure of 0.54mm under Observing Performance Conditions and a gap closure of 0.62mm under Facility Performance Conditions. Therefore the 1mm requirement includes some margin.

Discussion: Gap change is applied over the full length of the edge and this is intended to cover both linear and rotational segment motions. This requirement applies for when the M1CS is in a phased state.

[REQ-1-OAD-1740] The telescope structure and primary mirror cell shall be designed such that segment to segment contact does not occur under the conditions defined in the table below.

Table 4-14: Combination of cases under which segment to segment contact must not occur

Case	Temperature (°C)	No. Failed Actuators	Earthquake (year)	Zenith Angle
Nominal Operation	2	0	No	All
Low temp, failed actuator	-14	1	No	All
Survival Low temperature	-16	0	No	All
10 year earthquake	-5	1	10	All
200 year earthquake	-5	0	200	All
1000 year earthquake	-5	0	1000	All
Jacking	-5	0	No	Zenith Pointing

[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:

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

α = 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, of [REQ-1-OAD-1750] shall be 0.1650.

[REQ-1-OAD-1772] The nominal (theoretically perfect) geometry of the segment vertex co-ordinates, segment co-ordinate systems, edge sensor locations, mirror cell to primary segment assembly attachment points and segment position actuator locations shall be as defined in the TMT M1 Segmentation Database (AD16).

4.2.5.3 Positioning

[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).

4.2.5.4 M1 Optics Handling

The M1 Optics Handling equipment is a non-integrated system that operates in conjunction with the M1 Segment Handling System to remove, maintain, and reinstall M1 segments. It consists: (1) M1 Segment Handling Cart (SHC) that interfaces to SHS and MSA, and includes Segment Protective Cover (SPC); (2) M1 General Segment Lifting Fixture (GSLF) that interfaces to the MSA; (3) M1 Segment Storage Cabinet

(SSC) for storage of 82 spare M1 segments; (4) M1 Segment Handling Cart Restraint (SHC Restraint) as a means to tether the loaded or unloaded carts in the staging bays; (5) M1 Segment Lifting Jack to raise segments from the fixed frame and allow removal from the telescope.

[REQ-1-OAD-1774] The M1 SHC shall allow for the mounting and movement of one (1) MSA per handling cart.

[REQ-1-OAD-1776] The M1 SHC shall be compatible with pathways and openings provided throughout the Enclosure and Summit Facilities for the purpose of mirror maintenance and storage.

[REQ-1-OAD-1777] The M1 SHC shall provide a safe method of transporting each segment to and from the observing floor to the Segment Handling Platform (SHP).

Discussion: The SHS hands-off the MSA to HNDL at the SHP - however, the handover is not complete until the MSA reaches the M1 SHC Base at the Observing Floor. This means there is an atypical triple interface of M1S-STR-HNDL that spans the SHP to observing floor during this portion of a segment exchange activity.

To facilitate this, the Segment Handling Cart will include a separable Segment Exchange Frame - the MSA will be transported between the Observing Floor and SHP via this equipment.

[REQ-1-OAD-1778] The M1 SHC shall facilitate the stripping, washing and recoating operations.

Discussion: Rotation of the MSA about one axis will be necessary to complete mirror maintence activities. A rotation lock, and clamp to retain the MSA on the Segment Exchange Frame of the M1 Segment Handling Cart during any rotation will be a necessity.

4.2.6 M2 System

4.2.6.1 M2 General

The M2 System is designed to be compatible with the Laser Launch Telescope. No component of the M2 Assembly extends beyond a plane perpendicular to the M1 optical axis located 1.6 meters behind the vertex of the M2. The outer diameter of the M2 system is less than or equal to 3.6 m.

The M2 incorporates alignment features that allow its position and orientation to be accurately and quickly measured by the Global Metrology System (GMS).

4.2.6.2 M2 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. 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 or tertiary mirror.

Discussion: Analysis has shown that wet washing the baseline mirror coating restores mirror reflectivity to near fresh-coating performance. Additionally, M2 and M3 recoatings and in-situ washes can be staggered to maintain a consistent overall telescope throughput.

4.2.6.3 M2 Control

The M2 System includes a low level control system to control the M2 positioner. The M2 positioner control system can operate in the absence of the M2 Cell Assembly, for example, when the conventional M2 has been replaced with an adaptive M2.

[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 4-9: Maximum allowable deflection of the telescope top end'.

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

4.2.6.4 M2 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.

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

4.2.7 M3 System

4.2.7.1 M3 General

The optical surface of the M3 passes through the intersection of the telescope elevation and azimuth axes and rotates and tilts about that point. The intersection of the M3 rotation and tilt axes is coincident with the intersection of the telescope elevation and azimuth axes.

The M3 incorporates 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.

4.2.7.2 M3 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-1995] The M3 assembly shall be serviceable either using the aerial servicing platform with the telescope horizon pointing or in telescope zenith-pointing orientation by personnel who ascend into the center of the assembly through the rotation bearing of the M3 positioner.

Discussion: The M3 cable wraps need to leave adequate room for this access.

4.2.7.3 M3 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 per [REQ-1-OAD-1398]. The motion shall be achieved over a telescope zenith angle range of 0 to 65 degrees. All instrument optical axes are located in a plane perpendicular to the ACRS z-axis and coincident with the ECRS origin.

[REQ-1-OAD-2005] The M3 system shall be able to address APS field positions up to 10 arcmin off axis.

Discussion: The optical axis of APS lies in the same horizontal plane as the science instruments, but to obtain its full coverage, APS requires that M3 is used to point to multiple field points.

[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.

4.2.7.4 M3 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.

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

4.2.8 Primary Mirror Control System (M1CS)

[REQ-1-OAD-2100] The combined static stiffness of the mirror cell, actuators and segment support assembly relative to its immediate neighbours shall be no less than 10 N/um in the z direction.

Discussion: The static stiffness relative to its neighbours 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 and displacement of the segment relative to its 6 neighbours. Higher stiffness provides additional benefit. The compliance is dominated by the Primary Segment Assembly (including SSA and actuators) and the top chord of the mirror cell; the rest of the mirror cell does not contribute significantly to the relative stiffness as defined below and can be neglected for this calculation.

[REQ-1-OAD-2101] The M1CS bandwidth (3dB) shall be no less than 1 Hz for Zernike patterns with radial degree 5 or higher, and no less than 0.25, 0.5, and 0.75 Hz respectively for Zernike radial degree 2, 3 and 4.

Discussion: The bandwidth is defined as the frequency where the sensitivity is -3dB. 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. Higher bandwidths provide additional benefit and should be considered if achievable with little extra cost.

[REQ-1-OAD-2102] The stiffness of the combined segment support shall be no less than 0.8 N/um in the z direction for frequencies between 5 and 20Hz.

[REQ-1-OAD-2103] The stiffness of the combined segment support shall be no less than 4/f N/um in the z direction for all frequencies between 0.4Hz and 5 Hz.

Discussion: The requirement between 1 and 5 Hz is simply a linear relationship on a log-log scale joining the requirements at 1 and 5 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. 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-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.

[REQ-1-OAD-2115] The M1CS shall implement the driving of the segment warping harness motors and the readback of the segment warping harness sensors.

[REQ-1-OAD-2120] The M1CS shall provide the capability to measure and log the M1S segment temperature.

4.2.9 Alignment and Phasing System (APS)

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-2245] The APS shall have the ability to make off axis measurements at any point in the telescope field of view and characterize the wavefront in terms of Zernikes.

[REQ-1-OAD-2250] The APS shall measure the position of the pupil to an accuracy of 0.05% of the diameter of the pupil.

Discussion: In alignment maintenance mode, the initial M1, M2, and M3 optics are not to exceed the error requirements shown in 'Table 4-15: Alignment maintenance mode capture range' below.

Table 4-15: Alignment maintenance mode capture range

Requirement ID	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-2274]	M3 tip/tilt	+/- 60	mm (pupil mis-alignment at M1) in X and Y

[REQ-1-OAD-2257] In the absence of segment exchanges, the M1S, M2S, M3S, and M1CS shall meet all performance requirements for periods of no less than four weeks without calibration by the APS.

Discussion: In post-segment exchange mode the initial M1, M2 and M3 optics are not to exceed the errors shown in 'Table 4-16: Post-segment exchange mode capture range'.

Table 4-16: Post-segment exchange mode capture range

Requirement ID	Optical Element	Maximum Error	Units
[REQ-1-OAD-2290]	M1 segment tip/tilt	+/- 20	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-2304]	M3 tip/tilt	+/- 60	mm (at M1) in X and Y

[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-2330] The APS shall be able to perform all function necessary for on-axis alignment and M1CS calibration in 180 minutes when all optics are within the post-segment exchange specifications.

4.2.10 Cleaning System (CLN)

[REQ-1-OAD-2332] The CLN shall enable cleaning of the entire optical surface of the primary mirror once every two weeks.

[REQ-1-OAD-2334] The CLN shall enable cleaning of the entire optical surfaces of M2 and M3 using equipment that can be operated by a single person from the STR Aerial Service Platform.

[REQ-1-OAD-2336] The CLN shall have a maximum CO2 flow velocity normal to M1 optical surface of 6 m/s.

Discussion: This requirement limits the CO2 velocity to below what the M1CS dust boot is being tested and designed to.

4.2.11 ESEN

[REQ-1-OAD-1280] ESEN shall provide ultrasonic anemometers with resolutions of 0.01m/s and accuracies of ±0.1m/s to extract turbulence properties for M1 wind loading control, dome seeing, and telescope wind jitter.

Discussion: The number and location of anemometers is defined in ESEN interface documents. The plan is to operate the vents accounting for the flow pattern at M1 in the entire optical path volume using the SCMS and ESEN ultrasonic anemometers. Velocity measurements inside the Enclosure downwind of the vents, as an independent measure of wind direction and Enclosure wind attenuation, are also provided.

Discussion: An important input for wind jitter control is the knee frequency both from measurements at the M1 +Y level and at the M2/hex ring level.

[REQ-1-OAD-5175] ESEN shall provide air temperature measurements with resolutions of 0.01K, response rates of <1s, and an accuracy of <0.1K.

Discussion: The number and location of air temperature sensors is defined in ESEN interface documents. Calibration should be as reliable as possible, meaning near-linear temperature-resistance curves and minimal drift (<0.1K/y).

[REQ-1-OAD-2340] ESEN shall provide surface and structural temperature measurements with resolutions of 0.01K and response rates of <1s with an accuracy of <0.1K to calculate pointing corrections.

Discussion: There should be enough sensors to cover the different member thicknesses and sizes (that result in different thermal inertia) as well as resolve the expected gradients and asymmetries. The surface and/or structural temperature sensors should be able to adequately capture the thermal response of the telescope structure to HVAC.

[REQ-1-OAD-2342] ESEN shall provide dew point measurements with an accuracy better than ±0.2K, an averaging sampling rate <1min, and a response rate of <30s.

[REQ-1-OAD-2344] ESEN shall provide barometric pressure measurements with an accuracy better than 1 hPA to inform refraction and atmospheric-dispersion adjustments.

[REQ-1-OAD-2346] ESEN shall provide measurements of the lateral tilt (pitch) and longitudinal tilt (roll) of the telescope, with resolutions equal to or better than 0.05 arcseconds and long term repeatability equal to or better than 0.2 arcseconds, to compensate for mount tip/tilt effects on pointing.

Discussion: Accelerometers mounted to the telescope structure are required for monitoring vibration and related dynamic disturbances, and assessing structural dynamics for model validation and control design.

[REQ-1-OAD-2348] ESEN shall provide single-axis accelerometers, with a frequency range of at least 5 Hz to 200 Hz and a noise floor at 5 Hz better than 0.25 µg/√Hz, to capture both image motion and focus/astigmatism at M1.

[REQ-1-OAD-2350] ESEN shall provide accelerometers, with a frequency range of at least 5 Hz to 200 Hz and a noise floor at 5 Hz better than 0.25 µg/√Hz, to capture both tip/tilt and decentering motion at M2.

[REQ-1-OAD-2352] ESEN shall provide single-axis accelerometers, with a frequency range of at least 5 Hz to 200 Hz and a noise floor at 5 Hz better than 0.25 µg/√Hz, to capture both tip/tilt and decentering motion at M3.

[REQ-1-OAD-2356] ESEN shall provide three-axis accelerometers, with a frequency range of at least 5 Hz to 200 Hz and a noise floor at 5 Hz better than 0.25 µg/√Hz, on each Nasmyth platform to resolve key structural modes and help identify vibration sources.

[REQ-1-OAD-2358] ESEN shall provide three-axis accelerometers, with a frequency range of at least 5 Hz to 200 Hz and a noise floor at 5 Hz better than 0.25 µg/√Hz, on the pier to resolve whether vibration sources are coming from off the telescope.

4.2.12 Site Conditions Monitoring System (SCMS)

[REQ-1-OAD-2364] The SCMS shall gather time-stamped measurements every 10 seconds of the following meteorological and atmospheric sensors located at the weather tower on the north edge of the TMT site:

- Barometric pressure
- Temperature
- Relative Humidity
- Wind speed
- Wind direction

[REQ-1-OAD-2367] The SCMS shall provide fog measurements with visibility resolution 5m up to 1km, every 10 seconds.

[REQ-1-OAD-2370] The SCMS shall detect precipitation at a level 10^{-7} mm/s every second.

[REQ-1-OAD-2371] The SCMS shall measure dust mass concentration as a function of particle size in particle size bins >0.3µm, >0.5µm, >1.0µm, >2.0µm and >5.0µm every minute.

[REQ-1-OAD-2372] The SCMS shall measure SO2 (TBC) and/or SO4 (TBC) concentration in parts every 10 seconds.

[REQ-1-OAD-2373] The SCMS shall measure the fraction of cloud coverage across the sky to with 10% every minute.

[REQ-1-OAD-2374] The SCMS shall provide measurements of the amount of Precipitable Water Vapor between 0 to 27mm every minute.

[REQ-1-OAD-2375] The SCMS shall provide measurements of the seeing and Fried Parameter (r_0) at 0.5µm, corrected for a zero exposure time at the zenith, every minute.

[REQ-1-OAD-2376] The SCMS shall provide measurement of the optical turbulence profile ($Cn^2(h)$ $m^{-1/3}$), turbulence coherence time at the zenith every minute.

[REQ-1-OAD-2378] The SCMS shall provide measurement of the sky transparency and background sky brightness at the zenith in UBVRI bands every minute.

4.2.13 Test Instruments (TINS)

[REQ-1-OAD-2380] The TINS PFC shall have an f number of 1.5.

[REQ-1-OAD-2382] The TINS PFC shall support guiding and acquisition.

[REQ-1-OAD-2384] The TINS PFC shall measure the subimage from a single segment with an accuracy of at least 0.1 arcsecond.

[REQ-1-OAD-2386] The TINS GMS shall facilitate the following use cases:

- M1 Sub-cell Alignment
- M1 Global Tip/Tilt - Operations
- M2 Installation and Position
- M3 Pointing Model Development
- M3 Installation and Position
- Initial Pre-observing Alignment Between M2 and M3
- NFIRAOS and NFIRAOS CLIENT Instrument Alignment
- APS Alignment to Support Pointing Budget

Discussion: A full detailed of the TINS Use cases is given in RD66.

4.3 Instrumentation

4.3.1 General

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

Discussion: This specification is looser than the telescope pointing requirement for risk reduction in case the requirement is not met. A normally distributed telescope pointing accuracy of 3 arcseconds RMS with 3-sigma uncertainty provides a 99% probability that the object being acquired lands within ~20 arcsec FOV.

[REQ-1-OAD-2705] TMT Instrumentation (Instruments/AO Systems) 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 and AO systems

[REQ-1-OAD-2707] Instruments shall be light tight to an extent that will allow internal calibrations to be performed during daytime operations with the enclosure lights on.

[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.

[REQ-1-OAD-2709] The design lifetime of AO systems (LGSF and NFIRAOS) and First Light science instruments (IRIS, MODHIS and WFOS) shall be 20 years.

Discussion: All performance requirements must be met over the period stated above assuming regular preventative maintenance within the allocated annual servicing allowance. An additional refurbishment period after approximately 10 years is also permitted providing this doesn't exceed 3 months downtime.

[REQ-1-OAD-2712] Instrument maintenance and servicing shall be done:

- Primarily on the Nasmyth Platforms or
- Secondarily on the Observing Floor Instrument reserve area.

[REQ-1-OAD-2711] Instrument lifetime for the first generation instruments shall be based on the following assumed duty cycles:

- WFOS: 50% of available science time
- IRIS: 25% of available science time
- MODHIS: 25% of available science time
- NFIRAOS: 50% of available science time

[REQ-1-OAD-3900] All TMT science instruments shall produce data with the meta-data necessary for later organization ("find all science data associated with this science observation"), classification ("identify the type of science data, e.g. environmental conditions, instrument, instrument mode, etc."), and association ("identify calibration data and processing algorithm needed to process these science data").

[REQ-1-OAD-3901] All TMT science instruments shall produce data and metadata compliant with the FITS and Virtual Observatory standards per REQ-1-OAD-9812.

Discussion: Metadata information includes: information about observing program; target information; system configuration at time of observation (telescope, AO system, instrument, detector); and environmental conditions at time of observation.

4.3.2 First Light

4.3.2.1 NFIRAOS Subsystem

4.3.2.1.1 General

[REQ-1-OAD-2800] NFIRAOS shall have 2 deformable mirrors conjugate to 0 km and 11.8 km

[REQ-1-OAD-2810] NFIRAOS Subsystem in LGS MCAO mode shall utilize six Na (Sodium) laser guide stars to improve sky coverage.

[REQ-1-OAD-2811] The NFIRAOS throughput to science instruments shall exceed 60% over 0.8 – 1.0 microns, and 80% over the 1.0 - 2.4 micron wavelength range [Goal: 90% from 0.6 to 2.5 microns].

[REQ-1-OAD-2713] The NFIRAOS unvignetted field of view shall be at least 2 arcmin diameter.

[REQ-1-OAD-2714] Useful NFIRAOS correction shall be achieved over a 2.3 arcmin diameter field of view, with no more than 30% vignetting.

[REQ-1-OAD-3360] NFIRAOS shall not increase the (inter-OH) background by more than 15% over natural sky + the telescope for median night time temperatures on the TMT site (assume 7% telescope emissivity at 273 K).

[REQ-1-OAD-3361] NFIRAOS shall provide a transmitted technical field with a focal ratio of f/15.

[REQ-1-OAD-3362] NFIRAOS shall operate with values of r0 (in the direction of the observation) as small as 0.10 m.

[REQ-1-OAD-2715] The NFIRAOS Subsystem in LGS MCAO mode shall utilize atmospheric tomography to minimize the impact of the cone effect.

Discussion: NFIRAOS supports the IRIS and MODHIS system configurations in First Light.

Discussion: NFIRAOS provides a common mechanical, thermal and optical interface at each of its three instrument interface ports.

Discussion: NFIRAOS is designed to accommodate instruments with a mass of up to 6800 kg at any of its three instrument interface ports.

Discussion: The intent is to allow any of the NFIRAOS client instruments to be mounted to any of the three output ports without significant modification to either NFIRAOS or the instrument interface. Minor changes including modification or replacement of the client instrument support truss would be permitted to allow relocation from the side port to either the top or bottom port of NFIRAOS.

[REQ-1-OAD-2830] NFIRAOS System, in LGS MCAO mode, shall utilize in closed loop up to three (3) near infra-red natural guidestar tip/tilt wavefront sensors located on the client instrument to maximize sky coverage.

[REQ-1-OAD-2770] NFIRAOS Subsystem 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.

[REQ-1-OAD-2840] NFIRAOS System 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.

[REQ-1-OAD-2755] NFIRAOS Subsystem shall meet its requirements without pupil derotation.

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

Discussion: NFIRAOS operates off-null in order to compensate non-common path aberrations in science instruments, with a maximum offset of 0.350 arcsec slope on each wavefront sensing subaperture.

Discussion: The worst case for slope errors in the non-common path wavefront between the LGS WFS and the Science Instrument are to be as defined in 'Table 4-17: Non-common path slope error allocation' below.

Table 4-17: Non-common path slope error allocation

Requirement ID	Sub-System	Slope Allocation across wavefront sensing subaperture (mas)
[REQ-1-OAD-2767]	NFIRAOS errors	295
[REQ-1-OAD-2768]	Instrument non-common path errors	55

[REQ-1-OAD-2842] The NFIRAOS Subsystem night time calibrations shall consume no more than 0.7% of its scheduled observing time.

[REQ-1-OAD-2843] The NFIRAOS Subsystem in NGSAO and LGS MCAO mode shall operate with full performance using an extended object as a Pyramid WFS guidestar with size up to 0.2 arcsec FWHM.

[REQ-1-OAD-2844] The NFIRAOS Subsystem in NGSAO and LGS MCAO mode shall operate with degraded performance using an extended object as a Pyramid WFS guidestar with size greater than 0.2 arcsec FWHM and up to 1.7 arcsec FWHM.

Discussion: NGSAO and LGS MCAO operation are not feasible for guide objects greater than 1.7 arcsec FWHM.

[REQ-1-OAD-2825] NFIRAOS Subsystem shall be designed to be upgradeable to a higher order AO system [REQ-1-OAD-2745] that interfaces to a wider-field near infra-red science instruments.

4.3.2.2 LGSF

4.3.2.2.1 General

[REQ-1-OAD-2900] The LGSF at early light shall be capable of projecting a sodium laser guide star asterism for NFIRAOS, as shown in 'Figure 4-5: LGSF asterisms supporting different AO modes'.

[REQ-1-OAD-2905] The LGSF shall be upgradeable to project the MIRAO asterism, the MOAO asterism, and the GLAO asterism with up to 8 LGS as shown in 'Figure 4-5: LGSF asterisms supporting different AO modes'. As a goal, the 4 asterisms shall be available at early light.

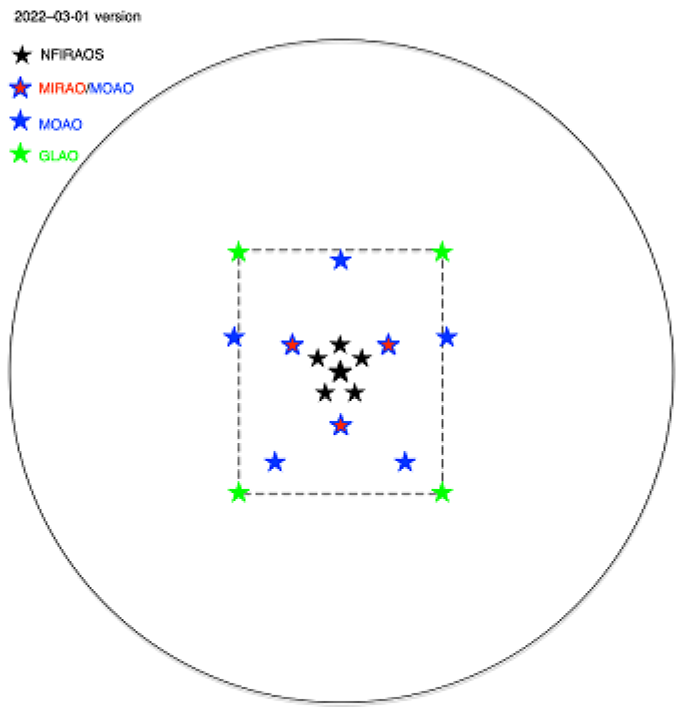

Figure 4-5: LGSF asterisms supporting different AO modes: NFIRAOS (black) 1 on axis, 5 on a 35 arcsec radius; MIRAO (red) 3 on a 70 arcsec radius; MOAO (blue) 3 on a 70 arcsec radius, 5 on a 150 arcsec radius; GLAO (green) 4 on a 276 arcsec by 330 arcsec rectangle

[REQ-1-OAD-2910] The LGSF system shall be able to switch between asterisms within 1 minute.

[REQ-1-OAD-2915] LGSF shall generate a signal level consistent with 25W or 20W with D2b repumping per LGS.

Discussion: 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-2917] The LGSF shall include all necessary alignment, calibration and diagnostic features required to meet its performance requirements.

[REQ-1-OAD-2920] The baseline LGSF shall utilize multiple lasers, and be operational with one laser down at the expense of degraded AO wavefront error performance.

[REQ-1-OAD-2925] The LGSF shall use 589 nm solid state lasers with a continuous wave (CW) format.

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

Discussion: Conventional optics means the use of refractive and reflective optics, but not fibers.

[REQ-1-OAD-2935] The LGSF Laser Launch Telescope shall be mounted behind the secondary mirror of the telescope (M2) or Adaptive Secondary Mirror (AM2).

[REQ-1-OAD-2939] LGSF shall provide a 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.

[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 4-9: Maximum allowable deflection of Telescope Top End'.

[REQ-1-OAD-2940] The LGSF Laser System shall be mounted on the inside of the -X ECRS elevation journal per TMT.SEN.GTY-0006 (AD101).

[REQ-1-OAD-2941] Space shall be reserved on the inside of the +X ECRS elevation journal to allow additional lasers to be mounted for future developments of the LGSF.

Discussion: The space requirements for the first light and/or first decade laser systems are to be defined in the STR-LGSF ICD.

[REQ-1-OAD-2942] The LGSF Beam Transfer Optics shall transport the laser beams from the laser system up to the LGSF Laser Launch Telescope via the Beam Transfer Optics Elevation Optical Path as defined in TMT.SEN.GTY-0006 (AD101)

Discussion: This is routed from the –X_{ECRS} telescope elevation journal up to the laser launch telescope via the (-X_{ECRS}, +Y_{ECRS}) vertical column and the (-X_{ECRS}, +Y_{ECRS}) hexapod leg.

[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 NFIRAOS [REQ-1-OAD-2745].

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%.

[REQ-1-OAD-2957] LGSF night time calibration shall consume no more than 0.3% of its scheduled observing time.

4.3.2.2.2 LGSF Access

[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 -XECRS, +YECRS vertical column including the intersection with the top ring, when the telescope is horizon pointing.

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

4.3.2.3 Adaptive Optics Executive Software

4.3.2.3.1 General

[REQ-1-OAD-3000] The AO Executive Software shall 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 Executive Software shall be upgradeable to control the first decade AO system upgrades.

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] NFIRAOS shall offload tip, tilt, focus, coma, M1 scalloping modes, and up to 100 M1 modes to the Telescope Control System.

[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.

4.3.2.4 IRIS

4.3.2.4.1 General

[REQ-1-OAD-3060] IRIS shall provide diffraction-limited moderate spectral resolution NIR spectra using an integral field unit (IFU), and images over a small field of view.

[REQ-1-OAD-3062] IRIS shall be fed MCAO corrected light from the NFIRAOS adaptive optics system.

[REQ-1-OAD-3064] IRIS, or the IRIS to NFIRAOS interface, shall provide both field derotation and pupil derotation.

[REQ-1-OAD-3068] The IRIS OIWFS sensors shall provide pixel intensities to NFIRAOS.

Discussion: From these pixel intensities, the NFIRAOS RTC will compute:

- *the tip-tilt modes necessary to perform fast guiding*
- *the focus mode necessary to calibrate the focus biases in the LGS WFS induced by the variations in the range to the sodium layer*
- *the DM Tilt anisoplanatism modes, which compensates for tilt anisoplanatism over the extended FOV without introducing higher order wavefront errors.*

[REQ-1-OAD-3069] The IRIS imager shall provide up to one configurable on-detector guide window per IRIS imager science detector.

[REQ-1-OAD-3070] IRIS shall operate at a wavelength range of 0.84 - 2.4 µm.

[REQ-1-OAD-3074] The field of view of the IRIS IFU coarsest scale shall be at least 3 arcsec in one spatial direction for integral field mode.

[REQ-1-OAD-3076] The IRIS Imaging field-of-view shall be greater than 30x30 arcsec

Discussion: Gaps within the field shall be permitted if a single detector cannot provide the required FoV for the delivered plate scale. In this event, IRIS is permitted to mosaic detectors.

[REQ-1-OAD-3080] IRIS spatial sampling shall be adjustable to offer plate scales of 0.004, 0.009, 0.025 and 0.050 arcsec/spaxel for the IFU.

[REQ-1-OAD-3082] IRIS detector sampling for imaging shall be Nyquist sampled (λ/2D) (0.004 arcsec) over 10x10 arcsec.

[REQ-1-OAD-3084] IRIS shall provide wavelength coverage ($\Delta\lambda/\lambda \leq 0.05$) for an area equivalent to 100*100 spatial pixels.

[REQ-1-OAD-3086] IRIS shall have a minimum spectral resolving power of R=4000 over entire z, Y, J, H, K bands, one band at a time.

[REQ-1-OAD-3087] The IRIS imager shall allow imager filters with a greater than 1% bandpass.

[REQ-1-OAD-3088] Throughput of the entire IRIS instrument from entrance window to detector shall be greater than 30%, not including telescope or NFIRAOS.

Discussion: This only applies whilst using Y, z, J, H and K broadband filters. Throughput is defined as an average transmission within the bandwidth which is defined by cut-on and cut-off wavelengths at 50 % of the peak throughput.

[REQ-1-OAD-3089] Throughput of the IRIS imager from entrance window to detector shall be greater than 45%, not including telescope or NFIRAOS.

[REQ-1-OAD-3090] IRIS shall not increase the (inter-OH) background by more than 15% over the sum of: inter-OH sky, telescope and NFIRAOS background (assume 7% emissivity at 273 K).

[REQ-1-OAD-3092] IRIS, in imaging mode, shall not increase the K-band background by more than 15% over natural sky.

Discussion: Future update needed to add additional OAD requirements to cover background in other bands for the IRIS CSRO, Imager, IFS and cryostat. Flow-down to Level 2 IRIS requirements for background will be needed.

[REQ-1-OAD-3094] IRIS detector dark current and read noise shall not increase the effective background by more than 5% for an integration time of 900 s.

4.3.2.5 WFOS

4.3.2.5.1 General

WFOS is a wide field, seeing limited multi-object optical spectrometer and imager.

[REQ-1-OAD-3300] In seeing limited mode, the image jitter resulting from the WFOS rotator shall be less than 33 mas RMS.

Discussion: A total of 50 mas RMS image motion for guiding and field de-rotation is allocated. This is interpreted as also including the effects of jitter due to wind and vibration. The image quality budget (RD19) includes allocations for control noise, wind and vibration, the total allowable telescope jitter resulting from these allocations is 28 mas. Allocating 33 mas for the instrument rotator leaves a contingency of 25 mas RMS.

[REQ-1-OAD-3304] WFOS shall be able to take an image of its spectrometric mode field of view.

[REQ-1-OAD-3306] WFOS shall provide atmospheric dispersion correction.

[REQ-1-OAD-3308] WFOS shall provide an acquisition and guiding system.

Discussion: If the WFOS field is not contiguous, a guider may be needed in each field to ensure slit transmission in each sub-field. Functional and performance requirements on the acquisition and guiding system are given in Sections 5.1.1 and 5.1.4.

[REQ-1-OAD-3310] WFOS shall provide a LOWFS (low order wavefront sensor) to supply active optics feedback signals.

Discussion: It is expected that this higher order LOWFS can serve as a guider for one of the fields.

[REQ-1-OAD-3324] The WFOS wavelength range shall be 0.31 - 1.0 µm.

Discussion: The waveband blue limit assumes Mauna Kea and appropriate TMT mirror coatings. The blue cutoff should be the wavelength at which the telescope + atmospheric transmission is > ~5%.

[REQ-1-OAD-3326] WFOS, in imaging mode and excluding atmospheric seeing and telescope contributions, shall yield an image quality measured at the instrument focal plane, including polychromatic correction residuals, no worse than 0.45 arcsec FWHM.

Discussion: This requirement ensures that aberrations and residual atmospheric dispersion after the ADC correction do not significantly degrade WFOS image quality in imaging mode.

Discussion: The spectroscopic image quality requirement for WFOS defines the performance for the post-focal plane optics in the instrument. The imaging requirement also includes the residual atmospheric dispersion, and is relevant primarily in the UV where dispersion is changing very rapidly with wavelength. The problem of residual atmospheric dispersion may be mitigated by using narrower broad-band filters in the UV.

[REQ-1-OAD-3328] WFOS in spectroscopy mode, excluding atmospheric seeing and telescope contributions, shall yield encircled energy > 80% within an angular diameter of 0.25 arcsec on-sky.

Discussion: 0.25 arcsec on-sky is equivalent to 72 µm at the detector focal plane. This requirement is equivalent to measuring a PSF FWHM of 48 µm at the detector focal plane, and ensures adequate image quality of a 0.25 arcsec wide slit without degrading the resulting LSF. A 0.25 arcsec slit provides a higher effective spectral resolution (if desired) and is appropriate for GLAO point-source observations.

[REQ-1-OAD-3330] The WFOS spectroscopy field of view shall be ≥ 25 $arcmin^2$.

Discussion: The field need not be continuous.

[REQ-1-OAD-3331] The WFOS imaging field of view shall be ≥ 25 $arcmin^2$.

[REQ-1-OAD-3332] The WFOS total slit length shall be ≥ 500 arcsec.

Discussion: This requirement is motivated by the desire for a multiplex of at least 60 given reasonable assumptions about slitlet length and targeting efficiency.

[REQ-1-OAD-3336] WFOS shall provide a medium resolution mode with a median spectral resolution of R > 3500, with a 0.75 arcsec slit.

[REQ-1-OAD-3337] WFOS shall provide a low resolution mode with a median spectral resolution of R > 1500, with a 0.75 arcsec slit, over the full waveband in one exposure.

[REQ-1-OAD-3338] WFOS, in spectroscopy mode, shall have an on-axis throughput of ≥ 25% from 0.31 µm - 1.00 µm, and ≥ 30% from 0.35 µm - 0.90 µm, not including the telescope.

Discussion: Throughput includes detector quantum efficiency. Throughput does not include losses due to slit masks. There may be vignetting at the edge of the field.

[REQ-1-OAD-3340] WFOS systematic errors, arising from background subtraction, scattered light, and detector noise, evaluated over a cumulative 8 hours of on-source integration time and at the channel centers of the low and medium resolution modes, shall degrade the sky background-subtracted signal-to-noise ratio by no more than 5% of the sky background Poisson error.

[REQ-1-OAD-3341] WFOS systematic errors, arising from background subtraction, scattered light, and detector noise, evaluated over a cumulative 8 hours of on-source integration time and at the channel centers of the low and medium resolution modes, shall introduce biases in accuracy no greater than 10% of the sky background Poisson error.

Discussion: Nod and shuffle capability in the detectors may be desirable.

[REQ-1-OAD-3342] Stability of the spectral format on the WFOS detector focal plane, excluding atmospheric seeing and telescope contributions, shall be less than 1 pixel over a duration of 3 hours.

Discussion: Spectral format is the position layout of spectral and spatial information formed on the detector by the WFOS optics. The 3 hour duration is driven by the typical time to track an observation on the sky.

4.3.2.5.2 WFOS Desirable Features

Discussion: A goal is to record the entire wavelength range in a single exposure. However, this wavelength range can be covered through multiple optimized arms covering suitable wavelength ranges.

Discussion: A goal is to provide enhanced image quality using Ground Layer Adaptive Optics, over the full wavelength range, and the full field of the spectrograph.

Discussion: A goal is to provide imaging through narrow band filters.

Discussion: A goal is to provide a cross-dispersed mode for smaller sampling density and higher spectral resolution.

Discussion: A goal is to provide an integral field unit (IFU) mode.

4.3.2.6 MODHIS

4.3.2.6.1 General

[REQ-1-OAD-3252] MODHIS shall be fed an adaptive optics corrected beam from the NFIRAOS adaptive optics system.

[REQ-1-OAD-3253] The MODHIS OIWFS sensors shall provide pixel intensities to NFIRAOS.

[REQ-1-OAD-3254] MODHIS shall include one NGS wavefront sensor to provide guide star position feedback.

[REQ-1-OAD-3256] The MODHIS to NFIRAOS interface shall permit instrument rotation to provide field derotation.

[REQ-1-OAD-3258] MODHIS shall provide a pupil mask that can rotate to match the telescope pupil.

[REQ-1-OAD-3260] The MODHIS science channel shall provide wavelength coverage over the 0.95 µm – 2.4 µm range.

Discussion: MODHIS operates behind NFIRAOS and the baseline passband provided by NFIRAOS to its port-mounted science instruments is limited to the 0.8 – 2.45 µm range. Changing out the baseline NFIRAOS beam splitter would enable a broader bandpass. NOTE: NFIRAOS AO WFS also requires light below 0.8 µm.

Discussion: To enable real-time monitoring of its observed science field, MODHIS's front end may be required to provide broader wavelength coverage than its science channel. The blue end cut-off for science as well as the bandpass requirements needed for any field monitoring/acquisition camera should be assessed during its conceptual design phase. Providing requirements are met, WFS that exist outside of the science field-of-regard can operate freely over any bandpass selected from within the range of that delivered by NFIRAOS.

[REQ-1-OAD-3262] The MODHIS science channel shall provide simultaneous coverage for a given science target across the full yJ and HK astronomical bands.

[REQ-1-OAD-3264] MODHIS shall provide an average spectral resolution R ≥ 100,000 over its entire science passband.

[REQ-1-OAD-3266] MODHIS shall provide an instrumental radial velocity precision of ≤ 30 cm/s (goal of 10 cm/s).

Discussion: The requirement on MODHIS is only one term in the realized precision of an RV measurement. Overall precision depends on additional terms contributed by the telescope and the AO unit, as well as the coupling to the instrument, all of which are currently unspecified and unknown. Additional contributions to the error budget are the signal-to-noise of the observation, systematics from telluric correction, etc. Single measurement RV precision goals should not be limited by the internal stability of MODHIS.

[REQ-1-OAD-3270] The MODHIS science channel shall be capable of performing science on a single target with a goal of offering a multiplex of up to 4 separate simultaneous science targets.

Discussion: An instance of multiplex must include provisions for object, sky, and calibration.

[REQ-1-OAD-3272] MODHIS shall provide an unvignetted field-of-regard ≥ 4 x 4 arcsecs square.

Discussion: To maximize image quality the MODHIS field-of-regard is assumed to be centered on-axis relative to the 2 arcminute field-of-regard relayed by NFIRAOS.

Discussion: The MODHIS field-of-regard is deliverable to both its science channel as well as any required field acquisition/monitoring channel. WFS architecture is permitted to patrol outside this field but is required to provide WFS capabilities within the 2 arcmin diameter field as delivered by NFIRAOS.

[REQ-1-OAD-3275] The MODHIS science channel shall be capable of Nyquist sampling a point source from within the field-of-regard in each of y, J, H, and K bands.

Discussion: To prevent appreciable under-sampling in the redder end of the MODHIS broad bandpass science channel, it is acceptable to use different fibers for select bandpasses.

[REQ-1-OAD-3280] The MODHIS science channel end-to-end throughput shall be ≥ 10%.

Discussion: The requirement excludes the performance of both the telescope and NFIRAOS.

[REQ-1-OAD-3285] The MODHIS front end instrument shall not degrade the wavefront quality of that delivered by NFIRAOS by more than 40 nm RMS.

[REQ-1-OAD-3287] The MODHIS spectrograph shall provide an ensquared energy ≥ 80% within a single pixel across 95% of the detector area.

[REQ-1-OAD-3290] MODHIS shall enable subtraction of the background to better than 1%.

[REQ-1-OAD-3292] MODHIS shall provide raw contrast ratio of ≥ 100 from 0.5 λ/D to 2 λ/D and ≥ 1,000 from 2 λ/D to the edge of the field of regard.

[REQ-1-OAD-3295] MODHIS shall provide spectropolarimetry with 0.1% (goal) polarimetric precision in y and J bands.

4.3.3 First Decade

[REQ-1-OAD-3296] Implementation and commissioning of any of the first decade instruments described in this section shall not result in the loss of more than 15 nights per instrument of productive science observing time.

4.4 Services

4.4.1 Power, Lighting and Grounding

4.4.1.1 Power

The electrical power types delivered to various locations of the observatory are described in 'Table 4-18: Power Types Delivered to the Observatory'.

Table 4-18: Power Types Delivered to the Observatory

Type	Voltage	Power Conditioning	Phase	Backup Type
H3D	480Y277V	None	3	None
H3DG	480Y277V	None	3	Generator
H3CUG	480Y277V	Clean	3	UPS
L3D	208Y120V	None	3	None
L3DG	208Y120V	None	3	Generator
L3C	208Y120V	Clean	3	None
L3CUG	208Y120V	Clean	3	UPS
EMUPS	208Y120V	Clean	3	UPS

Discussion: The power conditioning types are currently identified as either ‘clean’ or ‘none’, depending on the anticipated level of power conditioning that will be applied. These descriptions will be replaced with reference to the appropriate standard. On the telescope azimuth and elevation structure, 120V single phase power will be taken off as single legs to neutral from the delivered 4 wire 3 phase power.

All three phase power will be delivered in four wire ‘Y’ configuration with at least full size neutral to allow use of single legs to neutral.

Discussion: Electrical power will be provided to the observatory at the locations described in 'Table 4-19: Power Loads Inside Dome' and 'Table 4-20: Power Loads Inside Summit Facilities'.

Table 4-19: Power Loads Inside Dome

Power Loads Inside Dome					
REQ ID	Subsystem	Location	Power Type	Allocated: Total Connected (kW)	Notes
[REQ-1-OAD-0801]	First Light	Distributed	EMUPS	0.43	(1)
			H3D	173.43	
			H3DG	1682.80	
			L3C	18.64	
			L3CUG	63.17	
			L3D	113.00	
			L3DG	0.00	
	First Decade	Distributed	EMUPS	0.92	
			H3D	173.43	
			H3DG	1682.80	
			L3C	30.64	
			L3CUG	94.04	
			L3D	123.00	
			L3DG	4.51	
[REQ-1-OAD-0986]	AM2	EL +X 5	L3CUG	12.02	(2)
[REQ-1-OAD-0911]	APS	NAS -X 4	L3C	0.61	
	APS	NAS -X 4	L3CUG	1.02	
	APS	NAS -X 4	L3D	4.19	
[REQ-1-OAD-0934]	CIS	EL -X 5	L3CUG	0.70	
	CIS	EL +X 5	L3CUG	0.70	
	CIS	FB 1	L3CUG	0.70	
	CIS	NAS -X 4	L3CUG	0.70	
	CIS	NAS +X 4	L3CUG	0.70	
[REQ-1-OAD-0907]	CLN	EL -X 5	L3CUG	0.32	
	CLN	EL +X 5	L3CUG	0.32	
	CLN	NAS -X 3	L3CUG	0.86	
	CLN	NAS +X 3	L3CUG	0.86	
	CLN	NAS -X 3	H3D	1.96	
	CLN	NAS +X 3	H3D	1.96	
[REQ-1-OAD-0908]	M2/M3 COAT	FB 1	H3D	160.00	
	M2/M3 COAT	FB 1	L3CUG	0.02	
	M2/M3 COAT	FB 1	L3D	40.20	
[REQ-1-OAD-0982]	CRYO	NAS -X 3	L3CUG	0.10	
	CRYO	NAS -X 3	L3D	0.50	
	CRYO	NAS +X 3	L3CUG	0.10	
	CRYO	NAS +X 3	L3D	0.50	
[REQ-1-OAD-0900]	ENC	FB 1	H3DG	1682.80	
	ENC	FB 1	L3CUG	2.70	
[REQ-1-OAD-0916]	ESEN	EL -X 5	L3CUG	0.60	
	ESEN	EL +X 5	L3CUG	0.40	
	ESEN	NAS -X 4	L3CUG	0.10	
	ESEN	NAS +X 4	L3CUG	0.10	
[REQ-1-OAD-0926]	HROS	NAS +X 4	EMUPS	0.49	
	HROS	NAS +X 4	L3C	3.00	
	HROS	NAS +X 4	L3CUG	2.02	
	HROS	NAS +X 4	L3D	10.00	
	HROS	NAS +X 4	L3DG	4.51	
[REQ-1-OAD-0923]	IRIS	NAS -X 4	L3C	2.25	
	IRIS	NAS -X 4	L3CUG	8.95	
[REQ-1-OAD-0927]	IRMOS	NAS +X 4	L3C	5.00	
	IRMOS	NAS +X 4	L3CUG	2.02	
[REQ-1-OAD-0920]	LGSF	EL -X 5	L3C	10.40	
	LGSF	EL -X 5	L3CUG	3.01	
	LGSF	EL -X 5	L3D	26.09	
	LGSF	TOP 7	L3CUG	1.73	
[REQ-1-OAD-0914]	M1CS	M1C 5	L3CUG	17.50	
[REQ-1-OAD-0905]	M2S	EL +X 5	L3CUG	2.58	(2)
	M2S	TOP 7	L3CUG	0.08	
[REQ-1-OAD-0906]	M3S	M1C 5	L3CUG	6.10	
[REQ-1-OAD-0929]	MIRAO	NAS -X 4	L3CUG	5.02	
[REQ-1-OAD-0930]	MIRES	NAS -X 4	L3CUG	2.02	
[REQ-1-OAD-0925]	MODHIS	NAS -X 4	L3CUG	1.95	
[REQ-1-OAD-0918]	NFIRAOS	NAS -X 4	EMUPS	0.43	
	NFIRAOS	NAS -X 4	L3C	5.38	
	NFIRAOS	NAS -X 4	L3CUG	8.54	
	NFIRAOS	NAS -X 4	L3D	41.53	
[REQ-1-OAD-0932]	NIRES-R	NAS -X 4	L3CUG	6.03	

Power Loads Inside Dome				
REQ ID	Subsystem	Location	Power Type	Allocated: Total Connected (kW)
[REQ-1-OAD-0903]	STR	AZ 0	H3DG	30.00
	STR	AZ 1	H3DG	27.83
	STR	AZ 1	L3CUG	0.24
	STR	AZ 2	L3CUG	0.92
	STR	AZ 2	L3DG	0.75
	STR	EL -X 5	L3CUG	1.12
	STR	EL -X 5	L3DG	17.80
	STR	EL +X 5	L3CUG	0.90
	STR	EL +X 5	L3DG	9.10
	STR	NAS -X 2	H3DG	12.00
	STR	NAS -X 2	L3CUG	1.70
	STR	NAS -X 3	L3CUG	0.30
	STR	NAS +X 2	L3CUG	1.70
	STR	NAS +X 3	L3CUG	0.70
	STR	NAS +X 3	L3DG	10.00
	STR	SHS 6	L3CUG	1.27
	STR	SHS 6	L3DG	10.30
[REQ-1-OAD-0917]	STR.TUS	AZ 0	EMUPS	0.08
	STR.TUS	AZ 0	L3D	0.36
	STR.TUS	AZ 0	L3DG	0.16
	STR.TUS	AZ 1	EMUPS	0.88
	STR.TUS	AZ 1	L3D	3.60
	STR.TUS	AZ 1	L3DG	1.23
	STR.TUS	AZ 2	EMUPS	0.19
	STR.TUS	AZ 2	L3D	1.08
	STR.TUS	AZ 2	L3DG	0.65
	STR.TUS	AZ 3	EMUPS	0.11
	STR.TUS	AZ 3	L3D	0.36
	STR.TUS	AZ 3	L3DG	0.11
	STR.TUS	EL -X	EMUPS	0.33
	STR.TUS	EL -X 5	EMUPS	0.09
	STR.TUS	EL -X 5	L3D	0.72
	STR.TUS	EL -X 5	L3DG	0.30
	STR.TUS	EL -Y	EMUPS	0.53
	STR.TUS	EL -Y	L3D	1.08
	STR.TUS	EL -Y	L3DG	0.33
	STR.TUS	EL +-X,-Y	L3D	0.36
	STR.TUS	EL +-X,+-Y	EMUPS	0.30
	STR.TUS	EL +-X,+-Y	L3D	0.72
	STR.TUS	EL +-X,+-Y	L3DG	2.20
	STR.TUS	EL +X	EMUPS	0.33
	STR.TUS	EL +X 5	L3DG	0.10
	STR.TUS	EL +Y	EMUPS	0.34
	STR.TUS	EL +Y	L3D	0.36
	STR.TUS	EL +Y	L3DG	0.16
	STR.TUS	M1C 5	EMUPS	0.66
	STR.TUS	M1C 5	L3D	7.56
	STR.TUS	M1C 5	L3DG	3.79
	STR.TUS	NAS -X 2	EMUPS	0.33
	STR.TUS	NAS -X 2	L3D	0.90
	STR.TUS	NAS -X 2	L3DG	0.62
	STR.TUS	NAS -X 3	EMUPS	0.19
	STR.TUS	NAS -X 3	L3D	2.34
	STR.TUS	NAS -X 3	L3DG	0.60
	STR.TUS	NAS -X 4	EMUPS	0.64
	STR.TUS	NAS -X 4	L3D	2.52
	STR.TUS	NAS -X 4	L3DG	1.43
	STR.TUS	NAS -X 5	EMUPS	0.06
	STR.TUS	NAS -X 5	L3DG	0.10
	STR.TUS	NAS +X 2	EMUPS	0.19
	STR.TUS	NAS +X 2	L3D	0.36
	STR.TUS	NAS +X 2	L3DG	0.46
	STR.TUS	NAS +X 3	EMUPS	0.22
	STR.TUS	NAS +X 3	L3D	2.34
	STR.TUS	NAS +X 3	L3DG	0.60
	STR.TUS	NAS +X 4	EMUPS	0.57
	STR.TUS	NAS +X 4	L3CUG	0.10

Table 4-20: Power Loads Inside Summit Facilities

Power Loads Inside SUM					
REQ ID	Subsystem	Location	Power Type	Allocated: Total Connected (kW)	Notes
[REQ-1-OAD-0803]	First Light	Support Building/ Tunnel	H3D	1284.64	(1)
			H3DG	255.81	
			L3C	25.02	
			L3CUG	109.15	
			L3D	125.51	
			L3DG	9.70	
	First Decade	Support Building/ Tunnel	H3D	1284.64	
			H3DG	255.81	
			L3C	25.02	
			L3CUG	121.15	
			L3D	125.51	
			L3DG	9.70	
[REQ-1-OAD-0987]	AM2	SF 1	L3CUG	2.00	(2)
[REQ-1-OAD-0962]	AOESW	SF 1	L3CUG	13.30	
[REQ-1-OAD-0952]	APS	SF 1	L3CUG	3.00	
[REQ-1-OAD-0975]	CIS	SF 1	L3CUG	7.60	
[REQ-1-OAD-0988]	CLN	SF 1	L3CUG	0.20	
[REQ-1-OAD-0949]	M1 COAT	SF 1	H3D	172.75	
	M1 COAT	SF 1	L3C	3.70	
	M1 COAT	SF 1	L3CUG	0.02	
	M1 COAT	SF 1	L3D	40.20	
[REQ-1-OAD-0984]	CRYO	SF 1	H3D	189.00	
	CRYO	SF 1	L3CUG	1.00	
	CRYO	SF 1	L3D	1.00	
[REQ-1-OAD-0976]	CSW	SF 1	L3CUG	7.70	
[REQ-1-OAD-0977]	DMS	SF 1	L3CUG	9.15	
[REQ-1-OAD-0980]	DPS	SF 1	L3CUG	1.50	
[REQ-1-OAD-0957]	ESEN	SF 1	L3CUG	0.50	
[REQ-1-OAD-0978]	ESW	SF 1	L3CUG	9.21	
[REQ-1-OAD-0967]	HROS	SF 1	L3CUG	1.50	
[REQ-1-OAD-0964]	IRIS	SF 1	L3CUG	4.60	
[REQ-1-OAD-0968]	IRMOS	SF 1	L3CUG	3.00	
[REQ-1-OAD-0961]	LGSF	SF 1	L3CUG	5.80	
[REQ-1-OAD-0955]	M1CS	SF 1	L3CUG	3.02	
[REQ-1-OAD-0946]	M2S	SF 1	L3CUG	1.50	(2)
[REQ-1-OAD-0947]	M3S	SF 1	L3CUG	1.50	
[REQ-1-OAD-0970]	MIRAO	SF 1	L3CUG	1.50	
[REQ-1-OAD-0971]	MIRES	SF 1	L3CUG	1.50	
[REQ-1-OAD-0966]	MODHIS	SF 1	L3CUG	1.50	
[REQ-1-OAD-0959]	NFIRAOS	SF 1	L3CUG	10.00	
[REQ-1-OAD-0973]	NIRES-R	SF 1	L3CUG	3.00	
[REQ-1-OAD-0943]	OSS	SF 1	L3CUG	0.75	
[REQ-1-OAD-0969]	PFI	SF 1	L3CUG	3.00	
[REQ-1-OAD-0985]	REFR	SF 1	H3D	25.00	
	REFR	SF 1	L3CUG	0.50	
[REQ-1-OAD-0981]	SCMS	SF 1	L3CUG	2.53	
[REQ-1-OAD-0979]	SOSS	SF 1	L3CUG	2.10	
[REQ-1-OAD-0944]	STR	SF 1	H3D	394.29	
	STR	SF 1	H3DG	20.10	
	STR	SF 1	L3CUG	3.12	
[REQ-1-OAD-0942]	SUM	AZ 0	L3D	2.00	
	SUM	SF 1	H3D	503.61	
	SUM	SF 1	H3DG	235.71	
	SUM	SF 1	L3C	21.32	
	SUM	SF 1	L3CUG	15.40	
	SUM	SF 1	L3D	82.31	
	SUM	SF 1	L3DG	9.70	
[REQ-1-OAD-0953]	TCS	SF 1	L3CUG	0.66	
[REQ-1-OAD-0950]	TINS	SF 1	L3CUG	1.50	
[REQ-1-OAD-0965]	WFOS	SF 1	L3CUG	1.50	

Notes:
(1) These values show total connected load and are not representative of power usage
(2) Power system is sized for larger of AM2/M2S

[REQ-1-OAD-4410] A backup generator shall be provided that allows automatic load transfer within 30 seconds of loss of normal power.

[REQ-1-OAD-4425] The backup generator shall be sized to support the loads (L3CUG, L3DG, H3DG, EMUPS) described in *'Table 4-19: Power Loads Inside Dome'* and *'Table 4-20: Power Loads Inside Summit Facilities'.*

Discussion: Typical loads supported by the backup generator include:

- *Any single 480V load on the enclosure rotating structure (e.g. shutter or crane, not concurrently)*
- *All UPS loads including computer room, instrument electronics, control panels, safety system etc.*
- *Computer room air handler*
- *Pumps for chilled water,*
- *Some chiller or equivalent cooling capacity*
- *Cryogenic Cooling*
- *Elevators*
- *Cranes*
- *Mirror stripping exhaust fan*

[REQ-1-OAD-4430] A centralized UPS shall be provided to cover a period of one minute between loss of normal power and transfer of load to the backup generator.

Discussion: The purpose of the UPS is to maintain power to systems and equipment that cannot tolerate the expected 30 second delay between loss of normal power and the availability of the backup generator. All UPS loads will be transferred to the backup generator when its operation allows load transfer. This approach is taken in preference to the alternative of maintaining power to equipment until it can be manually shut down in a predictable manner.

[REQ-1-OAD-4435] All equipment and sub-systems shall be able to withstand complete loss of power without sustaining damage or causing damage to other personnel and other equipment.

Discussion: This is to ensure that no damage will result should the backup generator fail to start within the time supported by the UPS.

[REQ-1-OAD-4505] All power within the observatory shall be protected via fuses or circuit breakers.

4.4.1.2 LIGHTING

The SUM subsystem is responsible for providing the end-to-end lighting system, including equipment such as lighting fixtures, lighting management control system and panel. The overall lighting system provides general, task, and emergency lighting, including exit signage lighting. The SUM lighting system interfaces with the STR and ENC lighting systems.

The STR (TUS) subsystem designs the telescope lighting system, including routing (including through cable wrap), mounting locations for equipment, and interfaces to the SUM lighting system. The telescope lighting system, including emergency lighting, is designed to provide lighting for the following areas:

- Telescope elevation
- Telescope azimuth
- Telescope fixed structures

The ENC subsystem designs the Enclosure lighting system, including routing and mounting locations for equipment. This lighting system includes emergency lighting. It also provides dedicated slip rings for lighting communication and interfaces with the SUM lighting system.

[REQ-1-OAD-5085] Lighting on the interior of the fixed and rotating enclosure shall be provided at the following illumination levels and locations:

- Illumination of interior of the enclosure at 100 lux
- Illumination of walkways and stairways at 300 lux

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

[REQ-1-OAD-4600] Telescope operational and emergency lighting shall be provided at the illumination levels and locations defined in the Telescope Work Areas (AD93).

[REQ-1-OAD-4615] Enclosure spot and emergency lighting shall be available for the defined work areas associated with ENC operation and maintenance activities on the interior of the fixed and rotating enclosure.

[REQ-1-OAD-4620] General illumination on lighting zones shall be controlled independently of each other and using a communication network.

4.4.1.3 Bonding/Grounding

The bonding/grounding system is used for the protection of mission critical equipment and personnel against abnormal voltage surge levels and elevated potentials due to lightning, static electricity, induced radio frequency (RF) and electromagnetic interference (EMI) and noise, and conductive surface touch and step voltage potentials as a result of abnormal electrical feeder and branch circuit phase to phase and phase to ground fault current events and levels.

4.4.2 Coolant

[REQ-1-OAD-4660] Chilled water shall be supplied to the observatory at the temperatures defined in '*Table 4-21: Observatory Chilled Water Supply*'

Table 4-21: Observatory Chilled Water Supply

Description	Temperature (ºC)	Comments	Anticipated Uses
Fixed Temperature Chilled Water (FTCW)	7	Chosen at operating temperature for standard chiller equipment	Majority of facility cooling including computer room, mirror coating equipment, CRYO and REFR equipment
Fixed Temperature Chilled Water, low temperature (FTCW-L)	-15		Enclosure air handlers and hydrostatic bearing system
Variable Temperature Chilled Water (VTCW)	See comments	Temperature approximately 5 degrees C below the desired enclosure temperature for the next night's observing. The offset below the enclosure temperature set point may vary depending on the set point.	LGSF electronics on the Laser Platform as well as STR drives and motors.

Discussion: 'Chilled water' refers to a water/glycol mixture appropriate to prevent freezing over the range of site temperatures. This includes both 'fixed' and 'variable temperature' chilled water types.

Discussion: To mitigate the risk of damage to optics and electronics from potential leaking, phase-change refrigerant cooling is used to remove waste heat from instruments and other electronics on the telescope, where possible.

[REQ-1-OAD-4670] The normal operating pressure of the chilled water supplies listed in '*Table 4-21: Observatory Chilled Water Supply*' above will be 5 bar.

[REQ-1-OAD-4675] The maximum pressure drop through any single chilled water heat exchanger shall be less than 1 bar.

[REQ-1-OAD-4610] TMT Instrumentation Cooling Subsystems (CRYO/REFR) defined in OAD Section 2.2.1.3 shall operate and meet all requirements for at least 50 years with preventive maintenance.

Discussion: Preventive maintenance means servicing, repairing, and replacing components and subsystems based on their expected lifetime, as opposed to their failure.

[REQ-1-OAD-4730] In the event of a failure of the normal power supply, the following cooling systems shall be maintained:

- Cooling to the summit facility computer room
- Refrigerant cooling
- Variable temperature chilled water

Discussion: It is expected that the variable chilled water temperature will be maintained at an elevated temperature, possibly by using the enclosure air handlers to cool it.

4.4.2.1 Fixed Temperature Chilled Water

Fixed Temperature Chilled Water is a chilled water/glycol mixture provided within the Summit Facilities for cooling the Enclosure air handlers, HBS oil supply, REFR compressors, CRYO compressors, STR drive amplifiers, and various pumps and chillers, as described in *'Table 4-22: FTCW Loads'*.

Two types of FTCW are provided for different cooling schemes. FTCW supplies chilled water at a nominal temperature of +7 ºC, and FTCW-L supplies chilled water at a nominal low temperature of -15 ºC.

Table 4-22: FTCW Loads

FTCW Loads				
REQ ID	Subsystem Equipment (Location)	FTCW Type	Allocation: Rejected Heat Load [kW]	Notes
[REQ-1-OAD-0811]	First Light	FTCW	329.7	
		FTCW-L	293.1	
	First Decade	FTCW	542.1	
		FTCW-L	316.7	
[REQ-1-OAD-0993]	SUM			
	Computer Room (AHU-01) (SF 1)	FTCW	82.4	
	Engineering & Optics Lab (AHU-02) (SF 1)	FTCW	12.3	
	Control Room (AHU-03) (SF 1)	FTCW	4.9	
	M1 Coating (FC-05) (SF 1)	FTCW	4.8	
	Facility Air Compressors (SF 1)	FTCW	45.0	
	Water/Electrical (FC-07) (SF 1)	FTCW-L	15.5	
	VTCW (HX-01) (SF 1)	FTCW-L	55.0	
	Enclosure Cooling (AHU-05,06,07) (FB 1)	FTCW-L	160.0	
[REQ-1-OAD-1998]	M1COAT			
	M1 Mirror Coating (SF 1)	FTCW	57.7	(1)
[REQ-1-OAD-1997]	M2M3COAT			
	M2/M3 Mirror Coating (FB 1)	FTCW	57.7	(1)
[REQ-1-OAD-0995]	CRYO			
	LN2 Compressors (SF 1)	FTCW	150.0	
	Sub-LN2 Compressors (SF 1)	FTCW	37.5	
[REQ-1-OAD-0996]	REFR			
	REF-A Cooling (SF 1)	FTCW	147.5	
	REF-SZ Cooling (SF 1)	FTCW-L	59.6	
	REF-H Cooling (SF 1)	FTCW-L	84.3	
Notes:				
(1) FTCW system is sized for M1COAT (not concurrently operated with M2M3COAT)				

4.4.2.2 Variable Temperature Chilled Water

The Variable Temperature Chilled Water system circulates water/glycol that has been cooled to +5 ºC below ambient conditions and is expecting the water to leave the instrument at ambient air temperature. It is capable of generating VTCW down to -10 ºC. VTCW is provided to the telescope Laser Platform on the Elevation structure for removal of heat from the lasers and laser electronics, and to STR equipment at the locations described in *'Table 4-23: VTCW (Glycol) Loads'*.

Table 4-23: VTCW (Glycol) Loads

VTCW (Glycol) Loads			
REQ ID	Subsystem Location	Allocation: CON [L/min]	Notes
[REQ-1-OAD-0812]	**First Light**	**184.0**	
	First Decade	**212.0**	
[REQ-1-OAD-0990]	LGSF		
	EL -X 5 (LGSF)	56.0	(1)
	EL -X 5 (LGSF + upgrade)	84.0	
[REQ-1-OAD-0991]	STR		
	NAS -X 2	28.0	
	NAS +X 2	28.0	
	NAS -X 3	16.0	
	NAS +X 3	16.0	
	AZ 0	40.0	
[REQ-1-OAD-0992]	STR.TUS		
	NAS -X 4 (Telescope Nasmyth General Supply)	10.0	(2)
	NAS +X 4 (Telescope Nasmyth General Supply)	10.0	
[REQ-1-OAD-1996]	SUM		
	Engineering & Optics Lab	10.0	(2)
	Instrument Station Observing Floor #1	10.0	
	Instrument Station Observing Floor #2	10.0	
	Instrument Station Wedge Room	10.0	
Notes:			
(1) VTCW system is sized for LGSF + upgrade			
(2) VTCW system should not be sized for these payloads but SUM/STR.TUS are responsible for routing stubs			

4.4.2.3 Refrigerant (CO2)

Liquid CO2 refrigerant is provided to the telescope for removal of electronics heat via phase-change cooling at the locations described in *'Table 4-24: REFR Loads'*.

Three types of CO2 refrigerant are provided for different cooling schemes. Ambient refrigerant (REF-A) is used to cool electronics and equipment enclosures on the telescope to ambient temperature. Sub-zero refrigerant (REF-SZ) is provided to instruments that require cooling to a temperature of approximately -35°C to reduce infrared thermal emission from optical surfaces. HBS oil refrigerant (REF-H) is used to cool the hydrostatic bearing subsystem (HBS) oil for the telescope.

Table 4-24: REFR Loads

REFR Loads				
REQ ID	Subsystem Location	REFR Type	Allocation: Cool-Down Power [kW]	Allocation: Steady-State Power [kW]
[REQ-1-OAD-1031]	First Light	REF-A	-	54.2
		REF-SZ	28.5	8.2
	First Decade	REF-A	-	91.8
		REF-SZ	38.2	16.8
[REQ-1-OAD-1031]	M2S*			
	EL +X 5	REF-A	-	2.4
	TOP 7	REF-A	-	10.0
[REQ-1-OAD-1032]	AM2*			
	EL +X 5	REF-A	-	2.4
	TOP 7	REF-A	-	10.0
[REQ-1-OAD-1033]	M3S			
	M1C 5	REF-A	-	3.0
[REQ-1-OAD-1034]	APS			
	NAS -X 4	REF-A	-	7.0
[REQ-1-OAD-1035]	NFIRAOS			
	NAS -X 4	REF-A	-	13.0
	NAS -X 4	REF-SZ	25.1	7.0
[REQ-1-OAD-1036]	LGSF			
	EL -X 5	REF-A	-	2.8
	TOP 7	REF-A	-	2.0
[REQ-1-OAD-1037]	IRIS			
	NAS -X 4	REF-A	-	7.0
	NAS -X 4	REF-SZ	1.7	0.6
[REQ-1-OAD-1038]	MODHIS			
	NAS -X 4	REF-A	-	2.0
	NAS -X 4	REF-SZ	1.7	0.6
[REQ-1-OAD-1039]	WFOS			
	NAS +X 4	REF-A	-	5.0
[REQ-1-OAD-1041]	HROS			
	NAS +X 4	REF-A	-	10.0
[REQ-1-OAD-1042]	IRMOS			
	NAS +X 4	REF-A	-	10.0
	NAS +X 4	REF-SZ	10.0	8.0
[REQ-1-OAD-1043]	MIRAO			
	NAS -X 4	REF-A	-	3.9
[REQ-1-OAD-1044]	MIRES			
	NAS -X 4	REF-A	-	3.9
[REQ-1-OAD-1046]	NIRES-R			
	NAS -X 4	REF-A	-	3.9
[REQ-1-OAD-1047]	PFI			
	NAS -X 4	REF-A	-	3.9
[REQ-1-OAD-1045]	NSI			
	NAS -X 4	REF-A	-	2.0
	NAS +X 4	REF-SZ	1.7	0.6
[REQ-1-OAD-1048]	STR			
	SUM	REF-H	-	74.2
	*REFR system is sized for larger of AM2/M2S			

[REQ-1-OAD-4740] For instrument cooled enclosures, the gaseous return pressure shall be regulated to maintain the refrigerant boiling point (REF-SZ) at temperatures not to exceed -35°C for steady state, and not to exceed -40°C for cooldown.

[REQ-1-OAD-4741] For electronics cooling, the gaseous return pressure shall be regulated to maintain the refrigerant boiling point (REF-A) within 2°C of the ambient enclosure cooling set point.

Discussion: The ambient enclosure cooling set point (REF-A) is selected whenever feasible to be above the anticipated dew/frost point in the observatory. For the purposes of design subsystem *teams can assume that the refrigerant boiling point is never set to a value below the local frost/dew point.*

4.4.2.4 CRYOGEN

Cryogen is provided to cool instrument detectors to temperatures with sufficiently low dark current and to cool optical components of IR instruments in large dewars to cryogenic temperatures sufficient to keep their contribution to background thermal emission as low as possible, as described in *'Table 4-25: Instrument Steady State Cryogenic Cooling Requirements'*.

Two types of cryogen are provided: Liquid Nitrogen (LN2) is provided for instrument components whose target temperature is above the LN2 boiling point, and sub-LN2 is provided for instrument components whose target temperature is below the LN2 boiling point.

Requirements for cooling future instruments below the boiling point of LN2 at the ambient pressure in the observatory are under development.

[REQ-1-OAD-4748] Cryogenic cooldown heat removal for a single instrument shall not exceed 400 MJ, removed over a time constant of not less than 68,000 s.

Table 4-25: Instrument Steady State Cryogenic Cooling Requirements

CRYO Loads

Requirement ID	Instrument	Location	Generation	Cooling Type	Subsystem	Steady-State Target Temperature (K)	Allocated Steady-State Cooling Power (W)
[REQ-1-OAD-0814]	Various	Nasmyth	First Light	LN_2	-	-	291
	Various	Nasmyth	First Decade	LN_2	-	-	1577
				sub-LN_2	-	-	141
[REQ-1-OAD-4760]	IRIS	NAS -X	First Light	LN_2	Detector+Dewar	77	100
				LN_2	OIWFS	80	36
[REQ-1-OAD-4761]	MODHIS	NAS -X	First Light	LN_2	Detector	77	57
				LN_2	Dewar	120	
				LN_2	OIWFS	82	8
[REQ-1-OAD-4762]	APS	NAS -X	First Light	LN_2	Detector	160	30
[REQ-1-OAD-4763]	WFOS	NAS +X	First Light	LN_2	Detector	173	60
				N/A	AGWFS	N/A	N/A
[REQ-1-OAD-4764]	MIRES	NAS -X	First Decade	sub-LN_2	Detector	6	1
				sub-LN_2	Structure	20	30
				LN_2	Structure + Shield	80	170
				LN_2	OIWFS	82	8
[REQ-1-OAD-4766]	NIRES-R	NAS -X	First Decade	sub-LN_2	Detector	30	10
				sub-LN_2	Structure	60	30
				LN_2	Structure	80	320
				LN_2	OIWFS	82	33
[REQ-1-OAD-4767]	PFI	NAS -X	First Decade	sub-LN_2	Detector+Dewar	40	70
				LN_2	OIWFS	82	25
[REQ-1-OAD-4768]	IRMOS	NAS +X	First Decade	LN_2	Detector	77	620
				LN_2	Dewar	80	
				LN_2	OIWFS	82	50
[REQ-1-OAD-4769]	HROS	NAS +X	First Decade	LN_2	Detector	173	60
				LN_2	AGWFS	N/A	N/A

Discussion: Target temperatures are specified at sea level.

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

[REQ-1-OAD-4750] Cryogenic cooling of instruments to temperatures between 77 K and 200 K shall use liquid nitrogen in boil-off mode.

[REQ-1-OAD-4751] The cryogenic cooling system shall provide intermittent daytime filling of instrument LN2 reservoirs from the CRYO LN2 reservoirs on the Nasmyth platforms.

Discussion: LN2 filling will occur either once or twice daily so that the instruments can be maintained at low temperatures at all times. Refilling once per day is sufficient if adequate space is available within the instrument's LN2 reservoir.

[REQ-1-OAD-4752] The cryogenic cooling system shall generate LN2 at a sufficient rate to supply the steady cooling requirements of the full TMT instrument suite, cool down one instrument, and replenish the minimum LN2 storage capacity within 40 days.

[REQ-1-OAD-4753] The cryogenic cooling system shall provide sufficient LN2 storage capacity on the Nasmyth platforms to supply the steady state cooling requirements of the full TMT instrument suite for a period of at least 5 days.

[REQ-1-OAD-4754] The cryogenic cooling system shall provide sufficient LN2 storage capacity on the Nasmyth platforms to cool down one instrument, while supplying the steady state cooling requirements of the remaining TMT instrument suite, with LN2 remaining in Nasmyth storage at the time of maximum depletion during cooldown sufficient to provide steady state cooling and replace generation for 1 day.

[REQ-1-OAD-4755] The cryogenic cooling system shall provide sufficient LN2 storage capacity in the SUM facility to supply the steady state cooling requirements of the full TMT instrument suite for a period of at least 48 hours.

[REQ-1-OAD-4756] The cryogenic cooling system shall transfer the daily generated amount of LN2 to the Nasmyth platform LN2 reservoirs within 4 hours during uninterrupted daytime operation.

Discussion: Filling of the LN2 reservoirs on the Nasmyth platforms can be performed at the same time as filling the instrument LN2 reservoirs.

4.4.3 Compressed Air

4.4.3.1 Facility Compressed Air

The Summit Facility Compressed Air (FCA) system provides compressed clean dry air to various locations of the observatory. The FCA system delivers air at 6 bar or higher to each selected telescope subsystem or instrument. The air is filtered and dried at the air compressor. Pipe sizing is adjusted so that the system has less than a 1 bar friction pressure loss.

Continuous (CON) and Intermittent (INT) Facility Compressed Air will be provided to the telescope at the locations described in *'Table 4-26 FCA Loads'*.

Table 4-26: FCA Loads

FCA Loads					
REQ ID	Subsystem	Location	Allocation: CON [L/S]	Allocation: INT [L/S]	Notes
[REQ-1-OAD-0805]	First Light	Distributed	60.1	2.0	
	First Decade	Distributed	96.5	2.0	
[REQ-1-OAD-0999]	M1CS	M1C 5	14.8	0.0	
[REQ-1-OAD-1002]	M2S	TOP 7	1.0	1.0	(1)
[REQ-1-OAD-1003]	AM2	TOP 7	1.0	1.0	(1)
[REQ-1-OAD-1028]	CLN	NAS -X 3	0.0	1.0	
	CLN	NAS +X 3	0.0	1.0	
[REQ-1-OAD-1006]	M1 COAT	SF 1	2.0	0.0	
[REQ-1-OAD-1999]	M2/M3 COAT	FB 1	0.0	2.0	
[REQ-1-OAD-1007]	APS	NAS -X 4	0.0	1.0	
[REQ-1-OAD-1008]	NFIRAOS	NAS -X 4 (NFIRAOS only, no instruments attached)	3.9	1.0	(2) and (3)
	NFIRAOS	NAS -X 4 (NFIRAOS portion while air sharing with 3 instruments)	4.7	1.0	
	NFIRAOS	NAS -X 4 (NFIRAOS + 3 instruments total while integrated)	6.4	1.0	
[REQ-1-OAD-1009]	LGSF	EL-X 5	10.1	0.0	
	LGSF	TOP 7	3.4	0.0	
[REQ-1-OAD-1011]	IRIS	NAS -X 4	0.8	0.0	
[REQ-1-OAD-1012]	MODHIS	NAS -X 4	0.8	0.0	
[REQ-1-OAD-1013]	WFOS	NAS +X 4	1.0	0.0	
[REQ-1-OAD-1014]	CRYO	NAS -X 3	0.5	2.0	
	CRYO	NAS +X 3	0.5	2.0	
	CRYO	AZ 2	0.0	1.0	
	CRYO	SF 1	42.8	0.0	
[REQ-1-OAD-1017]	HROS	NAS +X 4	1.0	0.0	
[REQ-1-OAD-1018]	IRMOS	NAS +X 4	1.0	0.0	
[REQ-1-OAD-1019]	MIRAO	NAS -X 4	1.0	0.0	
[REQ-1-OAD-1021]	MIRES	NAS -X 4	1.0	0.0	
[REQ-1-OAD-1023]	NIRES-R	NAS -X 4	1.8	0.0	
[REQ-1-OAD-1024]	PFI	NAS -X 4	1.0	0.0	
[REQ-1-OAD-1029]	STR.TUS	NAS -X 4 (air dryer)	13.6	0.0	(4)
	STR.TUS	NAS -X 4 (service port +Y side of platform)	1.0	0.0	(5)
[REQ-1-OAD-1994]	SUM	Engineering & Optics Lab	1.0	1.0	(5)
	SUM	Instrument Station Observing Floor #1	0.8	0.0	
	SUM	Instrument Station Observing Floor #2	0.8	0.0	
	SUM	Instrument Station Wedge Room	0.8	0.0	

Notes:

General: specified in liters of free air per second at 0.6 bar and 0?C

(1) FCA system is sized for larger of AM2/M2S

(2) When instruments are connected to NFIRAOS an "air sharing" approach will be followed where NFIRAOS will consume a portion of the instruments' air allowance. In this case 1m^3/hr per instrument (without margin) and 1.8 m^3/hr per instrument (including margin) will be transferred from the instrument air allowance to NFIRAOS. Thus, the pipe sizing to NFIRAOS should account for the increased airflow during air sharing. When instruments are not connected to NFIRAOS they will have access to their full air allowance and their piping should be sized appropriately.

(3) FCA system is sized for the integrated FCA demand including NSCU. The NFIRAOS client instruments' standalone allocations should not be double counted in the total continuous FCA demands.

(4) This allocation is for an air dryer used to deliver the NFIRAOS requirement of [P:W:O] grades [1:1:1]. It includes the NFIRAOS and instrument payloads and vents a percentage of the loads (feeding only the max continuous FCA demand to NFIRAOS + client instruments).

(5) FCA system should not be sized for these payloads but SUM/STR.TUS are responsible for routing stubs

[REQ-1-OAD-0998] The normal operating pressure of the FCA listed in '*Table 4-26: FCA Loads'* shall be above 6 bar to each selected telescope subsystem or instrument.

4.4.4 Communications and Information Services (CIS)

The CIS encompasses the IT architecture (hardware, software, and cabling) necessary to implement the generalized communications backbones and establish connection to Internet. The four networks described below (ENET, CNET, PNET, and SNET) comprise a fiber-based distribution system out to various network distribution junction boxes located on the telescope structure and the summit facility control room, laboratory, utility room, and site conditioning and monitoring system. An additional network, the INET, is not part of the CIS but may be referenced in this document. CIS will also include a communications backbone for the Headquarters facility which will include a computer room, remote control room, and offices.

Enterprise Network (ENET): The ENET includes connectivity to the Internet, remote access from partner locations (US, China, India, Japan, and Canada) and backup or disaster recovery facilities, corporate communication, email servers, Domain Name System (DNS) servers, and IT business systems.

Common Network (CNET): CNET is the common software (CSW) based network. It includes common infrastructure network, management network (IPMI), and reference clock (PTP). The CNET network extends between the computer room and locations in the observatory. It is where the majority of subsystem monitoring and control takes place.

Point-to-Point Network (PNET): The PNET is a CIS-provided physical network infrastructure for dedicated fiber point-to-point network from the computer room to a specific subsystem.

Safety Network (SNET): The SNET runs the Observatory Safety System (OSS) fiber network. It contributes to the enforcement of a safe operational environment and the minimization of the risk to safety of personnel and equipment within the TMT Observatory. The OSS provides the cabling for the SNET, while CIS provides the sizing of the SNET fibers.

The CIS network will employ a collapsed core architecture with the core and distribution layers located in the Summit facility data center, and access layer components providing connectivity at each of the significant observatory locations:

- Azimuth Wrap Distribution
- +X/-X Nasmyth Platform Distribution
- +X/-X Elevation Wrap Distribution
- -X Laser Platform
- Top End
- Utility Room
- SCMS Tower
- Observatory Floor
- M1 Coating Room
- Control Room
- Computer Room

4.4.4.1 CIS General

[REQ-1-OAD-4800] The TMT observatory-wide CIS network shall run on top of a communication protocol stack that has a physical IT communications network.

Discussion: The CIS Network LAN reference design is Ethernet based on TCP/IP protocols.

[REQ-1-OAD-4802] CIS shall minimize any cross-talk or interference from power sources or supplies.

[REQ-1-OAD-4825] CIS shall provide the means to connect to the nearest Internet service point, whether by physical connection or microwave links, to establish internet connectivity.

[REQ-1-OAD-4845] The CIS shall provide fiber infrastructure and access ports for the following networks:

- ENET: Enterprise Network
- CNET: Common Software (CSW) based Network
- PNET: Point to Point Network
- SNET: Safet Network (OSS)

[REQ-1-OAD-4850] The CIS shall support standard Internet services (e-mail, Web, video conferencing, voice-over-IP, etc.).

4.4.4.2 CIS Attenuation, Bandwidth, and Latency

[REQ-1-OAD-4860] CIS Fiber Optic attenuation shall not exceed 6dB loss over longest path (Computer Room to Top End).

Discussion: Assuming baseline OM4 multimode fiber with the highest number of patch panel (fiber-to-fiber) connections. Fiber junction attenuation was calculated using 0.75dB drop for each fiber-to-fiber connection and 3.5dB/km drop proportional to length of fiber. Calculations assume no bending radius attenuation. At 13.9dB, the optical fiber can no longer interpret the light signal.

Discussion: Bandwidth requirements are flowed down to subsystems based on which of their components are located at the areas described in the following requirements.

[REQ-1-OAD-4865] The CIS CNET shall accommodate a bandwidth of at least TBD Gbps.

[REQ-1-OAD-4870] The CIS CNET shall accommodate a bandwidth of at least 0.032 Gbps to the Top End.

[REQ-1-OAD-4871] The CIS CNET shall accommodate a bandwidth of at least 0.002 Gbps to the -X Laser Platform.

[REQ-1-OAD-4872] The CIS CNET shall accommodate a bandwidth of at least 0.030 Gbps to the -X Elevation Wrap.

[REQ-1-OAD-4873] The CIS CNET shall accommodate a bandwidth of at least 0.020 Gbps to the +X Elevation Wrap.

[REQ-1-OAD-4874] The CIS CNET shall accommodate a bandwidth of at least 0.020 Gbps to the +X Elevation M1.

[REQ-1-OAD-4875] The CIS CNET shall accommodate a bandwidth of at least 0.020 Gbps to the +X Elevation Tertiary.

[REQ-1-OAD-4876] The CIS CNET shall accommodate a bandwidth of at least 1.698 Gbps to the -X Nasmyth Platform.

[REQ-1-OAD-4877] The CIS CNET shall accommodate a bandwidth of at least 1.328 Gbps at the +X Nasmyth Platform.

[REQ-1-OAD-4878] The CIS CNET shall accommodate a bandwidth of at least 0.080 Gbps to the Utility Room.

[REQ-1-OAD-4879] The CIS CNET shall accommodate a bandwidth of at least 0.010 Gbps to the SCMS Tower.

[REQ-1-OAD-4880] The CIS CNET shall accommodate a bandwidth of at least 0.030 Gbps to the Observing Floor.

[REQ-1-OAD-4881] The CIS CNET shall accommodate a bandwidth of at least 0.018 Gbps to the M1 Coating room.

[REQ-1-OAD-4882] The CIS CNET shall accommodate a bandwidth of at least 0.500 Gbps for fire, security, and video monitoring.

[REQ-1-OAD-4883] The CIS CNET shall accommodate a bandwidth of at least 24.0575 Gbps to the Computer Room.

[REQ-1-OAD-4885] The TMT System latency from the computer room to end point devices shall be less than 5ms for each telescope-mounted subsystem, as shown in Table 4-27: Latency for Subsystems Terminating in a CIS or Subsystem Switch.

Table 4-27: Latency for Subsystems Terminating in a CIS or Subsystem Switch

	CIS Switch (µs) (CNET/ENET/SNET)	Internal Subsystem Switch (µs) (PNET)
CIS Components	33	3
CSW Based Components	4967	4997

Discussion: For CIS-specific testing, the netperf application can be used to determine bi-directional data performance (see figure below). For operational use, applications will utilize CSW and *therefore a major allocation is expected to go to the CSW components (command, events, telemetry).*

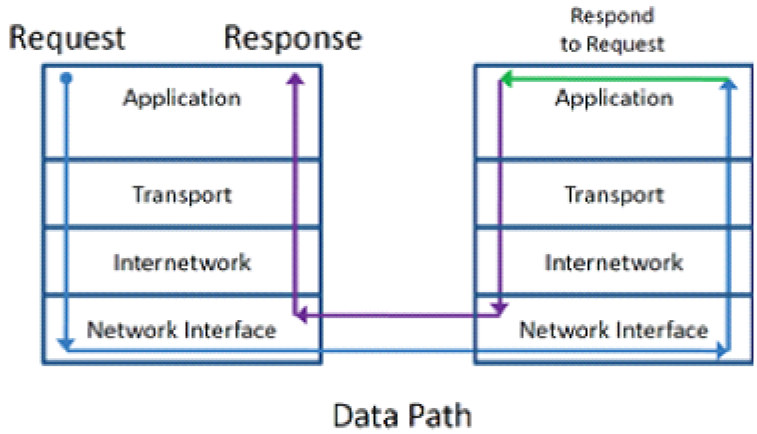

Figure 4-6: Bi-directional data performance

4.4.4.3 CIS Security

[REQ-1-OAD-4888] The CIS shall provide a security and monitoring system that includes still and video cameras, sensors, and identification systems for the purposes of access monitoring, remote monitoring of subsystems, and remote inspection after an earthquake.

[REQ-1-OAD-4890] The CIS shall allow only authorized users to access Observatory networks.

[REQ-1-OAD-4892] The CIS shall protect the Observatory from any external traffic on the public internet.

4.4.5 Fire Alarm

The SUM subsystem is responsible for providing the end-to-end fire alarm system, including equipment such as detection, warning devices (audible and visible), fire alarm management control system and panel, and fire suppression equipment including water storage. The overall fire alarm system has the ability to detect smoke or heat in most areas of the observatory. The SUM fire alarm system interfaces with the STR and ENC mounted components of the fire alarm systems.

The STR (TUS) subsystem designs the telescope fire alarm system, including routing (including through cable wrap), mounting locations for equipment, and interfaces with the SUM fire alarm system.

The ENC subsystem covers routing and mounting locations for fire alarm system components mounted to the rotating Enclosure. It also provides safety-rated communication across the rotating interface for the fire alarm signal and interfaces with the SUM fire alarm system. There is no fire suppression capability anywhere inside the Enclosure.

4.4.6 HBS Oil

HBS oil is continuously supplied to the azimuth and elevation hydrostatic bearings.

[REQ-1-OAD-5000] HBS oil shall be supplied to the observatory with maximum allowed particle count per 1 ml of oil for each particle size as described in '*Table 4-28: HBS Oil Cleanliness'.*

Table 4-28: HBS Oil Cleanliness

Range code	Particle size (µm(c))	Particles per milliliter
17	4	640-1300
15	6	160-320
12	14	20-40

4.5 FACILITIES

[REQ-1-OAD-5010] TMT Observatory Facilities Subsystems defined in OAD Section 2.2.1.1 shall operate and meet all requirements for at least 50 years with preventive maintenance.

Discussion: Preventive maintenance means servicing, repairing, and replacing components and subsystems based on their expected lifetime, as opposed to their failure.

4.5.1 ENCLOSURE

4.5.1.1 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.

[REQ-1-OAD-5056] The enclosure shutter shall open or close within 2 minutes at any cap orientation.

[REQ-1-OAD-5057] The enclosure shall have an aperture opening and shutter of sufficient size to not vignette the 20 arcminute diameter field of the telescope during observations, plus additional clearance of 1 degree radius outside the field of view in all directions.

Discussion: The telescope must quickly reposition over small distances without requiring the enclosure to move at the same rate. With the enclosure stationary, the telescope must be able to move 1° in any direction from the center of the enclosure aperture without vignetting the 20 arcminute diameter optical field. Note that for moves close to 1 degree, margin can be gained by pre-biasing the enclosure pointing in the direction of the planned telescope move.

[REQ-1-OAD-5058] The enclosure aperture opening shall have a continuous and unlimited range of azimuth motion (no cable wraps) and zenith motion range from 0 to 65 degrees zenith angle.

[REQ-1-OAD-5060] The enclosure azimuth and cap axes shall be designed to operate with maximum acceleration and deceleration rates of 0.05 deg/s^2 and a maximum velocity of 1.15 deg/s.

[REQ-1-OAD-5065] The enclosure shall be capable of pointing the aperture opening to a target on the sky over the required range of motion within a peak error of 10 arcmin in each axis 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-5080] The enclosure aperture opening and closing shall be designed to prevent water, ice or snow from falling into the enclosure.

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

[REQ-1-OAD-5092] The observatory shall provide a secure environment for equipment.

[REQ-1-OAD-5105] Except when observing or when necessary in servicing and maintenance mode, the enclosure shall be parked such that the top end servicing platform is aligned with the telescope top end and the shutter is pointing north.

Discussion: [REQ-1-OAD-1270] defines the telescope parked position.

4.5.1.2 Enclosure Geometry

[REQ-1-OAD-5150] No part of the inner enclosure shall be within the volume defined in drawing TMT.FAC.ENC-ENV (AD70).

[REQ-1-OAD-5161] The ENC shall use the geometry parameters as shown in the TMT Enclosure Geometry Drawing TMT.ENC.GTY-0001 (AD75).

Discussion: The 30m primary mirror aperture as defined by the perimeter of the mirror is located 3.5 - 1.875 = 1.625 m below the elevation axis. The height of the aperture opening defined by the flaps is 32.5 m above the primary aperture. A 31.25 m opening gives an oversize in radius of tan-1{0.625/32.5} = 66 arcmin.

Discussion: The external radius of the enclosure is 33 meters per (AD75).

We need 10 arcmin for the science FOV radius, and about 10 arcmin for pointing and tracking, which leaves slightly less than 50 arcmin of radius or 100 arcmin of diameter for telescope tracking with the enclosure held fixed. At a sidereal rate of 15 degrees/hour, 100 arcmin of diameter oversize represents about 400 seconds of tracking with a strategy of fixing the enclosure 50 arcmin ahead of the telescope then letting the telescope track until the enclosure is 50 arcmin behind.

Discussion: The enclosure design includes vent openings with a minimum total vent area of 1500 m^2. The shape and location of the vent openings is defined in the TMT Enclosure Geometry Drawing TMT.ENC.GTY-0001 (AD75).

Discussion: The enclosure design includes 94 vents (42 x 3.4 m x 3.6 m vents, and 52 x 5.0m x 4.0 m vents). The useful vent opening area is somewhat less than the maximum defined by the vent openings to account for bracing, vent door frames and other obstructions (conservative estimate, 1,500 m^2).

4.5.1.3 Slewing

4.5.1.3.1 Enclosure Base Axis Slewing

[REQ-1-OAD-5162] In observing mode, the enclosure shall be capable of making all base axis moves rapidly, such that they can be completed, including smooth ramping profiles and settling time, faster than an equivalent move with a trapezoidal velocity profile with acceleration and deceleration rate of 0.25 degrees/s^2 and a maximum velocity of 1.25 degrees/sec.

Discussion: “Observing mode” for the enclosure indicates that the wind speed is within the observing performance conditions and that there are no snow and ice accumulations on the enclosure.

Discussion: This requirement does not imply that a trapezoidal velocity profile must be used, and is not intended to prescribe actual design accelerations or maximum velocities.

[REQ-1-OAD-5164] The maximum slewing rate of the enclosure base axis shall not exceed 1.25 degrees/sec.

4.5.1.3.2 Enclosure Cap Axis Slewing

[REQ-1-OAD-5168] In observing mode, the enclosure shall be capable of making all cap axis moves rapidly, such that they can be completed, including smooth ramping profiles and settling time, faster than an equivalent move with a trapezoidal velocity profile with acceleration and deceleration rate of 0.15 degrees/s^2 and a maximum velocity of 1.75 degrees/sec.

Discussion: “Observing mode” for the enclosure indicates that the wind speed is within the observing performance conditions and that there are no snow and ice accumulations on the enclosure.

Discussion: This requirement does not imply that a trapezoidal velocity profile must be used, and is not intended to prescribe actual design accelerations or maximum velocities.

[REQ-1-OAD-5170] The maximum slewing rate of the enclosure cap axis shall not exceed 1.75 degrees/sec.

4.5.1.4 Wind, Thermal and Environmental Management

[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 be 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-5195] The area averaged RSI insulation value of the enclosure including the fixed base shall be at least 6 m2K/W. This insulation value shall be provided between the enclosure interior and the interstitial space.

Discussion: This insulation value is averaged over the entire enclosure interior surface including the vent doors, shutter rail and other areas which may have lower insulation values than the bulk areas of insulation covering the interior walls.

[REQ-1-OAD-5197] Vent doors (including door seal conductance but not infiltration) shall provide an averaged RSI insulation value of at least 4 m2K/W.

[REQ-1-OAD-5198] Any heat loads related to operation of the enclosure shall be dissipated to the enclosure interstitial space.

[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: Aperture flaps increase the effective diameter of the enclosure for protection of the telescope top end from wind buffeting.

Discussion: The enclosure incorporates aperture flaps with geometry as per the TMT Enclosure Geometry Drawing TMT.ENC.GTY-0001 (AD75).

[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.

[REQ-1-OAD-5215] The external surface of the enclosure shall have the following properties:

- Emissivity < 0.4
- Absorptivity < 0.2
- Emissivity not less than absorptivity

[REQ-1-OAD-5217] For thermal purposes, the emissivity of the internal surface of the enclosure shall be < 0.4.

Discussion: Note that some surfaces may require different surface properties as a result of stray light analysis.

[REQ-1-OAD-5220] The enclosure shall include a vent to remove air at a rate of 4.7m^3/s from the top of the enclosure during daytime operation of the observatory air conditioning system.

Discussion: Thermal modelling of the enclosure daytime environment assumes that 20% of the total air volume output by the air handlers is vented from the enclosure. This prevents a thermal *gradient forming over the primary mirror when the telescope is in its daytime parked position (horizon pointing).*

4.5.1.5 Summit Facility Fixed Base

[REQ-1-OAD-1265] The summit facility shall provide vibration isolation between the foundations of each of the Telescope pier, Enclosure pier, and Summit Facilities.

[REQ-1-OAD-5255] The summit facility fixed base floor structure shall support HS 20-44 truckloads.

[REQ-1-OAD-5257] The observing floor shall be flat and continuous in the area between the outer radius of the telescope fixed walkway and the inner radius of the fixed enclosure walkway.

Discussion: This requirement specifies the floor only and excludes obstructions such as stairways, air handlers, mirror storage etc.

[REQ-1-OAD-5258] The observing floor shall be free from obstructions in the area between the outer radius of the telescope fixed walkway and the inner radius of the fixed enclosure walkway with the exception of the following items:

- M2/M3 coating chamber rails
- Air handlers
- Fixed base elevators
- Platform lifts and stairs to access telescope and enclosure fixed walkways

Discussion: The sector extending clockwise and counterclockwise from the main entrance into the enclosure is to be kept clear for vehicular access, M2 and M3 operations and transferring large components into the enclosure.

[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 4.88 m wide by 5.03 m high for equipment and component movement.

Discussion: The size restrictions for components that can be transferred into the enclosure via these doors is defined in TMT.SEN.TEC.11.014 (RD29).

Discussion: The size of component that can be lifted to the Nasmyth platform from the enclosure floor is limited by the outside radius of the pier walkway and the inner radius of the fixed base walkway. The width and length are related by the following equation:

$$W = \sqrt{\left(729 - \left(\frac{L}{2}\right)^2\right)} - 20.4$$

[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-5267] Two entrances at least 1 m wide by 1.9 m high shall be provided in the pier wall to allow personnel access to the area enclosed by the pier.

Discussion: At least one of these doorways may need to be an 'emergency exit' only to prevent personnel using the area within the pier as a throughway from one side of the telescope to the other.

[REQ-1-OAD-5270] The summit facility fixed base shall provide a tunnel from the facilities mechanical and electrical plant to the pintle bearing area housing the telescope cable wrap for delivery of utility services to the telescope and telescope mounted sub-systems.

[REQ-1-OAD-5272] An emergency egress route shall be provided from the pintle bearing/cable wrap area that allows personnel to exit to the observing floor outside the telescope pier in the event of a fire or other hazard occurring in the service tunnel.

[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 an enclosed space within the enclosure to store and individually access the equipment used for optics handling.

Discussion: The purpose of this area is to house handling carts in a semi-clean environment, with or without segments mounted on the cart (e.g. in preparation for a segment exchange). In this area, the carts can be restrained such that no damage can occur to a segment during a seismic event.

[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-5296] Two elevators and stairways that meet the location and space requirements of TMT.FAC.ELEV-ENV (AD72) shall be provided to gain access to the pier walkway.

[REQ-1-OAD-5300] Air handlers shall not be positioned in the following areas (defined as angles from TCRS x-axis, i.e. due east. Positive angle = clockwise when viewed from above):

- 80 to 100 degrees (to avoid directing air directly at telescope top end when telescope is in daytime parked position).
- 145 degrees to 220 degrees (to avoid positioning directly beneath -X Nasmyth platform)
- 320 degrees to 35 degrees (to avoid positioning directly beneath +X Nasmyth platform)

[REQ-1-OAD-5305] One air handler should be positioned as close as possible to 270 degrees clockwise from the TCRS x-axis (i.e. North). The remaining two air handler locations shall be located as close as possible to +/-120 degrees from this position.

[REQ-1-OAD-5310] The air handlers shall be located radially as far as possible from the centre of the enclosure.

[REQ-1-OAD-5315] The air handler nozzle orientation shall be manually adjustable to allow air flow direction to be modified.

4.5.1.6 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.

Discussion: To prevent possible collisions between the top end servicing platform and the telescope, the Observatory Safety System will provide interlock signals as required to prevent deployment of the top end platform unless the telescope and enclosure are aligned and stationary. It will also prevent motion of either the telescope or enclosure if the platform is not stowed.

[REQ-1-OAD-5326] When deployed, and during deployment, the top end servicing platform shall clear the telescope top end structure and top end equipment space envelope as defined in TMT.FAC.ENC.TEP-ENV (AD71).

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

[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.

4.5.1.7 Seismic and Snow/Ice Loads

[REQ-1-OAD-5306] Under all operating conditions and configurations, the ENC shall withstand the representative time series of site-specific seismic accelerations as described in (RD16) such that:

- After a 10-year return period earthquake, the ENC can resume normal operations after inspection by the normal operations staff.
- After a 200-year earthquake, the ENC can resume normal operations within two weeks after the observatory staff has resumed regular duty.
- After a 1000-year return period earthquake, ENC components do not damage the telescope optics or present worse than a marginal hazard to personnel in the event of their failure.

Discussion: A marginal hazard is defined in the ES&H Hazard/Risk Assessment Processes and Guidelines (AD80).

Discussion: The Enclosure also meets building code requirements per (RD60) for collapse prevention at the 2500-year return period MCE level earthquake.

Discussion: The levels of a 1000-year return period earthquake have a 5% probability of being exceeded in a 50-year period.

[REQ-1-OAD-5309] Under all operating conditions and configurations, Enclosure and Summit Facilities floor-mounted equipment shall withstand the seismic accelerations at the levels defined in 'Table 4-29: Seismic Limits on Floor-mounted Equipment within ENC/SUM' such that:

- After a 10-year return period earthquake, the observatory can resume normal operations after inspection by the normal operations staff.
- After a 200-year earthquake, the Observatory can resume normal operations within two weeks after the observatory staff has resumed regular duty.
- After a 1000-year return period earthquake, components do not damage the telescope optics or present a hazard to personnel in the event of their failure.

Table 4-29: Seismic Limits on Floor-mounted Equipment within ENC/SUM

Subsystems	Maximum Accelerations (g)					
	10-year return period		200-year return period		1000-year return period	
	Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical
Floor-mounted equipment within SUM/ENC	0.1	0.1	0.3	0.2	0.5	0.4

Discussion: These values are calculated using the average of the maximum accelerations from each of the seismic time histories for 1000-year and 10-year, provided by (RD16). The 200-year values were calculated using a factor of 0.58 applied to the 1000-year values as recommended in (RD16).

Discussion: The levels of a 1000-year return period earthquake have a 5% probability of being exceeded in a 50-year period.

[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:

- rotation of the enclosure cap or base.
- operation of the aperture flaps.
- operation of the aperture without snow or ice falling inside the enclosure.
- operation of the vents.
- the ability to safely observe.
- 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 4 people within an 8 hour daytime period once the aperture flaps can be opened. An area is considered critical if snow, ice or water can reach the inside of the enclosure from that area through an open observing slit or vent.

Discussion: The primary means of removing snow and ice accumulation from the dome will be passive. The enclosure exterior will be a smooth as possible to promote snow and ice shedding. When possible, the closed shutter will be pointed towards the sun to further promote snow and ice melting.

4.5.1.8 Enclosure Servicing and Maintenance

4.5.2 Summit Facilities

4.5.2.1 General

[REQ-1-OAD-5440] Under all operating conditions and configurations, the SUM shall withstand the time history response spectra of site-specific seismic accelerations as described in (RD16) such that:

- After a 10-year return period earthquake, the SUM can resume normal operations after inspection by the normal operations staff.
- After a 200-year earthquake, the SUM can resume normal operations within two weeks after the observatory staff has resumed regular duty.
- After a 1000-year return period earthquake, SUM components do not damage the telescope optics or present worse than a marginal hazard to personnel in the event of their failure.

Discussion: A marginal hazard is defined in the ES&H Hazard/Risk Assessment Processes and Guidelines (AD80).

Discussion: The Summit Facilities also meets building code requirements per (RD60) for collapse prevention at the 2500-year return period MCE level earthquake.

Discussion: The levels of a 1000-year return period earthquake have a 5% probability of being exceeded in a 50-year period.

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

[REQ-1-OAD-5503] A backup communications system independent of other observatory systems shall be available in case of emergencies.

4.5.2.2 Mirror Maintenance

[REQ-1-OAD-5505] A mirror stripping and coating facility sufficient to process the M1 mirror segments shall be located adjacent to the enclosure to minimize mirror transportation.

Discussion: A full sector of 82 spare segments is provided, due to the optical prescription. Efficient access to this storage is necessitated by the frequency and time limits of M1 segment exchanges.

[REQ-1-OAD-5507] A mirror stripping and coating facility sufficient to process the M2 and M3 mirrors shall be located either adjacent to or within the enclosure to minimize mirror transportation.

[REQ-1-OAD-5510] The M1 mirror coating and stripping facility shall be equipped with an overhead crane.

Discussion: It is anticipated that the M2 and M3 coating chamber will be located in an area accessible by the enclosure mounted crane or hoist.

[REQ-1-OAD-5515] The M1 mirror coating area shall be built and equipped to be capable of providing a class 10,000 clean room environment.

[REQ-1-OAD-5520] The Summit Facilities shall provide space to store and access the spare quantity of M1 mirror segments either adjacent to the mirror stripping and coating facility or within the enclosure.

4.5.2.3 Operations Spaces

[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] A computer room shall be provided adjacent to the enclosure with sufficient space for all centrally located observatory information technology resources.

[REQ-1-OAD-5551] The computer room shall provide class A1 environmental conditions (per RD60: ASHRAE 90577) and be capable of operating in the recommended range when required.

4.5.2.4 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.

4.5.2.5 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 toilet facilities for access by the general public.

4.5.2.6 Shipping & Receiving

[REQ-1-OAD-5615] The Summit Facilities shall provide a platform lift in the shipping and receiving area with the following characteristics: 2 ton capacity, 1.0 m x 2.4 m platform area, capable of rising to 1.6 m above floor level.

[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.

4.5.2.7 MECHANICAL PLANT

[REQ-1-OAD-5620] A mechanical plant will be provided to house the mechanical equipment required at the summit facilities.

[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, building air conditioning, fire suppression, water & waste storage, LN2 storage.

[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 remove the heat loads listed in *'Table 3-2: Heat Dissipation Inside Summit Facilities and Dome'* and environmental heat loads (air infiltration, solar heating, etc.). via the chilled water cooling systems described in section 4.4.2.

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.

[REQ-1-OAD-5632] The TMT Observatory shall provide air conditioning with a total flow of 23.6 m^3/s at the following operating points with 80% of air being re-circulated:

Table 4-30: Nozzle Temperatures

Case	Target Temperature (°C)	Nozzle Temperature (°C)	Temperature Difference (°C) (outside temperature to nozzle temperature)
Minimum Nozzle Temperature	-5	-7	11
Maximum temperature difference (external to dome air)	-0.5	7	17

[REQ-1-OAD-5635] The TMT Observatory shall provide an exhaust located on the northwest corner of the summit facilities building with the outlet directed to the north, to remove heat from the summit facilities mechanical plant.

[REQ-1-OAD-5637] The maximum outlet temperature of the Summit Facilities exhaust shall not exceed 15°C above the ambient nighttime temperature at the exit of the vent.

Discussion: As a goal, the temperature delta should be 10°C. There is no requirement on the daytime limit to the temperature of the exhaust air. It is assumed that the fluid cooler runs at lower flow rates in the daytime to conserve power which results in higher temperatures.

4.5.2.8 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, electrical generators and uninterruptible power supply.

4.5.2.9 ROADS & PARKING

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

[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.

4.5.2.10 Grounding and Lightning Protection

[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 (RD60: NFPA 780).

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

4.5.2.11 Fire Protection and Safety

[REQ-1-OAD-5690] A fire suppression system shall be supplied throughout the summit facilities building.

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

[REQ-1-OAD-7000] The CIS shall incorporate a video system to allow operations staff to monitor the enclosure environment.

4.5.3 Headquarters

4.5.3.1 General

[REQ-1-OAD-5745] The TMT Observatory Headquarters Facility shall be established within two (2) hours drive of the summit.

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

4.5.3.2 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 headquarters 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.

4.5.3.3 Remote Control Room

[REQ-1-OAD-5800] A remote control/observing room including two full observing consoles shall be provided at the headquarters building.

4.5.3.4 Lab & Shop Spaces

[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 Headquarters engineering workshop shall be equipped with overhead bridge cranes with sufficient hook height for associated component movements.

[REQ-1-OAD-5825] The headquarters shall provide a mask cutting facility including space for mask storage, mask cutter, handling carts, workstation and workbenches.

4.5.3.5 WAREHOUSE STORAGE

[REQ-1-OAD-5830] Storage and capacity shall be provided at the headquarters that is sufficient to house the equipment, tools and spares used to support sea level technical work.

Discussion: It is anticipated that the majority of the storage space required for observatory spares will be in rented warehouse space.

4.5.3.6 SHIPPING & RECEIVING

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

4.5.3.7 ELECTRICAL PLANT

[REQ-1-OAD-5865] An emergency generator shall be provided to ensure that remote observing can take place in the event of a power outage.

4.5.3.8 ROADS AND PARKING

[REQ-1-OAD-5875] People vehicle parking shall be provided close to the headquarters building entrances 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 area.

4.6 SERVICING AND MAINTENANCE

4.6.1 CRANE SYSTEMS

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.
- 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-6212] The 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 5.75m (between R 23.25m to R 29.0 m relative to the TCRS z-axis)
- The maximum hook height shall be at least 24.8 m above the TCRS XY plane

- 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 30.9m above the TCRS XY plane
- At 0.0 m radius, the maximum hook height shall be at least 48.5 m above the TCRS XY plane
- 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-6205] It shall be possible to deploy any of the enclosure mounted cranes without colliding with the telescope structure when the telescope is either zenith or horizon pointing. The volume which the cranes must clear is defined in the enclosure stay out volume drawing TMT.FAC.ENC-ENV (AD70).

Discussion: This requirement applies only to the mechanical components of the cranes when the hook is fully retracted. When the hooks, cables or payloads are being lowered there is obviously potential for collision between these components and the telescope. These hazardous operations must be covered by appropriate procedures.

[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 the M1S Mounted Segment Assembly (MSA) is 232.2 kg and 70 kg for the HNDL General Segment Lifting Fixture (GSLF).

[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, hoist or other suitable handling equipment provided for servicing the elements of the LGSF laser system and beam transfer optics mounted on the inside of the -X ECRS elevation journal.

Discussion: The mass of the components to be lifted by this crane is documented in the STR-LGSF ICD.

[REQ-1-OAD-6260] An overhead crane shall be available in the Freight and delivery area and mechanical workshop: monorail crane with 5 tonnes capacity, hoist with continuously variable speed control from 0.5 to 5m per minute, trolley with continuously variable speed control from less than 0.2m per minute to at least 20m per minute.

[REQ-1-OAD-6270] An overhead bridge crane shall be available in the M1 mirror coating area with the specifications:

- 1 ton (907 kg) capacity,
- hoist with continuously variable speed control from 0 to 4m per minute,
- trolley with continuously variable speed control from less than 2m per minute to at least 20m per minute,
- oil shields.

[REQ-1-OAD-6271] An overhead monorail crane shall be available in the M1 mirror segment maintenance area with the specifications:

- 1 ton (907kg) capacity,
- hoist with continuously variable speed control from 0 to 4m per minute,
- trolley with continuously variable speed control from less than 0.2m per minute to at least 20m per minute,
- oil shields.

[REQ-1-OAD-6272] The M1 mirror segment storage area shall be accessible by overhead monorail crane/s with the specifications:

- 1 ton (907 kg) capacity,
- hoist with continuously variable speed control from 0 to 4m per minute,
- trolley with continuously variable speed control from less than 0.2m per minute to at least 20m per minute,
- oil shields.

[REQ-1-OAD-6274] An overhead monorail crane shall be available in the engineering lab:

- 5 ton (4,535 kg) capacity,
- hoist with continuously variable speed control from 0 to 4m per minute,
- trolley with continuously variable speed control from less than 0.2m per minute to at least 20m per minute.

[REQ-1-OAD-6275] An overhead bridge crane shall be available in the mechanical workshops:

- 3 tonnes (3,000 kg) capacity,
- 2-speed electric hoist with slow speed approximately 30 cm per minute,
- oil shields.

[REQ-1-OAD-6276] An overhead monorail crane shall be available in the Utility Room:

- 2 ton (1,814 kg) capacity,
- hoist with continuously variable speed control from 0.5 to 5m per minute,
- trolley with continuously variable speed control from less than 0.2m per minute to at least 20m per minute.

Discussion: The monorail crane specified is to service the in-line coating chamber. The crane should extend far enough past the coating chamber to unload removed magnetrons or isolation valves.

4.6.2 Maintenance

[REQ-1-OAD-6280] The TMT Observatory shall implement and maintain a comprehensive maintenance system, which includes scheduling and details of both predictive and preventative maintenance, component and assembly replacement, and alignment procedures.

[REQ-1-OAD-6282] A failure database shall be established by the end of construction, and maintained throughout operations, which allows the logging of errors of the system and its subsystems, including corrective actions taken.

4.7 Environmental, Safety and Health Requirements

The safety priorities of any subsystem needs to be: (i) protection of persons, (ii) guarding the technical integrity of the observatory and other equipment potentially affected by the operation of the observatory, and (iii) protection of scientific data, in this order.

The environmental protection, safety and health aspects of the TMT System require the provision of several requirements, standards and functions which are provided by multiple sub-systems of the observatory. These include:

- Environmental protection through the application of requirements and standards.
- Specific ES&H Functions, as follows:
    - Fire Detection and Suppression
    - Emergency Lighting
    - Access and Security
    - Emergency Stops
    - Interlocks
    - Hazard Detection
    - Seismic Detection
    - Protection of aircraft and satellites from Lasers
    - Laser Safety
    - Protection of Scientific Data
    - Emergency Communication
    - Gas monitoring (CO, CO2 etc.)
    - Lockout/Tagout
    - Situational Awareness

The TMT Safety Architecture document (RD18) allocates these functions to the appropriate TMT sub-systems and identifies the requirements that apply to each function. The collection of sub-systems and components that provide these functions is referred to as the 'TMT Safety Architecture'.

The Functional Safety Architecture is the part of the TMT Safety Architecture responsible for providing emergency stops, hazard detection and interlocks. The Functional Safety Architecture involves any sub-system connected to the Observatory Safety System (OSS) as well as the OSS itself. Requirements applying to the entire Functional Safety Architecture are contained in section 4.7.1.1.

The OSS is responsible for monitoring and in some cases imposing interlocks across the Functional Safety Architecture. It monitors and provides the appropriate response to e-stops. It also provides the seismic detection function and, in some cases, may participate in the provision of the other safety functions. Section 4.7.2.1 contains requirements that apply only to the OSS.

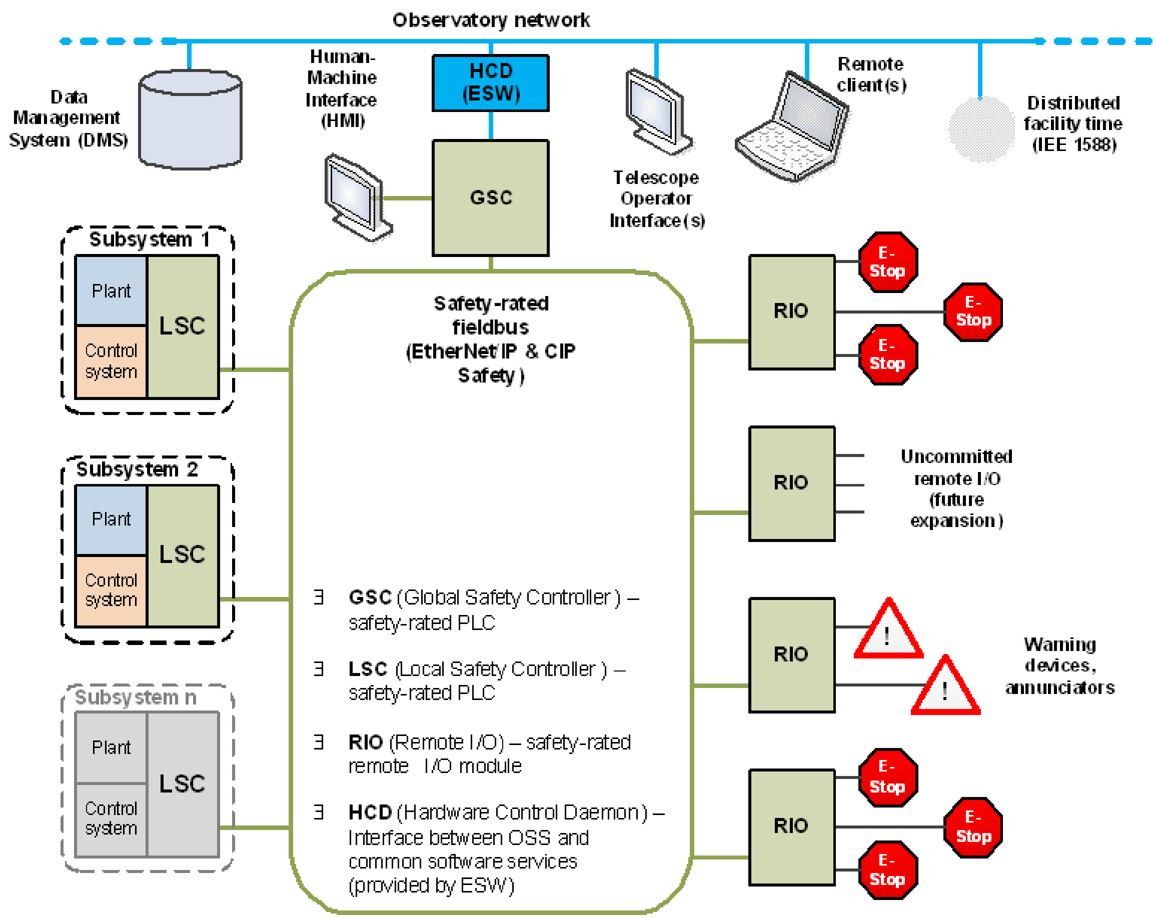

Figure 4-7: Functional Safety Architecture.

Discussion: GSC, field bus RIOs and e-stops are contained within OSS sub-system. Items within dotted lines are responsibility of connected sub-systems.

4.7.1 General Requirements on Subsystems

4.7.1.1 Functional Safety System Requirements

[REQ-1-OAD-6900] Each subsystem shall continuously monitor its own status and operation for the purpose of detecting faults or other hazardous conditions that can cause safety hazards and increase risk.

Discussion: Wherever possible, fault and hazard detection, and the initial response to these conditions, shall be handled at the subsystem level.

[REQ-1-OAD-6909] The TMT Observatory shall incorporate fixed, automatic, or other protective safety devices into the design of subsystems identified in hazard analysis.

Discussion: The hazard analysis is an output of the process defined in (AD80). The safety priorities of the subsystems are: (i) protection of persons, (ii) guarding the technical integrity of the observatory and other equipment potentially affected by the operation of the observatory, and (iii) protection of scientific data, in this order.

[REQ-1-OAD-6901] The OSS and other sub-systems in the Functional Safety Architecture (those requiring a safety related control function to mitigate a hazard and/or those sub-systems providing safety related telemetry to the OSS) shall comply with (RD60: IEC 62061).

*Discussion: **(RD60: IEC 62061)** requires that a functional safety management plan be followed to ensure that safety functions are designed, implemented and verified properly. TMT has developed a Functional Safety Plan (RD46) that can be applied by any sub-system that is covered by **(RD60: IEC 62061)**. It is recommended that sub-systems in the Functional Safety Architecture follow this document or an equivalent functional safety plan as agreed by TMT.*

Discussion: The decision as to whether a sub-system requires a safety related control function to mitigate an SRCF is based on the sub-systems hazard analysis conducted per RD40.

[REQ-1-OAD-6902] Any sub-system whose hazard analysis identifies a hazard that needs to be mitigated by a 'Safety Related Control Function (SRCF)' per (RD60: IEC 62061) shall provide a Local Safety Controller to implement the SRCF.

Discussion: (RD60: IEC 62061) considers a safety related control function to be a function that maintains a safe condition or prevents an increase of risk and is implemented by an electrical or electronic control system. The local safety controller will be connected to the OSS as shown in Figure 4-7: Functional Safety System Architecture

[REQ-1-OAD-6903] The Local Safety Controller provided by the sub-system shall follow the use the hardware defined in AD85.

Discussion: A typical LSC comprises the components shown in 'Figure 4-8: Illustration of the components that comprise a local safety controller' below.

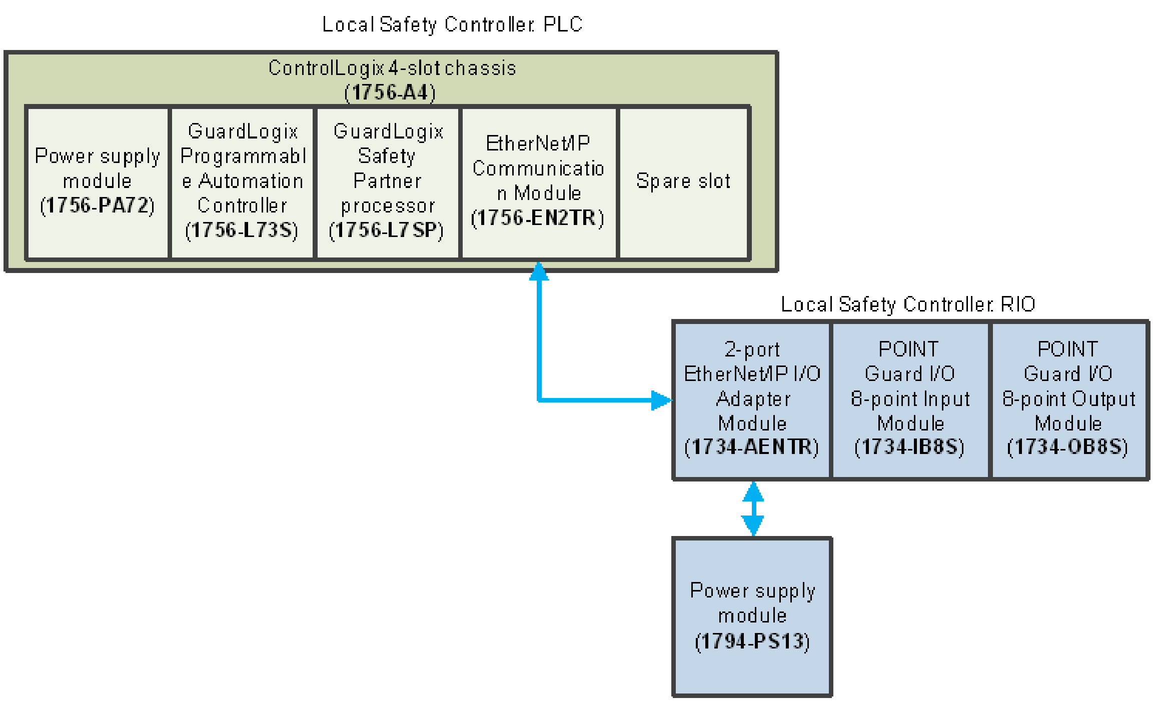

Figure 4-8: Illustration of the components that comprise a local safety controller

[REQ-1-OAD-6904] Each LSC shall provide a local user interface.

[REQ-1-OAD-6905] Upon detecting a hazardous fault or condition, a subsystem shall independently and immediately take action to alert personnel and mitigate the hazard without any interaction with, or the presence of, the OSS.

[REQ-1-OAD-6908] Sub-systems required to enter an interlocked state due to hazards occurring in other areas of the observatory shall respond to interlocks imposed by the OSS by implementing behaviour as agreed in the appropriate sub-system to OSS ICD.

[REQ-1-OAD-6910] Upon detecting a hazardous fault or condition and imposing the appropriate interlock, a subsystem shall provide the OSS with Safety Status information.

Discussion: (a) All Global SRCF information must be reported from an LSC to the GSC via the interlock events. (b) All local SRCF information, modes and hardware status for an LSC must be reported from an LSC to the GSC via the safety status (as per the architecture & ICD) (c) An LCS does not publish SRCF information via common software and HCD. Only the GSC does this via a HCD.

[REQ-1-OAD-6912] A special mode implemented via a sub-system's LSC and associated HMI shall be used when recovery from an interlocked condition requires the temporary inhibition of interlocks.

Discussion: An example of this would be when telescope axis motion is interlcoked by passing an over travel limit. To move back into its normal operating range under power the interlock would temporarily need to be suspended and other restrictions such as local control, velocity limits etc. imposed to maintain safety whilst operating in this mode.

[REQ-1-OAD-6906] All safety-related communication between the OSS GSC, the sub-system LSCs, and all Remote I/O shall be via a safety-rated EtherNet/IP & CIP Safety network provided by the OSS (or by the responsible sub-system for connections between an LSC and remote I/O module).

[REQ-1-OAD-6907] Sub-systems incorporating a Local Safety Controller (LSC) shall comply with the requirements contained in the Local Safety Controller Design Requirement Document (AD84).

[REQ-1-OAD-6911] The OSS Global Safety Controller and Local Safety Controllers used by sub-systems shall be developed following the OSS Developer's Guide (AD85).

4.7.1.2 ACCESS CONTROL AND TRAPPED KEY SYSTEM

[REQ-1-OAD-7601] Barriers and/or gates shall be used to prevent access to areas where hazards to personnel may be caused by release of stored energy during normal operations.

Discussion: Normal operations include maintenance. Release of stored energy is terminology used in (RD60: OSHA 29 CFR 1910); its sources may be hydraulic, electrical, mechanical, pneumatic, chemical, or thermal. Hazards caused by release of stored energy include crushing, pinching, electric shock, etc.

[REQ-1-OAD-7602] Access to the hazardous areas shall only be possible when all sources of hazardous energy have been locked out using an energy isolating device.

Discussion: 'Energy isolating device' is terminology used by (AD11). It is expected that for TMT these will usually be devices locking out electrical power.

[REQ-1-OAD-7613] Operating modes supporting special operating procedures that allow entry without isolating energy sources shall be defined and included in the functions of sub-system local safety controllers.

Discussion: These special operating procedures need to be agreed by TMT on a case-by-case basis.

[REQ-1-OAD-7603] Trapped key devices shall be used that allow each person entering a hazardous area to carry a personal safety key with them that guarantees that sources of hazardous energy affecting that area are isolated.

[REQ-1-OAD-7604] The gates preventing access to hazardous areas shall be locked at all times when entry/exit is not in progress, and may only be unlocked from the outside using a personal safety key.

[REQ-1-OAD-7605] Exiting any hazardous areas shall, in normal circumstances, be achieved using a push button to unlock the gate.

[REQ-1-OAD-7606] When a personal key is used to gain access to a hazardous area, or the push button is used to exit the area, the gate shall unlock only for a period sufficient to allow a person to enter or exit, and shall re-lock after that period has elapsed or after each person as entered or exited the hazardous area (except in emergency situations as described in [REQ-1-OAD-7607]).

[REQ-1-OAD-7607] In emergency situations, it shall be possible to open every gate from the inside using a manual override that unlocks the gate and keeps it unlocked.

[REQ-1-OAD-7608] The system shall monitor and display the status of all lockouts implemented by trapped keys and the removal of trapped keys from any key exchange devices.

[REQ-1-OAD-7609] The design of the trapped key system shall be consistent with that described in the Observatory Safety Access Summary (AD91) and figure 'Trapped Key System Schematic' below.

Discussion: AD91 defines the interlocks and other safety devices required when accessing hazardous areas, as well as the recommended hardware to be used in the trapped key system. Figure 4-9: 'Trapped Key System Schematic' below shows the typical trapped key system schematic required by AD91.

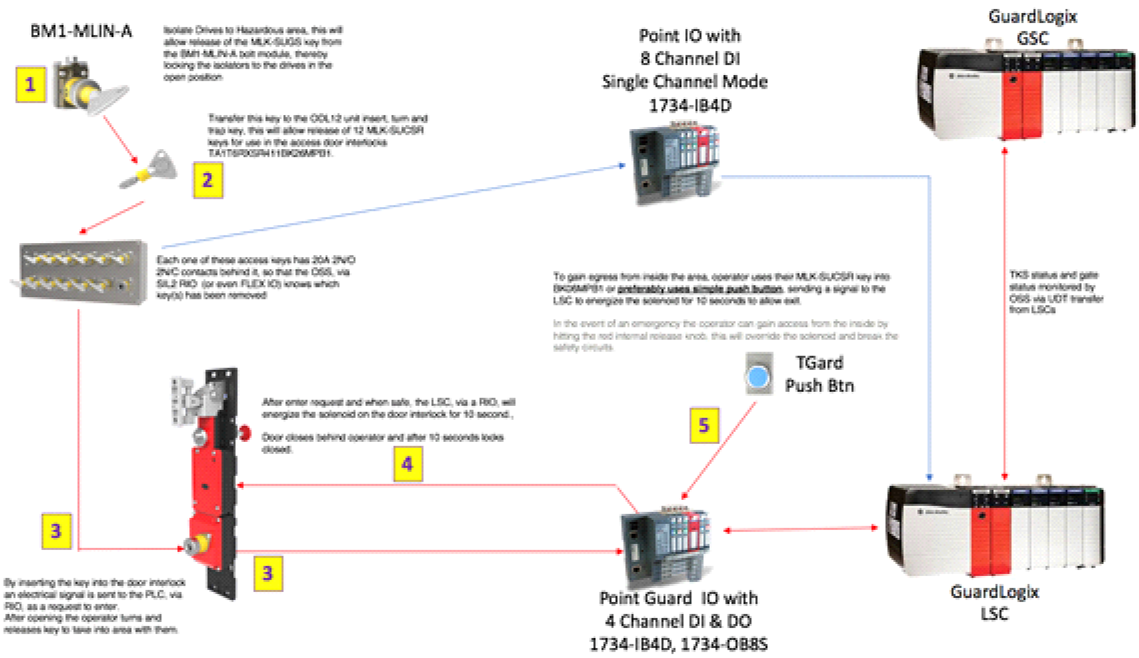

Figure 4-9: Trapped Key System Schematic

4.7.1.3 Environmental Requirements

4.7.1.3.1 Restriction of Hazardous Substances in Electrical & Electronic Equipment (ROHS)

[REQ-1-OAD-6950] Except when safety would be compromised, cost would be significantly increased, schedule would be significantly prolonged, performance would be significantly degraded, electrical and electronic commercial-off-the-shelf (COTS) equipment contained in TMT systems shall be compliant with the Directive of 2011/65/EU of the European Parliament and of the Council of 8 June 2011 (AD39) on the restriction of the use of certain hazardous substances in electrical and electronic equipment, commonly known as Restriction of Hazardous Substances in Electrical and Electronic Equipment, or ROHS.

Discussion: Verification of this requirement will at minimum be through review of the manufacturer's documentation of ROHS compliance of COTS equipment, and for cases where non-ROHS equipment is used evidence of agreement by TMT Project Management that cost, schedule and performance trade-offs merit the use of these materials.

[REQ-1-OAD-6952] Except when cost would be significantly increased, schedule would be significantly prolonged or performance would be significantly degraded, custom build electrical and electronic equipment contained in TMT systems shall not contain ROHS prohibited materials, as defined in (AD39).

Discussion: Verification of this requirement will at minimum be by Design, with identification of ROHS materials (AD39) included in designs and evidence of agreement by TMT Project Management that cost, schedule and performance trade-offs merit the use of these materials. Infrared detectors are an example of devices that would merit the use of ROHS restricted materials.

[REQ-1-OAD-6954] Electrical and electronic equipment that contains ROHS restricted materials shall be labeled, with details of restricted materials contained within, on a side or surface that is visible under normal maintenance conditions.

Discussion: Verification of this requirement will be at minimum by inspection during acceptance testing.

4.7.2 Observatory Safety System

This section contains requirements applicable to the Observatory Safety System.

4.7.2.1 Observatory Safety System (OSS), General

[REQ-1-OAD-7050] The Observatory Safety System shall be implemented as an independent PLC based system whose operation does not rely on the availability of any other sub-systems other than power.

[REQ-1-OAD-7052] The OSS shall provide different operational modes that support:

- Observing Operations
- Maintenance Operations
- Fault and Interlock Recovery

[REQ-1-OAD-7051] The OSS shall provide fault, interlock and emergency stop monitoring and control in a manner consistent with the TMT System Level Hazard Analysis Document (AD37).

Discussion: The TMT System Level Hazard Analysis document (AD37) identifies the possible faults and hazardous conditions associated with interactions between the sub-systems of the observatory and defines the necessary interlocks that have to be managed by the OSS in order to enforce functional safety under these circumstances.

[REQ-1-OAD-7053] The OSS shall be able to detect hazardous faults or conditions that are not associated with a particular sub-system.

Discussion: An example would be a gate switch that is triggered when accessing a certain area of the telescope for servicing purposes. In that case, it makes sense to allow the OSS to directly read such a switch and act upon it.

[REQ-1-OAD-7054] The OSS shall have the capability to detect earthquakes and respond by implementing and enforcing any interlocks on sub-systems that are required to maintain safety under these conditions.

[REQ-1-OAD-7059] The OSS shall have a Hardware Control Daemon (HCD) that allows OSS information to be communicated via the common services framework using a read-only OSW compliant interface.

[REQ-1-OAD-7061] The OSS shall include a simple user interface accessible via both a PanelView and the ESW via the OSS HCD (Hardware Control Daemon), that displays an indication of the state of the safety system and allows the user to:

- Reset interlocks
- Query which sub-systems have generated interlock requests
- Query which sub-systems are interlocked via interlock demand signals

Discussion: The user interface should be simple and functional. This is particularly important as it may have to be used in emergency situations where the ability to perform necessary tasks quickly is paramount. A remote interface should also be provided so that the same (or similar) interface is accessible over the network. In this case, access controls should be incorporated to prevent unauthorized use.

[REQ-1-OAD-7062] The OSS shall provide an indication to the Data Management System (DMS) and the Executive Software (ESW) of the status of any interlocks raised by either the OSS Global Safety Controller (GSC) or any sub-system Local Safety Controller (LSC).

[REQ-1-OAD-7063] Whenever the OSS alerts the ESW and/or the DMS to an interlock event, it shall include in the notification any relevant engineering information pertaining to the interlock condition (e.g. the sub-system that raised the interlock request, the time the event occurred, etc.).

Discussion: This data is limited to the information that is related to the receipt of an interlock request or the implementation of an interlock demand. It is not intended that the OSS provide or distribute telemetry from connected sub-systems. The sub-system is responsible for providing the telemetry data to the DMS and ESW by other means.

[REQ-1-OAD-7064] The OSS shall provide and control independent audible and visual warning devices located throughout the summit facility as per the Hazard Analysis.

4.7.2.2 OBSERVATORY SAFETY SYSTEM, INTERLOCKS

Definitions:

- Interlock event - communication from a local safety controller to the global safety controller, used by the global safety controller to impose interlock demands on other sub-systems
- Interlock demand - communication from the global safety controller to a local safety controller to implement interlocks or permissives
- Interlock - an interlock is an action taken to stop an ongoing process, or prevent a process or action from starting

[REQ-1-OAD-7065] The OSS shall continuously monitor the fault states of all connected devices and subsystems and, upon detection of faults or hazards, impose appropriate interlocks on other connected subsystems per the TMT System Level Hazard Analysis (AD37).

Discussion: This implies that all subsystems shall be able to receive an interlock demand signal from the OSS and provide an interlock event signal to it, transmitted exclusively via the EtherNet/IP safety fieldbus.

[REQ-1-OAD-7080] The OSS shall have the capability to latch an interlock until it is manually reset via the user interface.

Discussion: This is expected to be the normal behaviour, there may be exceptions where this is not desirable. These will be identified in the System Hazard Analysis.

[REQ-1-OAD-7081] The re-setting of sub-system interlocks shall be via a secure interface to the global safety controller.

[REQ-1-OAD-7085] Reset of the interlock demands generated by the OSS shall only be possible provided the interlock request is no longer present.

[REQ-1-OAD-7086] The OSS shall ensure that the system enters a safe state on system startup or if there is a power or network failure.

4.7.2.3 EMERGENCY STOP (E-STOP)

[REQ-1-OAD-7100] The OSS shall implement an emergency stop (E-Stop) system that operates without reliance on any other subsystem.

[REQ-1-OAD-7105] The OSS shall be responsible for continuously monitoring all emergency stops throughout the observatory. In the event of an emergency stop being triggered, it is responsible for ensuring that appropriate action is taken to enforce safety and reduce risk.

Discussion: The emergency stops described in the requirement above initiate action via the OSS to place all subsystems in a safe state, and are distinct from any local devices such as switches or buttons that shut off power or stop motion of an individual machine or device.

Discussion: In general, a system would be made safe when an emergency stop is triggered. This is not the only thing that could be done however; for example, the GSC could have a means of controlling circuit breakers so that power to a particular section of the facility could be removed *under GSC control. The need for such action would be determined by the TMT system-level hazard analysis (AD37).*

[REQ-1-OAD-7110] Emergency stop devices shall be conveniently and appropriately located throughout the Observatory as necessary to ensure adequate coverage and access in the event of an emergency.

Discussion: Emergency stop devices should be located in and near areas where hazards may occur or be detected. The guiding principle should be that of common sense; locate emergency stops where they are easy to locate and operate in the event of an emergency and where they will not be accidentally activated. The distributed I/O capabilities of the RIO modules make this task relatively easy.

[REQ-1-OAD-7112] The OSS shall provide any emergency stop devices and connect them to the nearest interface to the OSS, except for e-stops on the ENC.

Discussion: The OSS provides remote I/O modules at suitable locations to ensure that all emergency stops can be connected to it. The OSS provides the e-stops, the mounting hardware and the necessary cabling and connectors to make the interface at the nearest remote I/O module.

[REQ-1-OAD-7113] OSS E-stop devices shall adhere to ISO 1385 (AD102).

Discussion: This requires OSS E-stop switches to have a red actuator with a yellow background behind the actuator so they are distinguishable from equipment local stops or other similar devices.

[REQ-1-OAD-7115] All subsystems and equipment interlocked by the OSS shall be capable of withstanding multiple emergency stop occurrences without damage.

[REQ-1-OAD-7120] The OSS shall immediately identify and report the location of any triggered emergency stop.

Discussion: To speed fault recovery, the OSS reports the location of any triggered emergency stop. It correctly identifies the triggered device and reports the location even when more than one device has been activated.

4.7.3 TELESCOPE SAFETY

4.7.3.1 GENERAL

[REQ-1-OAD-7200] The elevation structure of the telescope shall have the capability to be physically restrained to inhibit motion or damage, even under Infrequent Earthquake Conditions, for any servicing or maintenance operation where a mass imbalance of the elevation axis is expected.

[REQ-1-OAD-7202] The elevation structure shall include locking devices that prevent motion during servicing operations when the telescope is zenith pointing or horizon pointing.

Discussion: The majority of major servicing operations will be performed with the telescope zenith pointing (e.g.M1 segment removal) or horizon pointing (e.g. M2 and M3 removal). Locking mechanisms will be engaged during these operations.

[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.

[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 to exit the observatory from any regularly accessed location.

Discussion: Exiting the STR from any regularly accessed location on the telescope is expected within 90 seconds.

[REQ-1-OAD-7230] Under an emergency stop condition, azimuth motion shall be stopped as quickly as possible without exceeding a deceleration rate of 2 degrees/sec^2.

Discussion: For a maximum azimuth speed of 2.5deg/s, the stopping time, stopping distance and deceleration at the edge of the Nasmyth platform are:

Table 4-31: Telescope azimuth stopping deceleration, time and distance

Azimuth deceleration rate	Stopping time	Stopping distance at Nasmyth platform edge (R=27.5m)	Deceleration at Nasmyth Platform edge
deg/s^2	sec	m	g
2	1.25	0.75	0.098

[REQ-1-OAD-7233] The elevation travel limit system shock absorbers and mechanical stops shall decelerate the elevation structure such that the maximum deceleration is no greater than 2.5 deg/s2.

[REQ-1-OAD-7235] Under an emergency stop condition, elevation motion shall be stopped as quickly as possible without exceeding a deceleration rate of 2.0 degrees/sec^2.

Discussion: For a maximum elevation speed of 1 deg/s, the stopping time, stopping distance and deceleration at the elevation journal and the top end are:

Table 4-32: Telescope elevation stopping deceleration, time and distance

Elevation deceleration rate	Stopping Time	Stopping distance at elevation journal (R=10.7m)	Deceleration at elevation journal	Stopping distance at top end (R=27.5m)	Deceleration at top end
deg/s^2	sec	m	g	m	g
2	0.5	0.05	0.038	0.12	0.098

4.7.4 Enclosure Safety

4.7.4.1 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.

4.7.4.2 Enclosure Safety System

[REQ-1-OAD-7350] The Enclosure Safety System shall monitor and protect the system and personnel under the conditions identified in the TMT Enclosure Hazard Analysis process.

Discussion: These conditions may include Enclosure cap, base and shutter over-speed; enclosure cap, base and shutter drive over-current; enclosure control system failure; seismic events; unstowed cranes; over temperature conditions; deployable platforms not correctly stowed.

4.7.5 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 the LGSF systems and the associated environment in order to enforce safety of both personnel and the facility and to mitigate the risks and hazards associated with the system identified in the TMT LGSF Hazard Analysis Document.

Discussion: The LGSF Safety System will be linked to the OSS in the same way as any other telescope subsystem. It will cover both general system risks and hazards as well as those specific to enforcing and maintaining safety around high-power sources of visible and invisible laser radiation. These include hazards such as stray laser light caused by scatter or misalignment, smoke produced by laser(s) damage, seismic events, AO system failure, temporary or permanent eye and skin damage due to accidental exposure, fire risks due to beams heating combustible material and accidental illumination of aircraft and satellites.

[REQ-1-OAD-7510] The Laser Guide Star Facility Safety System shall monitor and protect aircraft from accidental laser illumination via transponder based aircraft detection system.

[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

Definition: Active optics is the aggregate of sensors, actuators, and control algorithms (software and hardware) working together to maintain proper telescope optical performance during observations. The active optics system is not a subsystem, but rather the interaction of various subsystems.

Definition: Telescope Optical Feedback System (TOFS) is the functional component of active optics that is utilizing continuous optical measurements of starlight to maintain proper telescope optical performance. TOFS is not a subsystem, but rather the interaction of various subsystems, as described in the Telescope Optical Feedback System Architecture and Specification document (RD40).

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.

Discussion: The TMT Observatory establishes 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 Telescope Optical Feedback System (TOFS) 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 at least 0.1 Hz.

[REQ-1-OAD-8030] In seeing limited operation, guiding errors shall be directly calculated from the slopes of a guiding NGS WFS or the centroids of a guide camera by the Active Optics Reconstructor & Controller (aORC), which is part of the Telescope Control System (TCS) (See '*Figure 5-1: Control architecture for seeing limited observations*' below).

Discussion: The role of the aORC is (i) to read the WFS and guide camera, (ii) compute the required telescope modes with the appropriate sampling rate, and (iii) send setpoint updates to the telescope local control loops (MCS, M1CS, M2CS). The number of algorithmic operations required is relatively small and a single processor computer should be able to perform the work.

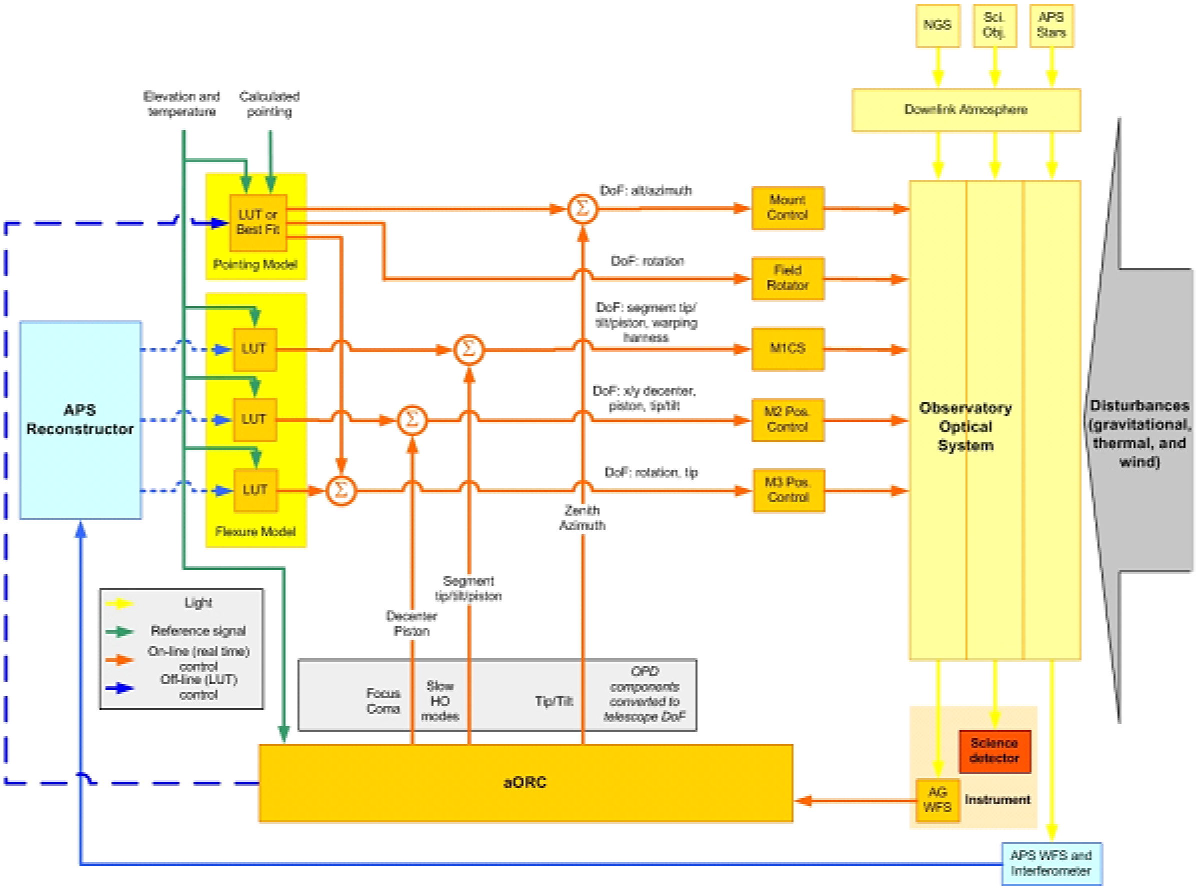

Figure 5-1: Control architecture for seeing limited observations.

[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 (see '*Figure 5-2: Control Architecture for adaptive optics observations*' below).

[REQ-1-OAD-8040] In seeing limited operations, the OPD information from guiders shall be scaled and rotated into telescope modes (degrees of freedoms) that are transferred to the Telescope Control System.

[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 sidereal, non-sidereal tracking, dithering, and differential refraction compensation.

[REQ-1-OAD-8052] The observatory shall guide/track at any rate up to 1.1 times the sidereal rate.

[REQ-1-OAD-8055] During dithering, the deviation of the telescope mount and NGS WFS probes from the profile commanded by the TCS shall not exceed +/- 0.25 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.

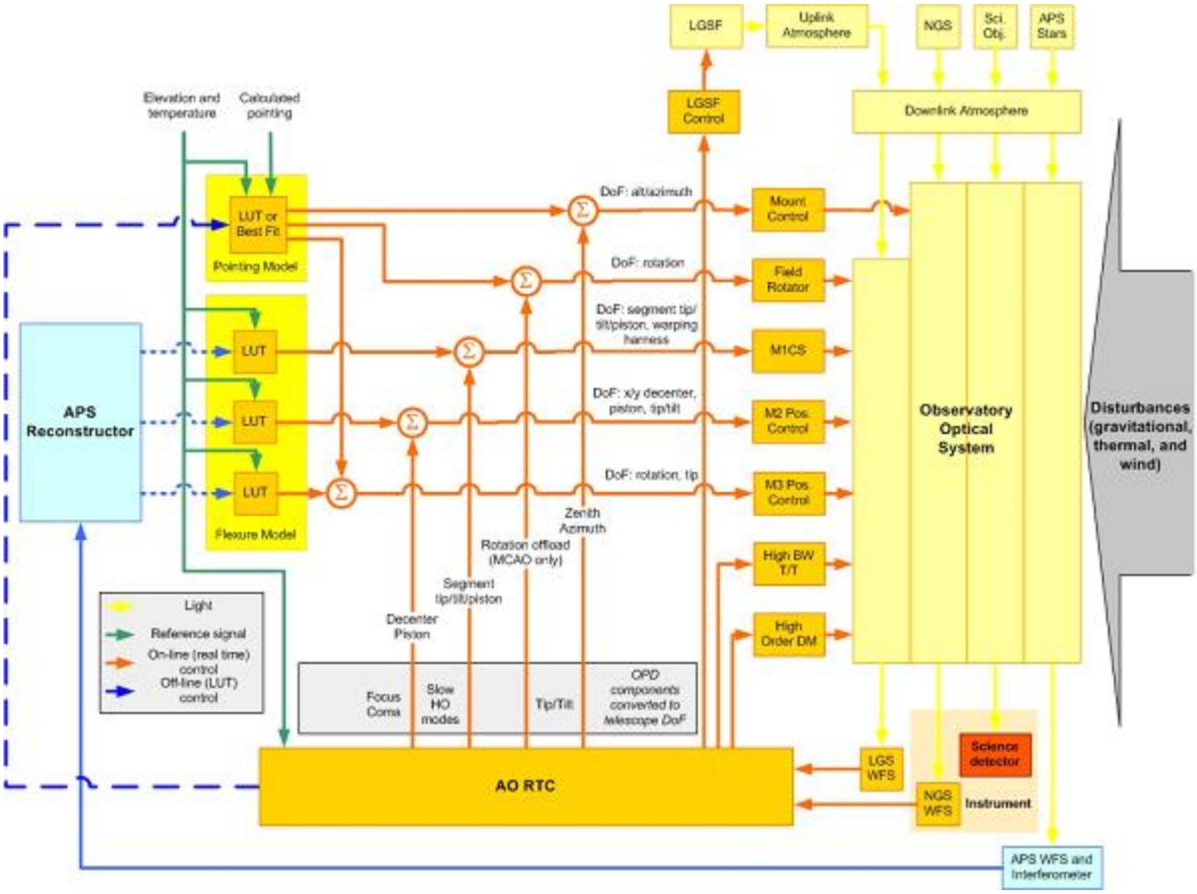

Figure 5-2: Control Architecture for adaptive optics observations

[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.

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 (see '*Figure 5-1: Control architecture for seeing limited observations*' and '*Figure 5-2: Control Architecture for adaptive optics observations*' in the previous section).

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] The telescope control system (TCS) shall provide pointing model open-loop telemetry for instrument atmospheric dispersion compensator (ADC) operation.

[REQ-1-OAD-8210] The TMT Observatory shall provide ADC compensation, applied either by the AO system or instrument, as agreed.

5.1.4 Active and Adaptive Optics Control Architecture

5.1.4.1 General

[REQ-1-OAD-8300] The TMT Observatory shall maintain the shape of the M1 optical surface and the alignment of M1, M2, and M3 relative to each other, i.e. the collimation of the telescope by means of active optics compensation of thermal, gravitational, and vibration disturbances (see '*Figure 5-1: Control architecture for seeing limited observations*' and '*Figure 5-2: Control Architecture for adaptive optics observations*' in the previous section).

Discussion: The most prominent vibration disturbance is expected to be wind buffeting.

[REQ-1-OAD-8310] The TMT Observatory shall 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.

[REQ-1-OAD-8320] The Telescope Optical Feedback System (TOFS) shall meet all performance requirements without degrading the sky coverage of the seeing limited science instruments: 95% for WFOS at the galactic pole.

[REQ-1-OAD-8330] The Telescope Optical Feedback System (TOFS) shall operate and meet performance requirements even when not all primary mirror segments are installed.

5.1.4.2 Active Optics Actuators

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-8412] The warping harness shall be capable of correcting low order errors present in each segment by the amount shown in the table below.

Table 5-1: Warping Harness Performance Parameters

Noll Zernike Mode		Correctable Zernike Amplitude on a 1.44m circle (nm RMS)	Correctable Zernike Amplitude on a hexagonal segment (nm RMS)	Correction Factor
Mode Name	#			
Focus ($Z_{2,0}$)	4	1067	911	17.3
Astigmatism ($Z_{2,+2}$)	5	1575	1331	24.5
Astigmatism ($Z_{2,-2}$)	6	1671	1410	24.4
Coma ($Z_{3,+1}$)	7	348	312	2.8
Coma ($Z_{3,-1}$)	8	222	200	2.8
Trefoil ($Z_{3,+3}$)	9	840	571	7.5
Trefoil ($Z_{3,-3}$)	10	936	813	24.9
Spherical ($Z_{4,0}$)	11	291	264	2.5
Secondary astigmatism ($Z_{4,+2}$)	12	707	639	1.4
Secondary astigmatism ($Z_{4,-2}$)	13	666	602	1.4

Discussion: The above correction factors and amplitudes are based on applying correction using 10 SVD modes. This is the baseline control scheme for the segment warping harness.

[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-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.

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 than 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)*
- *M3 Two degrees of rigid body motion (tip, tilt)*
- *AM2: Five degrees of segment rigid body motion (piston, tip, tilt, and x- and y decenter) 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” low order NGS WFS, shall provide time averaged wavefront errors to the Telescope Optical Feedback System (TOFS).

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 TOFS 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-8620] OPD coma shall be reconstructed into M2 decenter.

Discussion: Both focus and coma is primarily controlled by LUT developed through APS measurements (see appendix 'Table 7-4: Mount and active optics actuators and corresponding sensors with control bandwidths). TOFS provides adjustments for system uncertainties due to unmapped drift between APS measurements.

[REQ-1-OAD-8630] In seeing limited operations higher order OPD information including focus and coma shall be directly calculated from the slopes of the Low Order NGS WFS in the seeing limited instruments, by the Active Optics Reconstructor & Controller (aORC).

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 adaptive optics operations, the OPD information shall be scaled into telescope modes (degrees of freedom) that are transferred to the Telescope Control System.

[REQ-1-OAD-8645] OPD Zernike modes up to the 6^{th} radial order shall be reconstructed into M1 mirror modes.

[REQ-1-OAD-8650] In steady state conditions, the telescope system shall meet the image quality requirements over periods up to 300s without corrections from the optical feedback system.

[REQ-1-OAD-8655] The Low Order NGS WFS in the seeing limited instruments shall be either adjacent to the entrance window of the instrument, or preferably located inside the instrument.

[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 5-2: Control Architecture for adaptive optics observations*' below [REQ-1-OAD-8055].

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 PRESET AND ACQUISITION

Definition: The term *"preset"* refers to commanded “blind” motion of an actuator, or assembly of actuators, to a given position based on a specific input (Look-Up-Tables, coordinates, encoder position, etc.). If not explicitly denoted, preset motions involving different subsystems are triggered in parallel.

Preset is the process of (i) slewing the Telescope and Enclosure to point to the sky coordinates of a requested observation, and (ii) configuring all subsystems to execute the acquisition process.

Definition: The term "*acquisition*" refers to the execution of a coordinated sequence of functions that prepares the system for a science exposure. In contrast to preset, the motions are not blind and the involved subsystems typically require receiving star light.

Acquisition is the process of (i) locking the telescope to the sky (guide star acquisition or coarse acquisition), and (ii) establishing proper alignment of the science target with the instrument (science target acquisition or fine acquisition).

[REQ-1-OAD-8700] TMT Executive Software shall coordinate the preset and acquisition processes.

[REQ-1-OAD-8705] TMT instruments and AO systems shall provide their sensors for guiding.

Discussion: TMT doesn't include a facility acquisition and guiding system.

[REQ-1-OAD-8710] Each TMT 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.

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). 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.

Discussion: 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-8715] Early light instruments/AO combination 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-8725] TMT TCS shall command the position of the guiders or wavefront sensors (WFS).

Discussion: This includes any type of guide star mechanism such as AGWFS, ODGW, OIWFS and PWFS.

5.1.5.1 PRESET AND ACQUISITION SEQUENCES FOR DIFFERENT SYSTEM CONFIGURATIONS

Discussion: (RD44) illustrates and defines example preset and acquisition sequences for seeing-limited and adaptive optics modes (NFIRAOS NGSAO and NFIRAOS LGS MCAO) of the Observatory.

5.1.5.1.1 PRESET TIME

Discussion: TMT Preset Sequences Workflows are detailed in (RD44). The 1-minute average and 3-minute maximum preset times are allocated to subsystem as shown in Table 5-2: Preset Time Decomposition for Seeing Limited, NFIRAOS NGSAO and LGS MCAO. The LGSF terms do not apply for NGSAO and Seeing-Limited mode. This sequence includes pointing from any one position on the sky to any other in a way ensuring the uninterrupted execution of the next observation, and settle control loops and structural dynamics sufficiently to be ready for object acquisition.

Table 5-2: Preset Time Decomposition for Seeing-Limited, NGSAO and NFIRAOS LGS MCAO Modes

Requirement ID	Preset Time (s)	avg(s)	avg(s)	avg(s)	max (s)	max (s)	max (s)	Requirement ID
[REQ-1-OAD-8729]	TMT Observatory	60			180	180		REQ-0-SRD-0200, REQ-0-OpsRD-3022,REQ-0-OpsRD-3024 REQ-1-OAD-8729
[REQ-1-OAD-8730]	MCS & ECS		60			180		[REQ-1-OAD-1377/1379/5055]
[REQ-1-OAD-8732]	TCS		2			5		
[REQ-1-OAD-8733]	M3S		45			180		[REQ-1-OAD-2015]
[REQ-1-OAD-8734]	M2S		30			60		
[REQ-1-OAD-8735]	M1CS		30			75		
[REQ-1-OAD-8738]	ESW		2			5		
	ESW.ACQ			0			0	
	ESW.OCS.SEQ			2			5	
NGSAO & LGS MCAO IRIS/MODHIS ONLY								
[REQ-1-OAD-8737]	NFIRAOS System		30			45		
	NSEN			15			30	
	NCC			30			45	
	RTC			2			5	
[REQ-1-OAD-8736]	AOESW		15			18		
	AOSEQ			2			5	
	RPG			15			18	
[REQ-1-OAD-8739]	IRIS/MODHIS		45			60		
	IRIS/MODHIS OIWFS			15			25	
	IRIS ODGW			2			5	
	IRIS/MODHIS SEQ+ASSY			45			60	
[REQ-1-OAD-2910]	*LGSF		15			60		
	LIS			2			5	
	BTO			15			60	
Seeing Limited ONLY								
[REQ-1-OAD-8731]	WFOS		45			60		

5.1.5.1.2 Guide Star Acquisition Time

See (RD48) for the NFIRAOS LGS MCAO Modes for the acquisition time allocation to subsystems and individual Steps/Tasks times. These acquisition time allocations are based on (RD44) Sequence Workflows. Table 5-3 assume no user interactions -- requirements hold under totally automated operation. The LGSF terms do not apply for NGSAO.

Table 5-3: Guide Star Acquisition Time Decomposition for NFIRAOS NGSAO/ LGS MCAO Modes

Requirement ID	Subsystem	avg (s)	avg (s)	avg (s)	max (s)	max (s)	max (s)	Requirement ID
[REQ-1-OAD-8701]	NFIRAOS NGSAO/LGS MCAO Guide Star Acquisition Time	240			420			[REQ-1-OAD-8701]
[REQ-1-OAD-8740]	MCS		2			5		[REQ-1-OAD-8740]
	ECS		0			0		
	M2S		0			0		
	M3S		0			0		
[REQ-1-OAD-8741]	M1CS		30			30		[REQ-1-OAD-8741]
[REQ-1-OAD-8747]	TCS		6			6		[REQ-1-OAD-8747]
[REQ-1-OAD-8742]	AOESW		52			52		[REQ-1-OAD-8742]
	AOSEQ			52			52	
	RPG			0			0	
[REQ-1-OAD-8743]	NFIRAOS SYSTEM		109			177		[REQ-1-OAD-8743]
	NSEN			20			30	
	NCC			13			21	
	RTC			76			126	
[REQ-1-OAD-8744]	ESW		25			27		[REQ-1-OAD-8744]
	ESW.ACQ			5			7	
	ESW.OCS.Seq			20			20	
[REQ-1-OAD-8745]	IRIS/MODHIS		50			80		[REQ-1-OAD-8745]
	IRIS/MODHIS OIWFS			16			36	
	IRIS ODGW			12			12	
	IRIS/MODHIS Imager			20			30	
	IRIS MODHIS SEQ + ASSY			2			2	
[REQ-1-OAD-8746]	*LGSF		56			79		[REQ-1-OAD-8746]
	LIS			2			2	
	BTO			54			77	

Discussion: See (RD48) and Table 5-4: Guide Star Acquisition Time Decomposition for Seeing Limited Modes for the acquisition time allocation to subsystems. This table assume no user interactions -- requirements hold under totally automated operation. The guide star acquisition time allocations are based on (RD44), Sequence Workflows.

Table 5-4: Guide Star Acquisition Time Decomposition for Seeing-Limited Mode

Requirement ID	Guide Star Acquisition Time (s)	avg(s)	avg(s)	avg(s)	max (s)	max (s)	max (s)	Requirement ID
[REQ-1-OAD-8702]	Seeing Limited mode Guide Star Acquisition	120			300			[REQ-1-OAD-8702]
[REQ-1-OAD-8740]	MCS		17			17		[REQ-1-OAD-8740]
	ECS		0			0		
	M2S		0			0		
	M3S		0			0		
[REQ-1-OAD-8741]	M1CS		30			30		
[REQ-1-OAD-8747]	TCS		6			6		[REQ-1-OAD-8747]
[REQ-1-OAD-8750]	ESW		20			20		[REQ-1-OAD-8750]
	ESW.ACQ			TBD			TBD	
	ESW.OCS.SEQ			TBD			TBD	
[REQ-1-OAD-8751]	WFOS		60			120		[REQ-1-OAD-8751]
	WFOS OIWFS			TBD			TBD	
	WFOS Seq			TBD			TBD	

5.1.5.1.3 Science Target Acquisition Time

Definition: The guide star acquisition process delivers the telescope ready for science observation to the predefined Pointing-Origin position. Pointing-Origin is defined as the [x,y] position in the focal plane that receives the image of the target. If additional adjustments specific to a science observation are needed, these are covered by the science target acquisition time requirements.

[REQ-1-OAD-3096] IRIS science target acquisition time for IFU, in NGSAO or LGS MCAO shall take less than 2 minutes, after the guide star acquisition has been completed.

[REQ-1-OAD-3098] IRIS science target acquisition time for the Full Array Imager, in NGSAO or LGS MCAO shall take less than 0.5 minutes, after the guide star acquisition has been completed.

[REQ-1-OAD-3344] WFOS science target acquisition time for multi-slit masks, in seeing-limited, shall take less than 3 minutes, after the guide star acquisition has been completed.

[REQ-1-OAD-3346] WFOS science target acquisition time of a single target onto a long slit, in seeing-limited, shall take less than 1 minute, after the guide star acquisition has been completed.

5.2 OBSERVATORY SOFTWARE ARCHITECTURE

The TMT Observatory Software Architecture (OSA) is split into two parts called the Program Execution System Architecture (PESA) and Observation Execution System Architecture (OESA). The OESA includes the software that runs at the telescope and controls other hardware systems in order to gather and quick look science data. The PESA includes all software needed to prepare for observing at the telescope and all software used following observing to process and distribute science data.

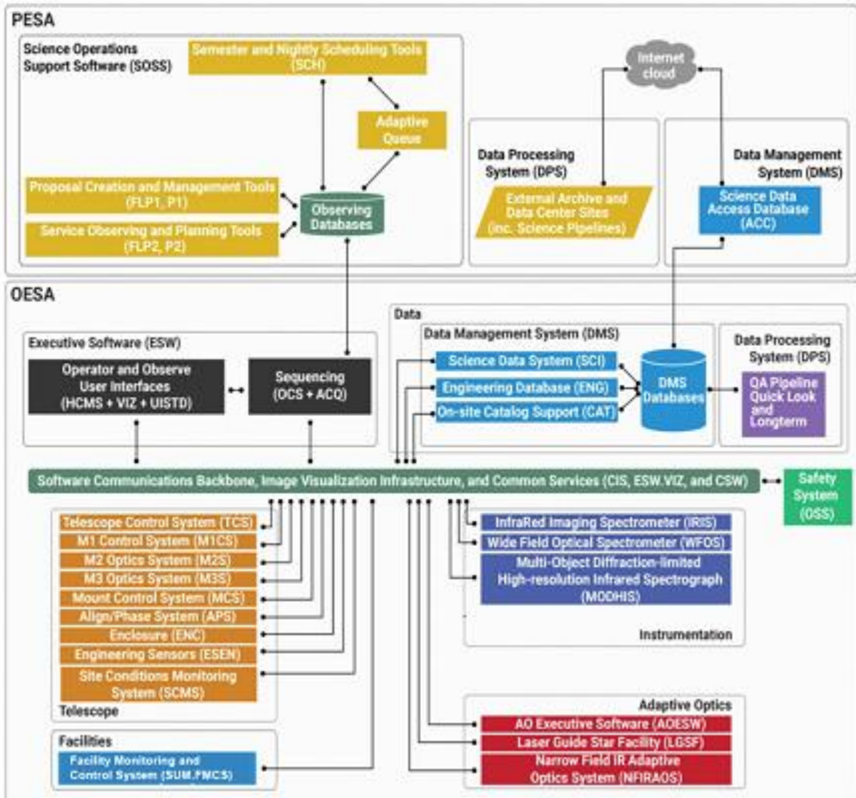

Figure 5-3: Observatory Software Architecture (OSA) Subsystem Decomposition

Discussion: The OSA subsystems are also partitioned into six logical groups of related functionality called Principal Systems to aid reasoning about the software system as shown in 'Figure 5-4: OSA partitions software subsystems into Principal Software Systems' below and 'Figure 5-3: Observatory Software Architecture (OSA) Subsystem Decomposition' above. The observatory subsystems that implement these functions are called out in 'Table 5-5: OSA subsystem allocation into Principal Software Systems'.

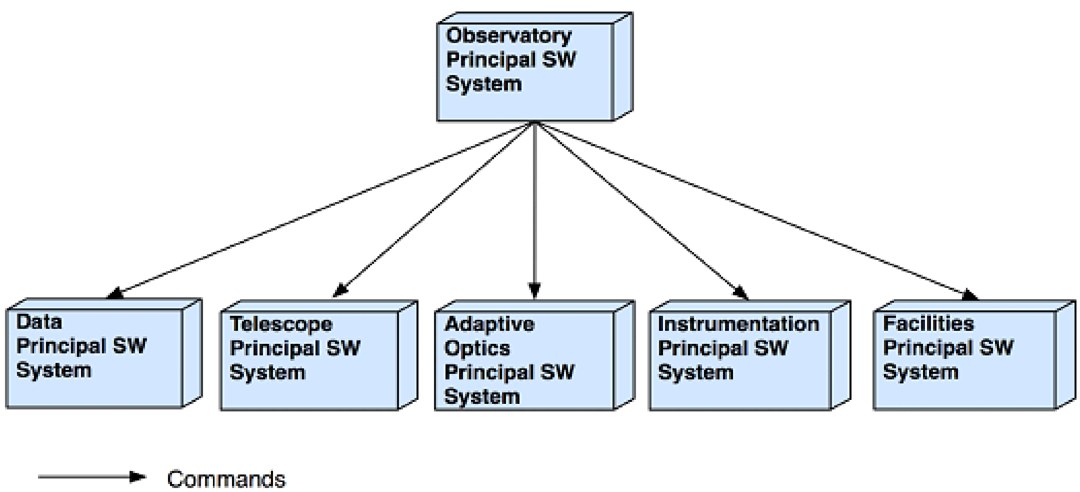

Figure 5-4: OSA partitions software subsystems into Principal Software Systems

[REQ-1-OAD-9351] The OSA principal systems shall be implemented per the Observatory Subsystem Allocation subsystem elements as shown in '*Table 5-5: OSA subsystem allocation into*

Principal Software Systems' and '*Figure 5-3: Observatory Software Architecture (OSA) Subsystem Decomposition*'.

Table 5-5: OSA subsystem allocation to Principal Software Systems

System	Principal Software System	OESA/PESA
Enclosure (ENC)	Telescope	OESA
Summit Facilities (SUM) -Facilities Control and Mgmt System (FCMS)	Facilities	OESA
Observatory Headquarters (HQ)	N/A	N/A
Telescope Structure (STR) -Mount Control System (MCS)	Telescope	OESA
M1 Optics System (M1)	N/A	N/A
M2 System (M2)	Telescope	OESA
M3 System (M3)	Telescope	OESA
Optical Cleaning Systems (CLN)	N/A	N/A
Optical Coating System (COAT)	N/A	N/A
Test Instruments (TINS)	N/A	N/A
Optics Handling Equipment (HNDL)	N/A	N/A
Alignment and Phasing System (APS)	Telescope	OESA
Telescope Control System (TCS)	Telescope	OESA
M1 Control System (M1CS)	Telescope	OESA
Observatory Safety System (OSS)	N/A	OESA
Engineering Sensors (ESEN)	Telescope	OESA
Narrow Field Near Infrared On-Axis AO System (NFIRAOS) (including NSCU)	Adaptive Optics	OESA
Laser Guide Star Facility (LGSF)	Adaptive Optics	OESA
Adaptive Optics Executive Software (AOESW)	Adaptive Optics	OESA
Refrigerant Cooling System (REFR)	N/A	N/A
Cryogenic Cooling System (CRYO)	N/A	N/A
InfraRed Imaging Spectrometer (IRIS)	Instrumentation	OESA
Wide Field Optical Spectrometer (WFOS)	Instrumentation	OESA
Multi-Object Diffraction-limited High-Resolution Infrared Spectrograph (MODHIS)	Instrumentation	OESA
Communications and Information Systems (CIS)	N/A	N/A
Common Software (CSW)	Observatory	OESA
Data Management System (DMS)	Data	OESA/PESA
Executive Software (ESW)	Observatory	OESA
Science Operations Support Systems (SOSS)	Observatory	PESA
Data Processing System (DPS)	Data	OESA/PESA
Site Conditions Monitoring System (SCMS)	Telescope	OESA

[REQ-1-OAD-9009] OSA subsystem command-and-control shall be strictly hierarchical as indicated by the arrows in '*Figure 5-4: OSA partitions software subsystems into Principal Software Systems*'.

Discussion: This limits command communication to flow from Observatory Controls to the other principal systems.

Discussion: Observatory Controls is responsible for coordinating and synchronizing activities occurring in different principal systems.

Discussion: The Observatory Software Architecture is defined with the intent that command rates between Observatory Controls and other principal systems is slow (e.g. less than 100 commands/sec between subsystems). All faster communication takes place within the individual principal systems and may use CSW services or other mechanisms based on requirements.

[REQ-1-OAD-9850] The OSA shall include all software necessary to implement the first light observing mode called Visitor Observing Mode.

Discussion: Individual users (or teams) are assigned specific blocks of time no shorter than one half night. During their assigned time, users have complete responsibility for how they use and configure the telescope and instruments.

Discussion: OSW provides software tools that support the proposal process for Visitor Observing Mode. OSW provides tools for planning observations prior to arrival at this telescope. Observers can use the user interface programs and tools provided at the telescope (or a remote observing site) to configure the telescope systems and instrument to obtain science data. Instrument user interfaces load sequences which are executed to control and coordinate the telescope software and hardware systems. The observing process creates entries in observatory databases to associate the science data created with the observer's program. The created science data flows to the local data storage system and is available via a data access web site.

[REQ-1-OAD-9852] The OSA shall include all software necessary to implement the first light observing mode called Service Observing Mode.

Discussion: Service observations are executed by TMT Science Operations Staff on behalf of PIs from a combined list of observation descriptions from all partners.

Discussion: OSW provides software tools that support the proposal process for observers. OSW provides tools for planning observations prior to arrival at this telescope. The planning tools are required for observers to enable later execution by TMT staff. Information sufficient for execution is stored in the observatory databases. Staff members use the user interface programs and tools provided at the telescope (or a remote observing site) to extract the information and configure the telescope systems and instrument to obtain science data. The tool loads a sequence, which is executed to control and coordinate the telescope software and hardware systems. The entries in observatory databases are updated to associate the science data created with the observer's program. The created science data flows to the local data storage system and is available via a data access web site.

[REQ-1-OAD-9854] The OSA shall include an observing mode called Adaptive Queue Observing Mode to ensure that this mode is available without significant re-design as part of the Service Observing Mode.

Discussion: Adaptive Queue Observing mode means onsite conditions are used to optimize the scheduling of observations on the telescope. This mode is not a first light observing mode, but it is required that our software system allow it in the future without significant rewrite of code. The majority of changes required are scheduling tool and observing database updates.

[REQ-1-OAD-9856] The OSA design shall include all software necessary to support Target of Opportunity (ToO) observations during time allocated for both Visitor and Service Observing Mode programs.

Discussion: The TMT support for ToO is described here. During the proposal phase, an observer specifically requests ToO observing time. The scheduling system tracks the amount of available ToO time to ensure that a limited number of ToO proposals are scheduled. By their nature, Successful ToO observers must complete observation planning by completing template observations that include instrument configurations and other details. When a ToO occurs, the observer uses the observation planning tool to update the template observation with final target and instrument information and submits the observation to the TMT site. The arrival of the ToO observation triggers an alert in the observing room that allows the ToO policy to be exercised.

Discussion: Support for ToO observations requires software throughout the software system. Details of the ToO requirements are added in lower level requirements documents for ESW and SOSS.

[REQ-1-OAD-9333] Each OSA software subsystem shall be built using the standard TMT software framework as provided by TMT Common Software and described in TMT Software Design Document (AD86), (AD87).

Discussion: This framework shall have three high-level goals:

- *Adopt and/or adapt open source and/or commercial solutions that are already widely used and supported within the IT industry and astronomy.*

- *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.*

Discussion: This is verified by showing compliance reports comparing the subsystem design with the TMT Software Design Document.

[REQ-1-OAD-9334] Each OSA software subsystem shall be compliant with the TMT Software Development Process (AD79).

Discussion: Adherence to the TMT Software Development Process (AD79) ensures that TMT software subsystems will be consistent with the TMT approved software systems engineering standard that includes software quality assurance, project management, requirements management, testing and configuration management supporting processes.

[REQ-1-OAD-9715] All OSA software subsystems shall have the same CentOS 7 Linux 64-bit deployment platform.

Discussion: The deployment platform was determined during the OSW CSW design process. Deviations from the standard deployment platform must be justified and approved by Systems Engineering. Subsystems using 32-bit may be approved as long as they are not coded to require a 32-bit version of CentOS.

[REQ-1-OAD-9953] OSA software subsystems that require a private non-relational database or technical datastore shall integrate with the Observatory Databases through an HTTP-based interface.

Discussion: The HTTP-based interface will be defined by DMS ENG and implemented by the subsystem. See 'Figure 5-6: Observatory database architecture' in Section 5.3.

[REQ-1-OAD-9027] OSA software subsystems shall use Graphical user interfaces (GUIs) as the default for all normal scientific and technical operations.

Discussion: User interface standards development and support are part of the Common Software and ESW requirements.

[REQ-1-OAD-9029] OSA software subsystems shall provide engineering GUIs if they include:

- Low-level technical software parameter settings that are modifiable during operations.
- Low-level engineering functions that are occasionally executed by an expert user.
- Are required to operate in standalone mode.

[REQ-1-OAD-9740] The combined set of OSA software subsystems shall be implemented such that, without warning, they can be removed from the TMT operational environment then re-installed and restored to their operational state in less than eight (8) hours.

Discussion: The restoration of the OSA subsystems will be solely based on information stored on the central configuration server supplemented by various high-level installation kits (e.g. operating system, common software packages, etc.).

5.2.1 OBSERVATION EXECUTION SYSTEM ARCHITECTURE (OESA)

This section contains general OESA requirements that pertain to all software that is part of the OESA. Section 5.4 contains detailed Observatory Software requirements for Common Software, Executive Software, and the Data Management System that supplement the requirements in this section.

[REQ-1-OAD-9000] The OESA shall enable efficient observation of astronomical objects as well as efficient command, control, and monitoring of all observatory functions.

[REQ-1-OAD-9003] OESA shall consist of a set of software subsystems that interact through a software connectivity backbone that is implemented in a software Subsystem called Common Software (CSW) layered on top of a physical communications network Subsystem called Communications and Information Systems (CIS) (see '*Figure 5-3: Observatory Software Architecture (OSA) Subsystem Decomposition*').

Discussion: The subsystems of the OESA form a distributed, concurrent application. The communication is decomposed into a set of communication common services, which are discussed later in this document.

[REQ-1-OAD-9300] Each OESA software subsystem shall consist of one or more lower-level software components.

Discussion: A software component is a software entity that encapsulates a set of related functions or data.

Discussion: Software subsystems generally consist of multiple lower-level software components that collectively provide the subsystem functionality. The requirements in this section pertain to subsystems as well as their lower-level components.

[REQ-1-OAD-9365] Any OESA software subsystems that contain hardware and software, such as instruments and telescope subsystems, shall be structured in a TMT-standard way consisting of an observing mode-oriented sequencer, assemblies and hardware control daemons.

Discussion: An example of this structure is shown in 'Figure 5-5: Standardized software components for subsystems with hardware and software' below.

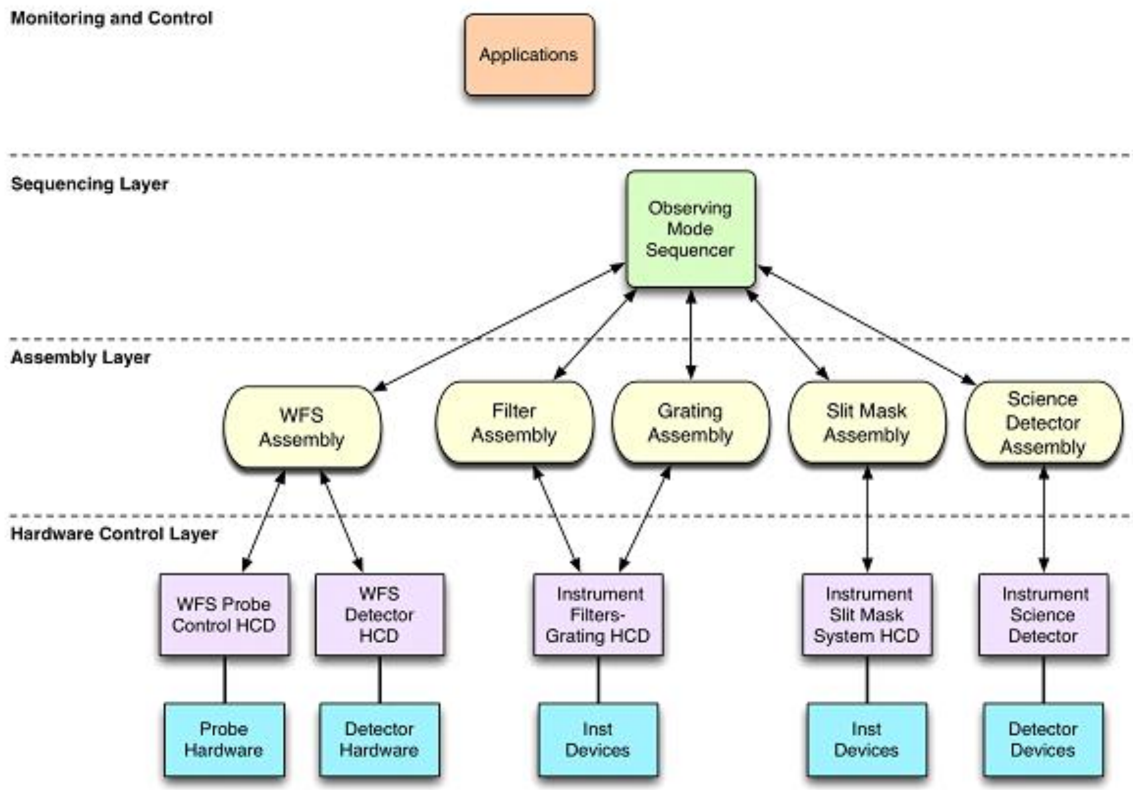

Figure 5-5: Standardized software components for subsystems with hardware and software

Discussion: The lowest layer in the software system, called the Hardware Control Layer, consists of all the controllable hardware that is available for use by higher levels of software. A sea of similar software components called Hardware Control Daemons (HCD) interfaces to hardware devices. The Assembly Layer exists just above the Hardware Layer. Software at this layer consists of components called Assemblies with two roles. The first role is to allow the grouping of HCDs into higher-level entities. This is required when individual hardware devices must be considered as a unit or requiring processing. The second role of components in the Assembly Layer is to provide more sophisticated hardware control functionality that integrates devices across different HCDs to produce higher-level devices or add uniformly useful capabilities. The Sequencing Layer contains components called sequencers because they control and synchronize the actions of the

HCDs and Assemblies. A Sequencer uses a script that to coordinate and synchronize the Assemblies and HCDs. The Monitoring/Control Layer is the layer of software that contains the user interface programs that are used to observe with the telescope.

[REQ-1-OAD-9330] Each OESA subsystem or component shall integrate and communicate with the other principal systems of the OESA using only the integration services and other software provided by the TMT Common Software (CSW) subsystem (see 'Table 5-8: TMT Common Software services definitions' below [REQ-1-OAD-9200]).

Discussion: This requirement constrains the software principal systems to use only the TMT Common Software for integration with OESA.

[REQ-1-OAD-9021] Each OESA software subsystem user interface shall support the tasks of the user types shown in '*Table 5-6: Software subsystem user types*' below.

Table 5-6: Software subsystem user types

User Type	Description
Observing Assistant	A TMT staff person at the telescope site who is responsible for controlling and monitoring the TMT telescope and software system on behalf of other system users.
PI-Directed Observer	A TMT user executing science observations and/or acquiring associated calibration data using the PI-Directed observing mode. The PI-Directed Observer may be physically present at the TMT telescope, TMT Support Facility or at an approved remote observing facility.
Pre-Planned Queue User	A TMT user who has submitted descriptions of science observations and/or associated calibration data acquisition sequences for the purposes of later execution by a Pre-Planned Queue Observer.
Pre-Planned Queue Observer	A TMT Support Astronomer or other individual who makes Pre-Planned Queue observations on behalf of Pre-Planned Queue Users. The Pre-Planned Queue Observer may be physically present at the TMT telescope or the TMT Support Facility.
Technical Staff	Anyone who is monitoring system performance, performing system maintenance tasks, and/or implementing system improvements.

[REQ-1-OAD-9024] All OESA software subsystem user interfaces shall have a common look-and-feel within each interface category (i.e. command-line interface, graphical user interface, Web interface).

Discussion: ESW will provide guidance for GUI patterns and look-and-feel.

[REQ-1-OAD-9309] Each OESA software subsystem shall initialize itself with a default configuration and make itself ready for operation without further human intervention in less than one (1) minute.

Discussion: See 'Figure 5-5: Standardized software components for subsystems with hardware and software'. This requirement also applies to all components within a subsystem.

[REQ-1-OAD-9306] Each OESA software subsystem shall provide a simulation mode, either independently or in conjunction with other subsystems or components of the TMT software system.

Discussion: This requirement also applies to each component within a subsystem. See [REQ-1-OAD-9300] and [REQ-1-OAD-9365] and their discussions for the definition of a component.

Discussion: The software simulation architecture/design will be added to the Software Design Document (AD86, AD87).

[REQ-1-OAD-9303] Each OESA software subsystem shall be capable of being built, run, controlled, and monitored in stand-alone mode, i.e. without starting the entire TMT software system.

Discussion: This requirement also applies to each component within a subsystem. See [REQ-1-OAD-9300] and [REQ-1-OAD-9365] and their discussions for the definition of a component.

[REQ-1-OAD-9305] Any TMT software subsystem platform, when operating at full capacity, shall have an available margin in computational power of 30% or more.

Discussion: This requirement is to ensure that delivered computer systems have enough reserve computational capacity to allow future reasonable changes during AIV and the first few years of operations that may impact CPU/core performance.

Discussion: For many systems, the requirement can be met by demonstrating that the average load at full capacity is 70% or less on all CPUs or cores. Where this approach does not apply, the system should provide another method for demonstrating that the 30% margin is achieved.

Discussion: An example of operating at full capacity includes performing maximum computations.

[REQ-1-OAD-9307] The OESA software subsystems shall allow remote/programmatic control of power to controllers and devices over the CIS network using TMT standard hardware.

Discussion: This is to support cold starts and to have the ability to remotely control power to equipment in panels that are heated, etc. This is distinct from devices being on UPS or conditioned power. The TMT standard hardware is the Eaton IPC34XX-NET series. For example, the IPC-3402-NET 16A 8 outlet Intelligent Power Controller. These controllers provide web interfaces for browser control. If this standard hardware does not satisfy subsystem requirements, other hardware can be substituted with TMT SE permission.

5.2.2 Program Execution System Architecture (PESA)

This section contains general PESA requirements. For more details, see section 5.4.4 for Science Operations Support System requirements and section 5.4.5 for Data Processing System requirements.

Due to construction resource limitations, much of the PESA implementation is not included in the scope of the construction project and is deferred until early operations. The PESA and subsystem design must take that constraint into account.

[REQ-1-OAD-9100] The PESA shall be implemented to enable efficient management of astronomical programs from proposal creation to data delivery based on the end-to-end observing workflow.

Discussion: The end-to-end observing workflow is described in the TMT Observation Workflow (RD44) and the TMT OSW OCDD (RD45).

[REQ-1-OAD-9405] The PESA software subsystems and tools shall support the operations workflow and operations modes of the TMT OSW OCDD (RD45).

[REQ-1-OAD-9400] PESA subsystems shall follow the same user interface standards and guidelines as OESA subsystems unless it is determined that they are not sufficient.

[REQ-1-OAD-9403] Unless otherwise noted, PESA subsystems shall follow the same communication stack solutions as OESA subsystems. However, PESA systems acting as web services may work synchronously with a request-response communication model.

Discussion: This requirement acknowledges that the PESA applications will have different requirements than OESA applications and different solutions and approaches may be needed.

5.3 Observatory Database Architecture

The reference design for the Observatory Database Architecture is shown in 'Figure 5-6: Observatory database architecture'.

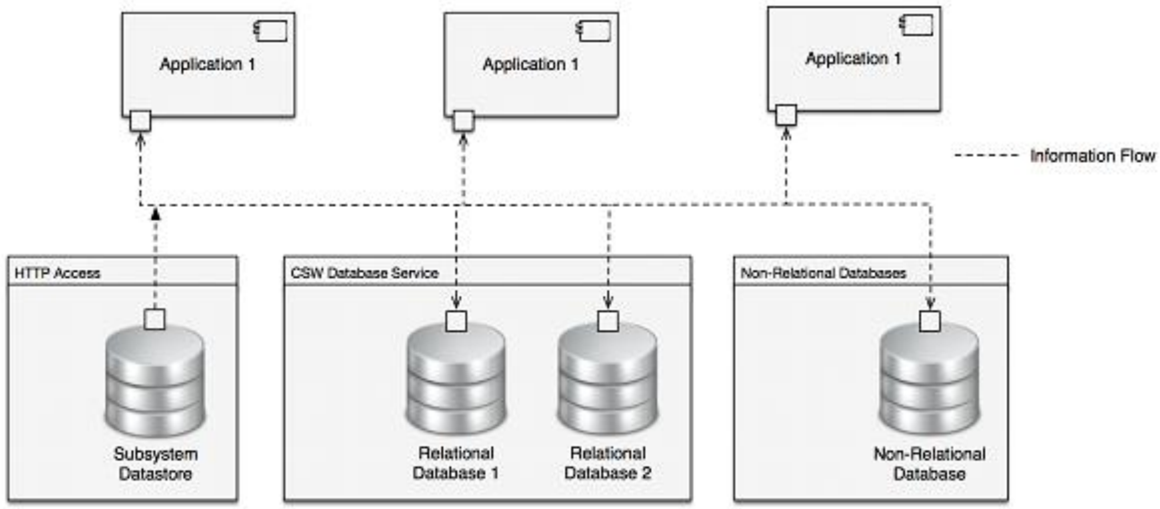

Figure 5-6: Observatory Database Architecture

[REQ-1-OAD-9106] All Observatory and observing-related information shall be stored in one or more databases, consistent with the architecture shown in *'Figure 5-6: Observatory Database Architecture'.*

Discussion: 'Figure 5-6: Observatory Database Architecture' shows that individual applications can access one or more databases.

[REQ-1-OAD-9500] The observatory databases shall be designed, as a minimum, to the following use cases as shown in '*Table 5-7: Observatory Database Use Cases*'.

Table 5-7: Observatory Database Use Cases

Use Case	Database
Proposal and planning information supporting pre-planned queue observing	SOSS Observing DB
Long-term Schedules	SOSS SCH DB
Locations of science data produced by science instruments	SOSS Observing DB, DMS ACC DB
Associations of science data and observations	SOSS Observing DB, DMS ACC DB
Telemetry data produced by technical systems	DMS ENG DB
Logging (history) data from all subsystems	CSW DB
Astronomical catalogs required on site	DMS CAT DB
System Configuration Database	
User contact information, authentication, and authorization data	CIS DB
RTC Database	
M1CS Database	
APS Database	

[REQ-1-OAD-9501] The observatory Databases shall provide one or more persistent data stores for observatory information as shown in '*Figure 5-6: Observatory Database Architecture*'

[REQ-1-OAD-9943] All observatory subsystems shall store their configuration information in a central observatory configuration database.

Discussion: It is planned that the observatory configuration can be loaded into subsystems from the configuration database during system initialization. This may be the operational model for the initializing the observatory each evening. A consequence is that engineering GUI's that allow direct modification of subsystem parameters should have a "save to configuration database" function to facilitate the persistence of desired changes.

Discussion: Local storage of configuration data by subsystems is not permitted.

[REQ-1-OAD-9942] The configuration of each observatory subsystem, and therefore the entire observatory, shall be accessible from a central observatory configuration database.

Discussion: This includes pointers to initialization files, look-up tables, hardware state. For example, the configuration of the primary mirror (segment serial numbers etc) should be retrievable from this database. Also, the LUT for M2 internal calibration should be retrievable.

Discussion: Some subsystems, such as APS and M1CS, will have very detailed data models that don't lend themselves well to the flat file structure planned for the configuration service. These data models may have follow a two step creation process, first generated as files (from queries to the DMS engineering database, for example) and stored on the configuration service before being loaded into the subsystem.

[REQ-1-OAD-9950] The observatory shall maintain a searchable status and alarms database, that includes both current and historical data.

Discussion: Since health and alarms are events that are logged to the engineering database, this could be implemented through queries to the existing database.

[REQ-1-OAD-9504] Each subsystem using its own database shall use standard choices for database technologies identified by TMT.

Discussion: This requirement recognizes that a single database technology is not appropriate for all TMT issues and that a single database provides a bottleneck for operations and development. It also recognizes that the number of database technologies must be controlled.

Discussion: Some applications require update-oriented data – small (few byte to several KB) data objects oriented towards an update-many, read-many, fast access model (e.g. status flags, mutable business objects). Other applications need to store bulk data – large (several to many MB) data objects oriented towards a write-once, read-many, slow access model (e.g. science detector pixel data).

Discussion: The use of standardized database system choices will allow combining databases during operations as needed.

[REQ-1-OAD-9909] Subsystems that store technical data locally shall provide an HTTP query interface to enable retrieval of data from local database.

[REQ-1-OAD-9524] If access and or update to a subsystem database is required by other subsystems, an Application Programmer Interface shall be provided by the subsystem containing the database that describes the available data structures and operations.

Discussion: In some cases, a database within a subsystem may need to be accessed by another subsystem.

[REQ-1-OAD-9526] When used between subsystems, database Application Programmer Interfaces shall be implementation neutral whenever possible.

Discussion: Some complex database interfaces may be too complicated to allow an implementation neutral API.

5.4 OBSERVATORY OPERATIONS SOFTWARE

[REQ-1-OAD-9701] TMT Operations Subsystems defined in OAD Section 2.2.1.4 shall operate and meet all requirements for at least 50 years with preventive maintenance.

Discussion: Preventive maintenance means servicing, repairing, and replacing components and subsystems based on their expected lifetime, as opposed to their failure.

5.4.1 COMMON SOFTWARE

Common Software is the software subsystem that provides the infrastructure for integrating all TMT software subsystems and their components. This section defines TMT Common Software.

The TMT Common Software includes (but is not necessarily limited to):

- Middleware APIs and/or Service APIs and supporting libraries

- Software templates for building software components
- Build process and other specifications for developing components
- A strategy and support for testing and automating tests of components
- Standard choices for (if appropriate):
    - Data and meta-data structures
    - Programming languages
    - Development environment (OS, hardware, compilers…)
    - Deployment environment (OS, hardware)
    - Associated documentation

[REQ-1-OAD-9712] Whenever possible, the TMT software framework shall use and be based upon widely used open source tools, libraries, data structures, etc. Commercial solutions are also possible if necessary. 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-9205] The communications backbone shall run on top of a communication protocol stack that has a physical IT communications network as provided by the CIS subsystem.

Discussion: it is a high priority goal to build TMT Common Software according to the principles of [REQ-1-OAD-9712]. In addition, it is important to: (1) implement solutions that are operating system neutral to the largest extent possible; and (2) support more than one main stream software language. Early in the design process, TMT will select reference middleware solutions and proceed to common services API specification.

[REQ-1-OAD-9356] The CSW shall allow integration of low-level hardware or vendor-software subsystems by providing TMT-standardized software Hardware Control Daemons for these systems (see [REQ-1-OAD-9365]).

Discussion: Examples are (but not limited to) the various low-level facility mechanical plant and electrical plant equipment and enclosure HVAC systems. Examples might be: FCS, SUM, STR, M2, M3, ENC and MCS.

5.4.1.1 Specific Common Software Requirements

[REQ-1-OAD-9028] The CSW shall include libraries and/or editors to support component and GUI development.

Discussion: Common Software will provide developers of user interfaces with solutions and demonstrations of common integration tasks. User interface templates and standards are part of ESW.

[REQ-1-OAD-9039] CSW shall implement support for automatic startup and shutdown of OESA subsystems and components as required by [REQ-1-OAD-9740].

[REQ-1-OAD-9200] The CSW shall include the set of software communication and integration services listed in '*Table 5-8: TMT Common Software services definitions*' below with a general description of their functionality

Discussion: Each Common Software service provides functionality needed to integrate the OESA components.

Discussion: This table is the current list of common software services, which may change as the software design evolves.

Discussion: Software with the functionality of Common Software services are often known as middleware in the software development arena.

Table 5-8: TMT Common Software services definitions

Name	Task
Single Sign-on Service	Centrally manage user authentication/access control
Connection and Command Service	Support for subscribing to, receiving, sending and completing commands in the form of configurations
Location Service	Locate and connect to components within the distributed system
Event Services	Provide an event publish/subscribe infrastructure to support events, telemetry, alarms and health
Configuration Service	Manage system and component configuration changes
Logging Service	Capture/store log information
Database Service	Common access to centralized, relational database
Time Service	Provides access to standards-based, precise and accurate time

[REQ-1-OAD-9312] CSW shall provide support for the use of the CSW services listed in '*Table 5-8: TMT Common Software services definitions*' above by OESA components. Service support includes the following:

- All OESA software subsystems or components shall have the ability to receive and parse TMT defined data structures containing command, control and configuration instructions using the Common Software Command Service.
- All OESA software subsystems or components shall have the capability of transmitting and receiving TMT-defined data structures containing health, status, alarms and events using the Common Software Event and Alarm Services.
- Each OESA software subsystem or component shall perform a health evaluation and transmit health information (i.e., a heartbeat) at least once per second.
- For the purposes of later diagnosis and analysis, each OESA software subsystem or component shall have the ability to transmit time-stamped logging information using the Common Software Logging Service.
- For the purposes of process control and synchronization, each software subsystem shall be able to transmit or receive events.
- For the purposes of fault detection, each OESA software subsystem or component shall have the ability to transmit an alarm using the Common Software Alarm Services when a situation occurs that prevents normal operations or abnormal condition occurs.

[REQ-1-OAD-9213] Each CSW 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 extensive code modifications to subsystems using that service.

Discussion: The API is used by the developers of components to interact with the TMT system and other TMT components.

5.4.1.2 SPECIFIC COMMON SOFTWARE SERVICE DEFINITIONS

[REQ-1-OAD-9223] The Single Sign-on (SSO) Service shall enable OESA users to authenticate once and gain access to authorized operations. For each user, one or more authorization roles shall be maintained.

Discussion: Single Sign-on is used in a variety of situations in the software system such as looking up an observer's personal information during planning, limiting access to control system functions, and making sure that one observer cannot view the science data of another observer.

[REQ-1-OAD-9226] The Connection and Command Service shall enable one software component to create a connection to another in order to perform command and control of a specific set of OESA subsystems for specific operations.

Discussion: When one component in the OESA needs to control the activities of another with a command, it uses the Connection and Command Service.

[REQ-1-OAD-9229] The Location Service shall provide a service that allows one software component to find other registered components for the purpose of creating connections for inter-process communication.

Discussion: The Connection and Command Service may include the functionality of the Location Service. In this case, a separate Location Service is not needed.

[REQ-1-OAD-9237] The Configuration Service shall manage a database containing *configuration files* and a historical record of changes made to those files. Clients use the Configuration Service to store and retrieve versions of configuration files.

Discussion: The configuration files stored in the Configuration Service are used for a variety of use cases in the software system including storing user interface parameters, look-up tables and default values for components that are used during their initialization.

[REQ-1-OAD-9900] The CSW configuration service design architecture shall be scalable in order to store the data necessary for operations, for the lifetime of the observatory, provided that periodic updates are made to storage, processing hardware, and database software.

[REQ-1-OAD-9238] The Logging Service shall allow software processes or components to record diagnostic or explanatory messages (with time-stamps) local to the process or component or to a central, shared log storage system or database.

[REQ-1-OAD-9247] The Database Service shall provide access to a relational database system that components or processes may use to create specialized databases that store complex relational data for which the Configuration Service is inadequate.

Discussion: Simple models can be stored with historical version access in the Configuration Service. The Database Service provides a shared Database Management System, but processes or components are responsible for their database design.

Discussion: Database Service provides one form of storage capability for software systems that require this kind of storage as required by [REQ-1-OPSRD-4130].

[REQ-1-OAD-9250] The Time Service shall provide software components and processes with access to precise and accurate time (based on RD60: IEEE 1588 V2) and a GPS-based time base.

Discussion: The Time Service provides synchronization between parts of the software system to an accuracy of ~100 microseconds without a hardware board and ~100 nanoseconds with a hardware board.

[REQ-1-OAD-9251] The TMT standard time provided by the time service and to be used as the baseline by other systems within the OESA and PESA is International Atomic Time (TAI).

5.4.1.2.1 Event Service Definitions

[REQ-1-OAD-9232] The CSW Event Services shall enable the publication of events or messages indicating a change of state, completion of task, etc. and the subscription to events from specific registered processes.

Discussion: The Event Services support a variety of use cases in the software system including distribution of demands as event streams from the Telescope Control System, keeping the user interfaces up to date with the latest status values and events that signal significant activities that occur in the software system.

Discussion: An event stream scenario includes the telescope pointing kernel calculating demands for another component at a periodic rate (e.g. example is 20 Hz).

[REQ-1-OAD-9257] After an event publishing component has initialized, the CSW Event Service shall immediately provide the most recently published value of an event to a newly subscribing component.

Discussion: Dependent systems subscribing to events are dependent on getting initial values for events.

[REQ-1-OAD-9258] The CSW Event Service shall provide a component the most recent value of an event, including an accurate time of occurrence, upon request. The component does not need to be a subscriber of the event to request the most recent value of the event.

Discussion: The implementation of this requirement must address the following edge cases: 1) If no value is available, the CSW Event Service will provide an invalid response. 2) If an old value exists, the CSW Event Service will provide it to the subscriber. Subscribers are responsible for checking the time stamp of the events they consume before making decisions based on the value of the event.

[REQ-2-OAD-9259] When an event publisher has not yet published an event value because it has not initialized, the CSW Location Service shall enable a subscribing component to determine that the publisher is not currently available.

Discussion: The subscribing subsystem can use the CSW Location Service to resolve the status of the publishing subsystem or even track the status of the publishing subsystem. This enables the subscribing system to determine how to proceed with their initialization when event publishers have not yet initialized.

5.4.2 Executive Software Subsystem

Executive Software (ESW) is the observatory software subsystem that provides the framework and support for command, control and synchronization of components during observing activities including target and science data acquisition.

An Observation Block (OB) is a description of an observation as a set of named parameters and their values that is provided by the observer during planning or observing. Examples of information contained in an OB:

- Targets (science, wavefront sensors)
- System configurations (instrument, telescope, AO system)
- Workflow information (observer, program and scheduling information)

[REQ-1-OAD-9354] The ESW shall support the end-to-end observatory workflow as shown in '*Figure 5-9: The TMT Operations Plan observing workflow*', including the future use of conditions-based scheduling (Adaptive Queue).

5.4.2.1 Executive Software Observatory Control System (ESW OCS)

[REQ-1-OAD-9353] The ESW OCS sequencer shall be responsible for the coordination and synchronization of subsystems.

Discussion: This requirement states the most important functionality of ESW is to provide a software system for the coordination and sequencing of the other subsystems.

[REQ-1-OAD-9806] The ESW OCS sequencer shall support the PI-directed and Pre-planned observing modes by accepting Observation Blocks as an input created by a user interface program or a database of Observation Blocks (Observation Block Generators) as shown in '*Figure 5-7: The ESW sequencing system accepts Observation Blocks (OBs) created by Observation Block Generators*' below.

Discussion: Observation descriptions are generated by users using a variety of interface tools and submitted to the ESW for execution. Based on those descriptions, the OESA orchestrates a sequence of system actions to accomplish the described observation. Science datasets are the primary output of this process.

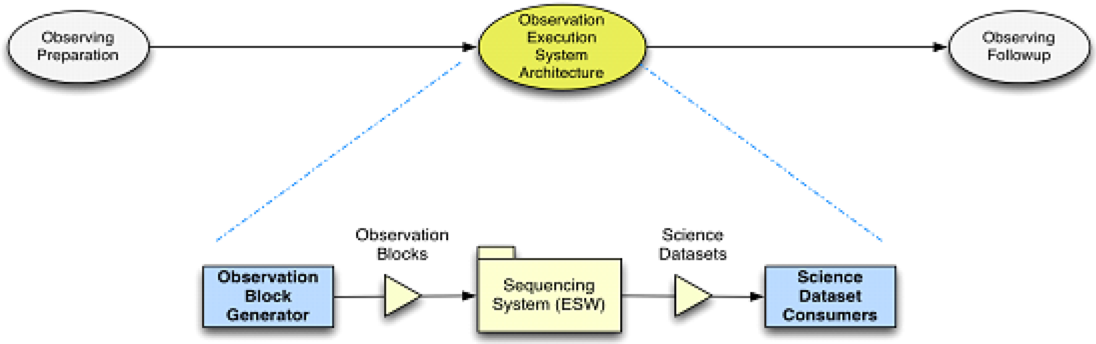

Figure 5-7: The ESW sequencing system accepts Observation Blocks (OBs) created by Observation Block Generators. The Sequencing System uses the OB to execute the observation resulting in one or more datasets, which are consumed by Science Dataset Consumers.

[REQ-1-OAD-9314] The ESW OCS shall define and develop the Observation Block describing the information created by observing user interfaces and observation planning tools (Observation Block Generators).

[REQ-1-OAD-9006] An ESW OCS sequencer shall be able to orchestrate a complete observation, including observatory configuration, target acquisition, and science data acquisition.

Discussion: This requirement sets the scope of ESW sequencing to include this functionality.

Discussion: This coordination will be accomplished in concert with a set of lower tier sequencers. See 'Figure 5-8: Observation execution system architecture sequencer hierarchy.'

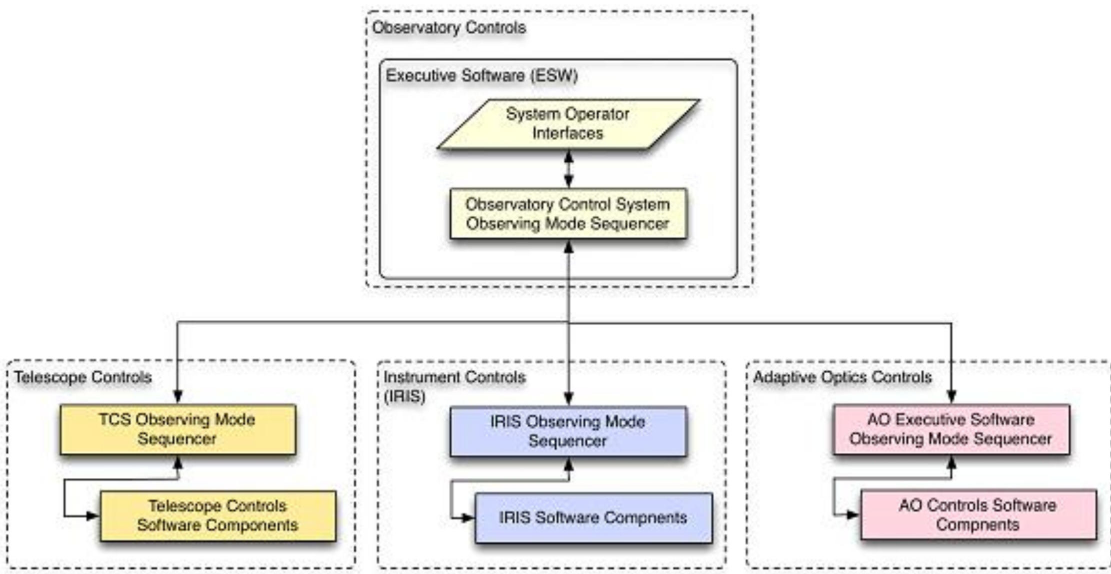

Figure 5-8: Observation execution system architecture sequencer hierarchy

[REQ-1-OAD-9012] The ESW OCS sequencer shall establish an appropriate command-and-control hierarchy depending on the requested observation (or observatory system re-configuration).

Discussion: For example, in the case of an instrument change, the ESW will direct the change of the command-and-control hierarchy from the previous to the new instrument.

Discussion: Different hierarchical relationships and sequencer arrangements can be established for different observing modes. For example, 'Figure 5-8: Observation execution system *architecture sequencer hierarchy' below shows a logical hierarchical relationship established to execute an IRIS observation using laser guide stars.*

[REQ-1-OAD-9340] The ESW OCS shall develop a common sequencer framework to be used by all subsystems that contain sequencers.

Discussion: The sequencer framework is available to component developers for reuse. It can be useful for testing all parts of the software system.

[REQ-1-OAD-9344] ESW shall provide a scripting language that integrates with TMT Common Services and allows development of sequences for operations and testing of software components.

Discussion: A scripting language is the obvious choice. There is a risk that specific technology choices may indicate a different solution. In this case, this requirement will be modified.

[REQ-1-OAD-9803] The ESW OCS sequencer shall allow the execution of more than one independent, non-conflicting sequence in parallel.

Discussion: Non-conflicting means that each sequence uses a different set of resources (examples of resources are the telescope pointing or NFIRAOS Science Calibration Unit). It is assumed that only one sequence has access to the telescope and that other sequences are executing calibrations that do not conflict with the sequence accessing the telescope.

[REQ-1-OAD-9346] The ESW OCS shall integrate with the DMS.SCI infrastructure to ensure information for dataset headers is gathered or made available at the appropriate times.

5.4.2.2 ESW High Level Control and Monitoring System (HCMS)

[REQ-1-OAD-9357] The ESW HCMS shall provide the high-level, operations-focused user interfaces necessary to display, command and operate the system including those of telescope controls, instruments, and adaptive optics controls during daytime and nighttime operations.

Discussion: In the case of the SCMS, user interfaces are read-only for monitoring by staff during operations.

Discussion: This requirement is also applicable for both local and remote operations.

Discussion: OESA user interfaces must be provided to accept user input, generate and submit observation requests and process and display ("monitor") health and status information.

Discussion: ESW delivers the following user interface programs: Telescope Observing Assistant user interface (TCS, AO control), Status monitors for telescope, AO and subsystems, Health/Alarm monitoring user interface, observation browser/selection user interface, instrument observing user interfaces.

Discussion: Engineering user interfaces, which are used to access lower-level system information and diagnose problems, are typically delivered by the teams developing individual subsystems.

[REQ-1-OAD-9360] The ESW HCMS shall provide an operations-based read-only user interface for monitoring of the OSS.

Discussion: The assembly/HCD interface to the OSS is provided by the TCS. The ESW HCMS read-only interface serves two purposes: to present OSS information (i.e. interlock status) to users during observing and to allow the archiving of OSS interlocks in the DMS.

5.4.2.3 User Interface Standards

The ESW provides user interface standards for use by other subsystems based on the use of Graphical User Interface (UI) technology.

The ESW UI standards should include software toolkits and style choices/patterns that optimize the number of windows and control screens.

[REQ-1-OAD-9016] The ESW UI Standards shall allow for the creation of reusable Graphical UI templates, frameworks, libraries, or tools as needed.

[REQ-1-OAD-9018] ESW UIs shall only be able to be executed by authenticated users on trusted machines.

Discussion: CIS provides the Authentication and Authorization (A&A) system that implements access policies and access control, which interfaces with CSW for execution of the A&A policies.

[REQ-1-OAD-9030] ESW user interfaces shall make use of the communication and integration services defined in '*Table 5-8: TMT Common Software services definitions*' below [REQ-1-OAD-9200] and libraries provided by ESW in [REQ-1-OAD-9312].

[REQ-1-OAD-9800] The ESW UI standards shall provide a user interface solution that accommodates remote observing from the Headquarters facility and from designated remote locations.

Discussion: Remote observing will only occur at specific observing sites that are designated as TMT observing sites configured according to TMT specifications. Designated remote locations are described in the Operations Plan (RD43). Only subsets of observing and engineering scenarios are planned for other locations (e.g., offices, homes).

[REQ-1-OAD-9804] The ESW UI standards shall accommodate an observer eavesdropping mode.

Discussion: In the Operations Plan (RD43), eavesdropping support consists of allowing a remote PI to participate via video conference to the observing site. The remote PI may be located in his/her office, home or elsewhere.

[REQ-1-OAD-9807] The ESW UI Standards shall include example applications showing typical user interface scenarios and solutions.

5.4.2.4 Visualization Support

[REQ-1-OAD-9033] ESW shall provide visualization UIs or tools that support the following applications:

- Target acquisition support (acquisition and WFS)
- Science data quick-look data quality assurance support
- Technical data presentation
- Environmental conditions presentation
- System status presentation

Discussion: The visualization user interfaces or tools must access the science and other data using the infrastructure for data movement provided by Data Management System. Science data quick-look data quality assurance support is handled by DPS but is not a construction deliverable.

Discussion: Whenever possible, data visualization tools will re-use or be based on existing solutions.

5.4.2.5 Acquisition Tools

[REQ-1-OAD-9358] The ESW ACQ shall provide extendable and customizable high-level sequences that integrate all observatory subsystems to enable and implement first-light target and data acquisition.

Discussion: ESW must provide the means to allow integration of the systems during science data acquisition (i.e. scripting, libraries).

Discussion: The ESW sequences should be extendable by operations staff to support operations needs.

Discussion: The ESW sequences will be identified in the TMT Observation Workflow (RD44).

[REQ-OAD-9348] ESW ACQ shall provide support for gathering and logging information for basic observing-oriented metrics including: total amount of science and non-science observing time, open shutter efficiency, target acquisition statistics, Target of Opportunity observations.

Discussion: The implementation should allow for additional related metrics that may be devised during construction and operations.

Discussion: Careful measurement of observing-oriented metrics allows a calculation of observatory downtime needed for [REQ-1-OPSRD-3085].

[REQ-OAD-9350] ESW ACQ shall provide support gathering and persisting information needed to monitor the amount of observing time used by each partner.

Discussion: The policy for calculating the amount of time used by a partner will be determined during construction. However, this requirement is expected to support the gathering of the required information.

Discussion: The intention is to state that we need to track telescope usage and tie it to the amount of time allocated to partners in a way that will be determined in the future, but is assumed to depend on statistics similar to those gathered for [REQ-1-OAD-9348].

5.4.3 Data Management System

The Data Management System (DMS) provides the necessary software infrastructure to capture, format (as necessary), store and manage the TMT science data streams.

[REQ-1-OAD-9366] The DMS shall capture and store science metadata during science data acquisition and associate it with an exposure or observation.

Discussion: The metadata to be captured from subsystems is defined in the DMS ICDs.

[REQ-1-OAD-9369] DMS shall provide a service that allows the retrieval of science metadata associated with an exposure or observation.

Discussion: The metadata retrieved should be formatted using commonly used formats such as FITS headers or JSON.

[REQ-1-OAD-9812] The DMS shall follow astronomy standards including FITS and the International Virtual Observatory Alliance.

5.4.3.1 Data Movement

[REQ-1-OAD-9368] The DMS shall provide infrastructure to move or copy science data and metadata from the telescope and instruments to the support facility and on to the archive and partner data centers.

5.4.3.2 Data Storage

[REQ-1-OAD-9370] The DMS shall provide a persistent data store as per [REQ-1-OAD-9600] with the ability to increase its capacity as needed over the lifetime of the observatory.

[REQ-1-OAD-9503] Two copies of all data objects covered by [REQ-1-OAD-9600] shall be kept in physically separate locations where the physical separation is 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] The DMS shall regularly check that the two data copies per [REQ-1-OAD-9503] are identical.

[REQ-1-OAD-9376] The DMS shall provide a database or other system that allows association of science datasets and calibrations as well as associations with other files such as Adaptive Optics Point Spread Function files.

5.4.3.3 Science Data Access

Science Data Access refers to accessing both the TMT Science Archive and the US-ELTP Science Archive.

[REQ-1-OAD-9372] The DMS shall provide authorized users with access to and retrieval capabilities for data packages associated with observations and science programs.

Discussion: A data package includes all related science, calibration, and ancillary data as well as any associated information such as observing logs. The list of authorized users for each archive is a policy decision and subject to change, and includes:

- *TMT Science Archive: Only TMT staff and on-site observers*
- *US-ELTP Science Archive: All users including TMT staff*

[REQ-1-OAD-9810] The DMS data access functionality shall provide access to TMT science data and other science data products to authorized users according to the TMT proprietary period policies.

Discussion: Science data products include science metadata, proposal metadata, observing logs, and ancillary data. Proprietary policies may only apply to subsets of these products.

The proprietary period policy is expected to change prior to the end of construction so the software must allow for expected changes.

[REQ-1-OAD-9814] The DMS access functionality shall use a Single Sign-on Service to authenticate and authorize user roles and set data access rights.

5.4.3.4 ENGINEERING DATABASE

DMS collects, stores and provides tools for monitoring engineering telemetry. DMS also includes an Engineering Database subsystem for this purpose.

[REQ-1-OAD-9378] The DMS shall capture and store event and non-event engineering/technical data.

Discussion: The two sources of data for the DMS Engineering Database are the events transmitted throughout the system via the CSW Event Service and the engineering files produced by subsystems. Some high-bandwidth engineering data sources write their data products to a local storage device (e.g., AO and ESEN) instead of writing it directly to DMS.

Discussion: The set of events that is persisted in the DMS Engineering Database is selected for operations and it is indicated by a flag in the ICDs generated from the ICD Database, but is assumed to be a subset of all events.

Discussion: The Engineering Database has access to all telemetry items made available by subsystems using the TMT Common Software Event Service.

[REQ-1-OAD-9823] The DMS Engineering subsystem shall be capable of capturing and storing a minimum of 10,000 events/second from the Event Service assuming event size is 128 bytes.

[REQ-1-OAD-9826] The DMS Engineering Database storage system and backup strategy shall use the same strategy as defined for science data.

[REQ-1-OAD-9828] The DMS Engineering Database shall provide an access user interface that allows time-based range queries, user selectable at query time, on a subset of stored telemetry items.

[REQ-1-OAD-9829] The DMS Engineering Database access user interface shall be restricted to authorized users using the CSW Authentication and Authorization Service.

[REQ-1-OAD-9830] The DMS Engineering Database shall include a service with an API that supports the ability to generate daily reports of telemetry trends for the purpose of monitoring technical performance.

5.4.3.5 CATALOG ACCESS SERVICE

[REQ-1-OAD-9253] The DMS Catalog Service, for use by all other TMT software subsystems, shall provide access to a defined set of astronomical catalogs stored at the telescope site and support facility using the DMS shared storage system.

Discussion: A typical Catalog Access Service action is to request possible guide stars for adaptive optics wavefront sensors near a specific celestial coordinate. A specialized TMT guide star catalog is required to support guide and wavefront sensor systems.

5.4.4 SCIENCE OPERATIONS SUPPORT SOFTWARE

Science Operations Support Software (SOSS) is the observatory software subsystem that provides the PESA infrastructure and applications (see Section 5.2.2) that support the operations plan observing workflow that occurs before observations are executed on the telescope. The workflow is described in the Operations Plan (RD43) and duplicated in '*Figure 5-9: The TMT Operations Plan observing workflow.* The workflow consists of a number of steps that take the observer from proposing to get time on the telescope to distribution of data after the data has been acquired.

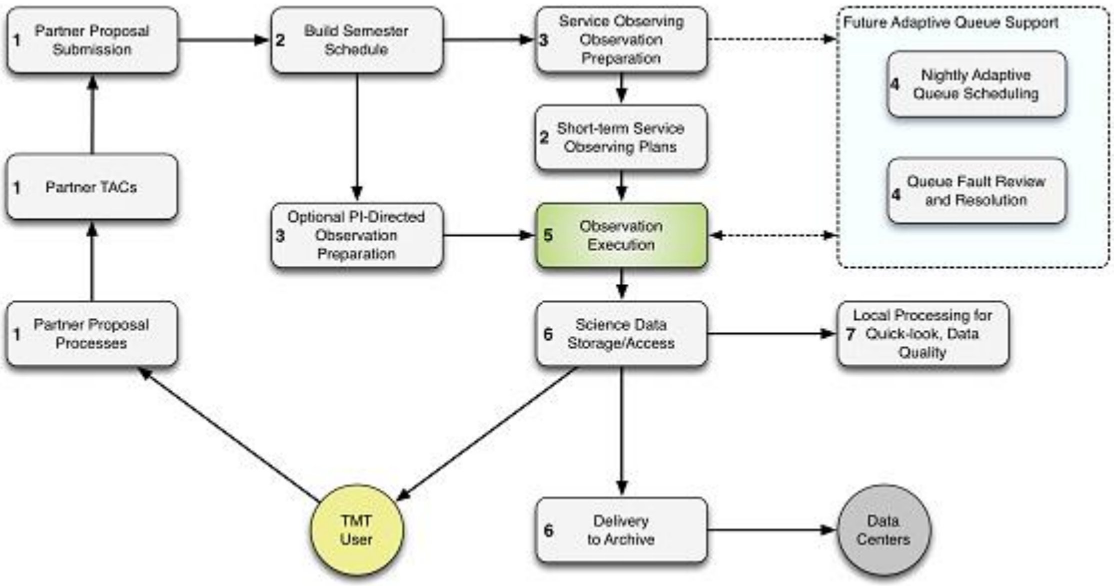

Figure 5-9: The TMT Operations Plan observing workflow

[REQ-1-OAD-9109] Each SOSS subsystem shall support one aspect of the TMT observing workflow (e.g. proposal management, observation preparation, scheduling, data processing, and data access and distribution).

Discussion: Each subsystem may be implemented independently, and they share information through the observatory databases (see 'Figure: Program Execution System Architecture decomposition and relationship to Observation Execution System Architecture' below).

Discussion: At each step of the observing workflow, SOSS tools can augment the observatory databases with additional information as needed. Examples are: allocated time, assigned scientific priority, observation descriptions, system status information, observing condition information, raw data frames, output from data processing systems and others.

[REQ-1-OAD-9426] The SOSS shall provide an Observation Manager with the functionality needed to browse the valid OB collection in the Observatory Databases, select one or more OBs for execution, and send the selected OB(s) to the ESW for execution.

Discussion: The Observation Manager functionality is required, but it may be implemented in some way other than creating an Observation Manager tool.

5.4.4.1 PROPOSAL SUBMISSION AND HANDLING (PHASE 1)

[REQ-1-OAD-9420] SOSS shall include a Proposal Submission and Handling Subsystem (PSHS, also known as Phase 1) that provides the functionality required to enable users and collaborations to create and submit proposals to TMT.

Discussion: The PSHS provides a user interface program that allows for creation of TMT Proposals. The subsystem shall also define a standard interchange format to allow partners to use their current Phase 1 systems and deliver their proposal information.

Discussion: Information from Phase 1 database is ingested in a proposal system database. It is ingested for scheduling and to the Science Program Database to form the basis for Observation Planning.

Discussion: The integrated Proposal Submission and Handling Subsystem is not part of the construction effort. Its development is deferred until first light.

Discussion: Construction includes development of a first-light Phase 1 submission tool that reuses an existing tool with minimal modifications for TMT. The construction Phase 1 system may not be fully integrated with other TMT SOSS tools.

[REQ-1-OAD-9422] The PSHS shall include a Proposer User Interface/Tracking Tool, Partner Proposal Interchange Document Specification, Proposal Ingest Tool, Support Staff Tracking, and Proposal Database.

Discussion: Proposer User Interface/Tracking tool allows the creation, submission, and tracking of proposals for telescope time. The Proposal Ingest Tool ingests proposals from partners in the Proposal Interchange Document Specification format into a Proposal Database. Support Staff Tracking Tool allows for tracking progress of proposals after ingest. The Proposal Database is created to hold the contents of proposals over the lifetime of the observatory.

5.4.4.2 Semester Scheduling

Based on the information gathered during the proposal process, a semester schedule and other scheduling artifacts are created.

[REQ-1-OAD-9425] SOSS shall provide a Semester Scheduling subsystem that uses the information provided by the Proposal Submission and Handling Subsystem and the policies of TMT Observatory to provide an observing semester's time allocation and long-term schedule products.

Discussion: The Semester Scheduling subsystem is not part of the construction effort. The development of Semester Scheduling is deferred until first light.

[REQ-1-OAD-9427] The integrated Scheduling System shall produce a long-term schedule that includes time allocations for visitor observing programs, service observing programs, engineering time and scheduled down-time.

Discussion: The contents of the schedule and policies for its creation may change with subsequent operations planning work.

[REQ-1-OAD-9428] The Semester Scheduling Subsystem shall include a Proposal Database Ingest or Access, Long-term Scheduling Algorithms/Engine, Scheduler User Interface, Generation of Time Allocation Notifications, Generation of Nightly Schedules for Support Staff, and Schedule Database or other long-term schedule storage.

Discussion: The Proposal Database Ingest or Access allows the Scheduling System to use the Phase 1 information for the development of the schedule. The Scheduling Algorithms/Engine contains the policies of TMT that must be followed in order to properly schedule the telescope. When the schedule has been set, the system shall allow emails to be sent to all proposers notifying them of the results of the scheduling process. The Scheduler User Interface allows a staff member to interactively configure and trigger schedule generation. Generation of Night Schedules for Support staff provides information to support nightly operations. Schedule Database or other long-term schedule storage is used to persist the observatory schedules over the lifetime of the observatory.

[REQ-1-OAD-9832] The Semester Scheduling Subsystem shall provide scheduling support for synoptic or cadence observations during Service Observing periods.

Discussion: Cadence and synoptic observations must be supported in the semester schedule. A cadence constraint might be 8 observations/month for 3 months. A synoptic observing constraint might be 1 observation each night at a specific time for 10 nights.

5.4.4.3 Observation Preparation

[REQ-1-OAD-9423] The SOSS shall provide an integrated Observation Preparation Subsystem (P2S, also known as Phase 2) that provides functionality required to allow users to create, plan, modify and submit information needed to enable the service and Visitor observing modes.

Discussion: The use of the P2S is required for the Visitor and Service Observing mode.

Discussion: The integrated Observation Preparation Subsystem is not part of the construction effort. Its development is deferred until first light.

Discussion: Construction includes development of a first-light Phase 2 tool, based on reuse of an existing tool with modifications for TMT.

[REQ-1-OAD-9834] P2S shall provide an integrated software tool/user interface (P2S Tool) that allows individual observers and multi-partner collaborations to enter Phase 2 observation information and track the progress of their observations. The tool shall act as an Observing Block Generator (see '*Figure 5-7: The ESW sequencing system accepts Observation Blocks (OBs) created by Observation Block Generators*' below [REQ-1-OAD-9806] and store information in an observatory database.

Discussion: The P2S Tool will be used by remote users and staff members.

[REQ-1-OAD-9836] P2S Tool and the P2S subsystem shall support the concept of backup programs.

Discussion: All observers are required to prepare a backup program in case weather conditions are not adequate for their observations or their primary instrument is not functional. During Pre-planned Service Queue observing, a queue of possible observations is made available in case the observer has no backup program. Observers will use the same planning tools for creating and planning their backup observations.

[REQ-1-OAD-9438] The Observation Preparation Subsystem shall include a Schedule and Proposal Database Ingest, P2S Tool, Science Program Access and definition of the Science Program Database or other long-term science program storage.

Discussion: Schedule and Proposal Database Ingest creates the set of initial Science Programs for a semester from the Phase 1 and Scheduling Database information. The P2S Tool is defined above. Science Program Access allows remote users to connect using the P2S tool and access and update the Science Program Database that contains the Observing Blocks and other Science Program information.

5.4.5 DATA PROCESSING

Most science data requires some amount of data processing in order to do even basic quality during observing. The Data Processing System is planned to support an observatory infrastructure for integrating data processing into the OESA.

The Data Processing System is no longer a part of the construction project, but the system design must allow for possible integration with data processing suites delivered by instrument builders, which are a part of observatory construction.

[REQ-1-OAD-9429] The integrated 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, science data quality evaluation and other data-related system performance measurements.

Discussion: This requirement establishes the scope of a future TMT DPS subsystem.

Discussion: An integrated data processing system would be configured by the ESW and use information about ongoing observations from observatory databases to process science data passing through the software system.

Discussion: The Data Processing subsystem is not part of the construction effort nor is it planned for operations development. Its future will be determined by TMT operation management.

[REQ-1-OAD-9430] The DPS acts as a wrapper around instrument-specific data processing modules. The DPS shall deliver a pipeline infrastructure and hardware compute engine (e.g., multi-processor cluster) that can execute software delivered by instrument groups.

Discussion: Instrument builders are delivering data processing modules for the observing modes of their instruments. These packages are standalone, in a sense that they do not depend on other observatory infrastructure.

Discussion: It is advantageous to specify a specific development environment for data processing including programming languages and libraries. (More?)

Discussion: Use of a hardware engine is aligned with common grid computing concepts related to high throughput computing (HTC). For one example, see the Condor project page (RD32).

[REQ-1-OAD-9432] The observatory shall provide disk space and computing capability for data reduction by users at remote facilities.

Discussion: The strategy for supporting remote users of data reduction software is to provide a hardware/software environment for data reduction that is accessible by off site users.

[REQ-1-OAD-9434] The software system design shall include a strategy for integrating data processing and visualization that meets the basic goals of the Data Processing System subsystem.

Discussion: Minimal capabilities are needed to support construction. The software system must determine and address the proper software effort for construction.

5.5 Technical Data Acquisition, Storage, Retrieval and Usage

5.5.1 Purpose

This section includes requirements for efficient acquisition, storage, and retrieval of technical data, in support of AIV and operations. Efficiency in these processes will reduce the required technical labor, reduce schedule in AIV, and increase observational efficiency during operations. The capabilities as specified will assist in timely debugging and troubleshooting of complex interconnected subsystem processes such as guiding and mirror alignment, that often require on-sky testing time. This functionality will additionally support the automated gathering of technical data for the generation of look-up tables, and verification and monitoring of system technical performance.

5.5.2 Definitions

Technical Data - Information that is generated and used by the observatory subsystems that are not the science product of the observatory. Included are command and control signals, sensor data, status information in the form of Events (see below), and non-event data for configuration and performance data stored as files.

Event - An event is a data item, including an accurate time of creation and if necessary, time of occurrence, that is published by an observatory component through CSW. Events can be subscribed to by other components, and are therefore a method of passing data. Events can be published at regular time intervals or can be intermittent (e.g. on-change events). Events are used for multiple purposes, including passing control signals between software components, for publishing informational data about system status and performance, and for making available technical data for testing, monitoring, diagnostic purposes and assessing performance. Events that are captured in the DMS engineering database are subscribed to by DMS. An observe event is a special category of an event. It uses the same CSW Event Service infrastructure but it serves a special purpose in the observatory as it is used for metrics and for associating metadata with science data.

Alarm - An alarm is asynchronously generated by a component, notifying other observatory systems of abnormal conditions that require attention and action within a required time frame based on the severity of the alarm. Alarms indicate warning, failure or okay (no alarm) state of a component. A warning could include a current lack of availability (such as a system that is not initialized or indexed), or that a measured parameter is outside its nominal range. A failure indicates that a component of the system is non-functional. The okay state of the alarm indicates that there are no current irregularities in performance.

Alarms are not utilized by the Observatory Safety System as inputs to safety critical functions. For example, an alarm may indicate a system temperature is out of its nominal range, even at a level that may damage a system, but this data would not be used by the OSS. The OSS will have a separate interface to observatory subsystems to monitor critical safety related system states.

Health - Health is a representation of the system's ability to operate properly. Health state can have values GOOD, ILL, BAD, or UNKNOWN. Health with GOOD indicates the component has no problems. Health ILL means that problems exist that are important and should be brought to the attention of the users. A component should be able to continue operating and observations can continue with ILL health, but with possible data degradation. BAD health indicates that a component is in a state that will not allow continued operations. The user or operator must solve a problem before continuing operations. ILL health does not go away until fixed. In this case, health includes a description of the cause. UNKNOWN health indicates that a component is not responding; it may or may not be operating.

As per the requirements below, it is required that system health information be readily available to the telescope operator, in the form of a graphical health tree, and the status and alarms database.

Health status is not utilized by the OSS in safety critical subsystems.

5.5.3 TMT Technical Data Requirements

The following requirements guide observatory software in support of acquisition, storage and retrieval of system technical data for system performance evaluation and trouble-shooting.

To support technical data requirements, most components will likely have two modes, diagnostic and regular operations. Diagnostic is likely to publish events at a higher bandwidth than is done for regular operations, but for each event it is at a predefined rate. Diagnostic mode data rates for each event will be picked from an agreed number of choices such as 1, 10, 100, 1000 Hz. For some components it may be necessary to have more than one diagnostic mode to support multiple use cases without creating unmanageably large data sets.

[REQ-1-OAD-9901] All TMT OSA subsystems (including instruments) shall publish diagnostic events through the CSW Event Service for the purposes of performance monitoring and failure analysis.

5.5.4 Technical Data Storage Capacity and Persistence

[REQ-1-OAD-9911] To reduce storage cost, the DMS shall be capable to delete technical data that is considered not necessary for operations according to observatory policy.

Discussion: The Data Retention Policy will be based on observatory staff experience and possibly informed by the information provided by subsystem teams in an ICD.

[REQ-1-OAD-9903] OSA subsystems shall support regular operations and the standard set of diagnostic modes defined by DMS per [REQ-1-OAD-9916].

Discussion: Rather than requiring real-time configuration of modes, which would be more difficult to implement, DMS defines the standard set of diagnostic modes that support standard observing use cases for monitoring performance, diagnostic testing, and verification.

Discussion: Depending on the system, more than one diagnostic mode may be necessary to support the identified test, problem diagnosis and verification use cases with reasonable data rates and volumes.

[REQ-1-OAD-9902] The DMS engineering database shall allow growth over the lifetime of the observatory according to the data estimates of [REQ-1-OAD-9600].

Discussion: It is assumed that after five years of operations, storage and database performance will allow for an upgrade to increased capacity at a reasonable cost. Maintaining this data for the lifetime of the observatory is needed for supporting technical operations.

5.5.5 Technical Data Acquisition and Retrieval General Requirements

The following requirements enable efficient acquisition, storage, and retrieval of technical data from the system. Further, the use of scripts or data objects enables self-documentation, storage, reuse of test procedures, and coordination of technical data gathering with the sequencing of commands through ESW. This eliminates errors in the execution of tests and ensures that repeated tests use the same data acquisition and retrieval methods.

[REQ-1-OAD-9904] The acquisition of technical data shall be able to be sequenced with an ESW sequencer and synchronized with science data acquisition or other absolute time.

Discussion: To support technical data acquisition requirements, most components will likely have two modes, diagnostic and regular operations. Diagnostic is likely to publish events at a higher bandwidth than is done for regular operations. The technical data acquisition during diagnostic mode would be run from a different script in ESW than the observation. The start of the diagnostic mode technical data acquisition can be triggered on an event, but also could start at a specific time.

Discussion: Therefore, data acquisition can be synchronized in time with the execution of observations.

Discussion: A potential implementation is to create a technical data sequence that runs alongside a science data sequence and listens to Observe Events or others we may define. For instance, *when an observation starts, the technical sequence would "turn on" the storage of the specific set of events.*

[REQ-1-OAD-9906] ESW shall be able to configure the DMS to collect technical data for any diagnostic mode.

Discussion: This requirement gives ESW the ability to configure the DMS as appropriate for specific diagnostic modes. For example, special engineering database collectors may be started to handle the high bandwidth stream of technical data for the more demanding diagnostic modes.

[REQ-1-OAD-9907] The ESW sequencing system shall support methods to notify users of the status of the execution of scripts, including starting and completion.

Discussion: This is expected to be implemented via e-mail or other messaging methods. When the script is used to trigger diagnostic data, the notification should include information about what subsystems were affected and the time range diagnostic data was acquired, to assist in retrieval.

[REQ-1-OAD-9908] DMS shall be able to retrieve non-event technical data products from the local storage of a subsystem for a specified range of time.

Discussion: Some technical data products will be stored locally on subsystems. An example is the NFIRAOS RTC, that will store many technical data products to a local storage device. This requirement requires DMS to have interfaces to other subsystem data repositories (where specifically called out in ICDs), to enable it to retrieve and supply such data to a technical data user. REQ-1-OAD-9909 and REQ-1-OAD-9524 requirs the subsystem to provide an HTTP service and client API to enable this access.

[REQ-1-OAD-9910] DMS shall be able to retrieve the values of all technical data from a subsystem at a specified point in time.

Discussion: Subsystem state includes information about the physical hardware configuration, operating parameters through identification of configuration file versions, and look-up table versions that are available from the configuration service, as well as all published events by that subsystem, and alarms and health information from the alarm service.

Discussion: This is an operations decision, but it is desirable that the system configuration be saved and available from the start of operations throughout the lifetime of the observatory.

[REQ-1-OAD-9912] DMS shall be able to retrieve information stored in the CSW Logging Service for a specified period of time.

5.5.6 Event Data

The following requirements ensure that event data is readily available for system diagnostics, trouble-shooting, verification of system performance, and tracking system performance over time. These requirements make it be possible to define a dataset that is stored when a test is executed. The requirements also ensure that datasets can be readily retrieved for analysis.

5.5.6.1 Event Publishing

[REQ-1-OAD-9914] An ESW sequencer shall have the ability to set the diagnostic mode of a component and return to operations mode after a specified period of time.

Discussion: This requirement requires the ability to set diagnositc mode or operations mode in a sequencer, which allows the sequencing system (i.e. one or more sequencers) to configure subsystems for troubleshooting modes and return them to operations mode when complete. These operations will be performed in a script, which can be written to provide custom functionality according to observing mode and/or the applicable diagnostic use case. REQ-1-OAD-9904 specifies the synchronization requirements.

[REQ-1-OAD-9916] The publishing behavior of OSA subsystem components for each diagnostic mode shall be specified in applicable ICDs as per (AD15).

Discussion: The ICD Database is a configuration controlled database of interfaces that subsystems are required to use to generate ICDs. The event publishing characteristics described in this database are levied as requirements on observatory subsystems.

[REQ-1-OAD-9919] The CSW Event Service shall provide the time of creation of each event using the CSW Time Service, as described in [REQ-1-OAD-9250].

Discussion: Every published event has a creation time stamp, which can be used by the subscriber to make a judgement about whether the latest value is useful or potentially whether the publisher is actually publishing values. (This assumes the subscriber knows the publisher's frequency.)

[REQ-1-OAD-9922] The CIS and CSW shall have the capacity to handle and store, over and above the peak loading during regular observing operations, up to 20 technical data event data streams, synchronized in time at 1 kHz each, of events containing 64 bytes of data each.

5.5.6.2 Event Data Retrieval

[REQ-1-OAD-9924] The DMS shall provide a service that allows time-based queries on one or more engineering events or data products.

[REQ-1-OAD-9928] It shall be possible to extract engineering event data from DMS in the form of a time series at a regular rate different than the publish rate as defined by the requester, as either linearly interpolated between data points, nearest matched time to a past or future event, nearest past time, or binned.

Discussion: Some event data may be logged at non-regular intervals or at different rates than what is used for analysis. Examples include the state of a switch that is only logged as an event when a change occurs, or when a data value falls outside a range or exceeds a threshold. For many types of data analysis, it must be possible to retrieve multiple events from multiple subsystems in the same regularly spaced time steps as a single dataset.

[REQ-1-OAD-9930] DMS shall be able to save results of requested event data queries to a file in standard machine parse-able ASCII formats.

Discussion: For example, as a CSV file. Date/time formats should be standard (such as RD60: ISO 8601). Engineers often prefer to do data analysis and visualization of telemetry in the tools with which they are familiar (i.e. Excel, Matlab, IDL). For this reason, the system supports extraction of data to formats recognizable by these tools.

[REQ-1-OAD-9932] Requested data products consisting of a query of a single event of less than 1 MB of data shall be delivered by DMS within 5 seconds of the request being submitted.

[REQ-1-OAD-9934] Requested data products consisting of a query of a single event of less than 1 GB of data shall be delivered by DMS within 1 minute of the request being submitted.

5.5.6.3 Real Time Display of Event Data

[REQ-1-OAD-9936] The DMS system shall provide a mechanism to create charts of engineering event data for previous time periods, supporting the display of all event data formats that can be extracted from the system as data files.

[REQ-1-OAD-9938] ESW shall provide a mechanism to display plotting with a common time axis, of the real-time values up to 10 events consisting of a mixture of "analog" traces and logic signals (e.g. telemetry status states).

Discussion: This capability is valuable for debugging complex interactions among subsystems during e.g. acquisition or dithering.

5.5.7 Observatory System Status and Alarms

The guiding requirements on health and alarm status GUI flow to more detailed reporting requirements in the level 2 DRDs.

[REQ-1-OAD-9948] Alarms, including alarm flags, and out of range numeric monitors, shall be assessed by each host subsystem and communicated using the CSW Alarm Service.

Discussion: Conditions for alarms for each subsystem are included in the appropriate ICD documents. An alarm summary document that is applicable to ICDs may also be an efficient method for documentation.

[REQ-1-OAD-9954] DMS shall provide simple statistical information for a range of health and alarm values.

Discussion: Simple statistical information includes, for example: frequency, mean-time between occurrence.

[REQ-1-OAD-9956] DMS shall provide the means to display a history of alarm values for a specified period of time.

5.5.8 OTHER TECHNICAL DATA PRODUCTS

[REQ-1-OAD-9958] Non-event data suitable for evaluating system performance shall be stored by observatory subsystems on either local storage within the subsystem and/or on the DMS system.

Discussion: DMS storage is preferred, but it is recognized that this is not always feasible. This requirement will flow to specific requirements on subsystems, guiding the storage of suitable products for evaluating system performance. ICDs or a reference technical data product document will summarize the data products needed to be stored by subsystems, in support of this flowdown.

6 DEFINITIONS

6.1 COORDINATE SYSTEMS

Discussion: The standard coordinate systems for the TMT are defined in (RD11).

Table 6-1: Coordinate systems for the ideal, undisturbed telescope

Coordinate System	Origin	X axis	Y axis	Z axis	Rotation Angle Definition	Notes
Observatory Floor (OFCRS)	The center of the pier in the plane of the observatory finished floor	Points to the East, in the plane of the observatory finished floor.	Points to the North, in the plane of the observatory finished floor.	Right hand complement to x and y axes. Parallel to local gravity		
Terrestrial (TCRS)	The center of the azimuth journal circle, in the plane of the azimuth journal, 3.5m above the level of the OFCRS	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. Parallel to local gravity		
Azimuth (ACRS)	Identical to TCRS	Aligned with TCRS X-axis when azimuth angle = 0. Is in the plane of the azimuth journal.	Right hand complement to the X and Z axes	Identical to TCRS	Azimuth angle (a) is defined as angle between TCRS x-axis and ACRS x-axis caused by rotation about the Z axis. By convention this increases in a clockwise direction when viewed from above. (This is the opposite to that stated by the RH rule)	

Coordinate System	Origin	X axis	Y axis	Z axis	Rotation Angle Definition	Notes
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, collinear with the elevation axis of the telescope	Rotated around the X axis according to the RH rule, by the zenith angle	Right hand complement to the X and Y axes; points to zenith at zero zenith angle	Zenith angle (z) is defined as angle between ACRS z axis and ECRS z axis resulting from rotation about ECRS X axis.	In northern hemisphere for azimuth angle=0 and zenith angle of 90, the telescope is pointing South. The height of the origin of the ECRS above the ACRS is defined in [REQ-1-OAD-1255].
Reference (RCRS)	The intersection on the Z axis of ACRS with the elevation axis of the telescope	Parallel to the X axis of the ACRS.	Parallel to the Y axis of the ACRS	Identical to TCRS		The RCRS rotates with the azimuth axis but does not rotate with changes of telescope zenith angle. This is plane in which all the instrument optical axes lie
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		The origin of the M1CRS relative to the ECRS is defined in [REQ-1-OAD-1315].
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		The origin of the M2CRS relative to the M1CRS is defined in [REQ-1-OAD-1056].

Coordinate System	Origin	X axis	Y axis	Z axis	Rotation Angle Definition	Notes
Tertiary Mirror (M3CRS)	Identical to ECRS origin	Aligned with ECRS + Y axis when M3 rotation angle (θ) = 0. Collinear with M3 tilt axis.	Right hand complement to the X and Z axes	Normal to M3 surface; points away from the reflective surface.	θ is the rotation angle of M3 about the ECRS z-axis, defined as the angle between the ECRS Y axis and the M3 X axis. F is the M3 tilt is rotation angle of M3 about the M3 x-axis defined as the angle between the M3CRS z axis and the ECRS z axis.	M3 position is described by the polar coordinates□θ and F of the M3CRS Z axis in the ECRS.
Focal Surface (FCRS)	Right hand complement to the Y and Z axes	Projection of the ACRS Z axis on the plane perpendicular to the FCRS Z axis	Normal to the focal surface at the origin; points towards the tertiary mirror			The location of the focal surface for different instruments is defined by the instrument bearing angle. This is the angle between the ECRS X axis and the FCRS Z-axis. The distance between the origin of the FCRS and the origin of the ECRS is given by [REQ-1-OAD-1020]

Coordinate System	Origin	X axis	Y axis	Z axis	Rotation Angle Definition	Notes
Segment (SCRS)	The midpoint of the segment optical surface, midpoint is the center of the hexagon transformed as defined in Section 4.1.52	Perpendicular to the Z axis; its projection on the X-Y plane of M1CRS is a line passing through the M1CRS Z axis; the positive SCRSj X axis points in the radial direction away from the M1CRS Z axis	Right hand complement to the X and Z axes	Normal to the segment optical surface at the origin		
Primary Segment Assembly (PSACRS)	Center of scaled flat pattern hex projected parallel to M1CRS z-axis onto optical surface. Coincident with origin of SCRS for corresponding mirror segment. (AD2) defines the co-ordinates of the origin of the PSACRS for each primary segment assembly.	Points towards projection of vertex 1 of best fit regular hexagon onto PSACRS XY plane.	Right hand complement to the X and Z axes	Optical surface normal at the origin.		

Coordinate System	Origin	X axis	Y axis	Z axis	Rotation Angle Definition	Notes
M1CS Actuator (ACTCRS)	Intersection of actuator line of action with PSACRS-XY plane. (AD2) defines the coordinates of the origin of the ACTCRS. Normal to actuator/SSA interface plane, points inboard towards SSA.	Normal to actuator/SSA interface plane, points inboard towards SSA (Note denoted as U Axis)	U-V-Z is right handed for primary mirror sector A, C and E. U-V-Z is left handed for sectors B, D, F. (Note denoted as V Axis)	Along actuator output shaft (parallel to PSACRS-Z).		
Edge Sensor (ESCRS)	On the optical surface, centered between edge sensor halves.	Generally, points towards the midpoint of the segment edge.	Generally, points inboard for sense halves and outboard for drive halves.	Optical surface normal at the origin.		
Edge Sensor Pocket (ESPCRS)	On the edge sensor pocket mounting surface. Co-ordinates of the origin are defined in AD16 (TMT M1 segmentation database).	Parallel to corresponding ESCRS x-axis	Parallel to corresponding ESCRS y-axis.	Parallel to corresponding ESCRS z-axis and normal to edge sensor pocket mounting surface		

Coordinate System	Origin	X axis	Y axis	Z axis	Rotation Angle Definition	Notes
Enclosure Base (EBCRS)	Coincident with the TCRS z-axis, lies in the plane of the enclosure azimuth track	Aligned with TCRS x-axis when enclosure base rotation angle (b) = 0	Right hand complement to the X and Z axes	Identical to TCRS Z-axis	Enclosure Base Rotation Angle (b) is defined as angle between TCRS x-axis and ECCRS x-axis caused by rotation of the enclosure base about the ECCRS z-axis. Angle increases in a clockwise direction when viewed from above.	The highest point of the cap base interface plane is defined as being coincident with a line parallel to the EBCRS +ve Y axis.
Enclosure Cap (ECCRS)	Coincident with ECRS origin	Parallel to EBCRS x-axis when e = 0	Right Hand complement to X and Z axes	Lies in the plane of the EBCRS Y and Z axes. Inclined at an angle of 32.5 degrees from the EBCRS Y axis	Enclosure Cap Rotation Angle e is defined as clockwise rotation (when viewed from above) of the enclosure cap about the ECCRS z axis, e = 0 when ECCRS x axis is parallel to EBCRS x-axis.	The enclosure shutter is zenith pointing when e = 0.

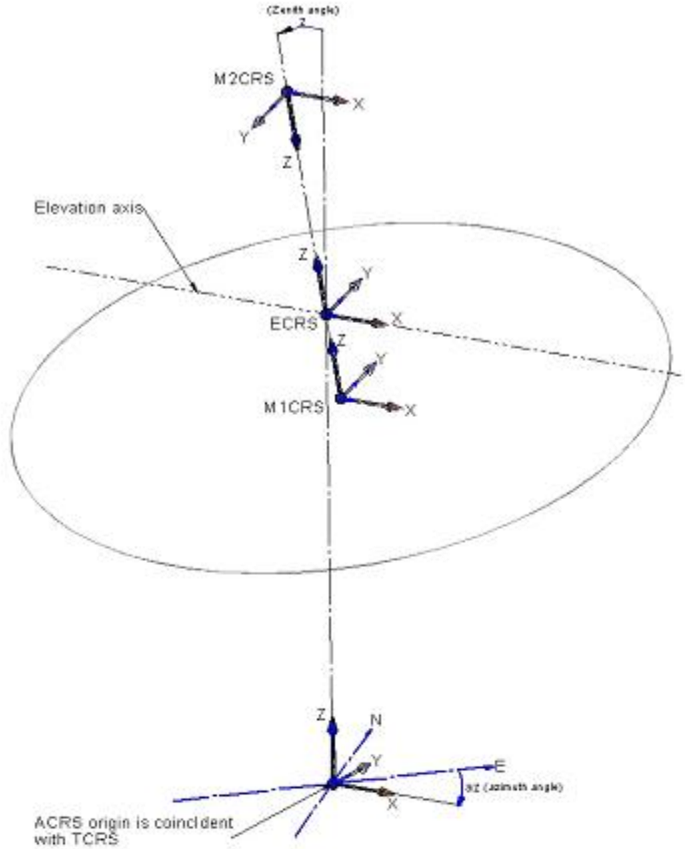

Figure 6-1: The basic coordinate systems of the telescope

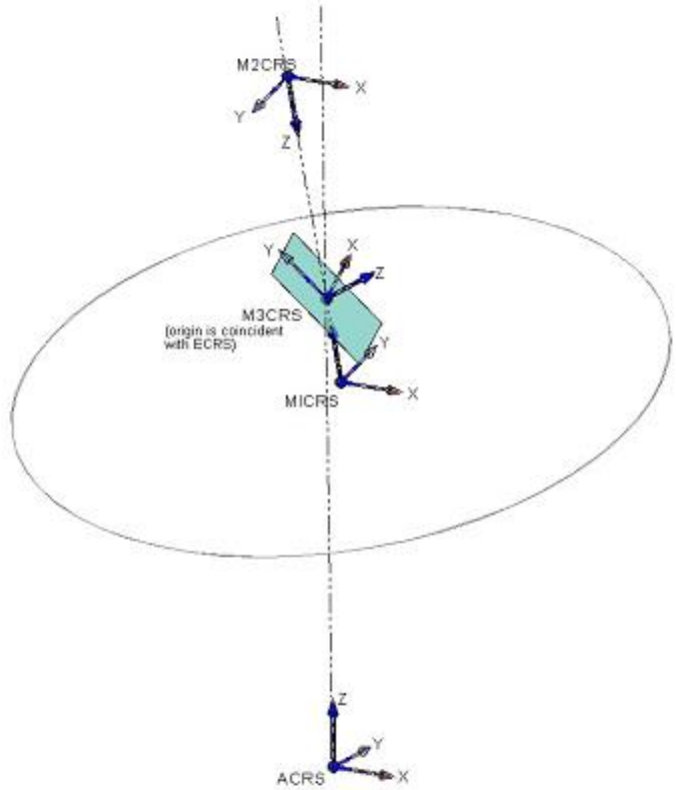

Figure 6-2: Tertiary mirror coordinate system (M3CRS) shown in context of M1CRS and M2CRS

6.2 IMAGE QUALITY ERROR DEFINITIONS

Table 6-2: Telescope Image Quality Error Budget Notes Definitions

Acronym	Definition
TS	**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.
SRFE	**Segment Residual Figure Error** 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) warping harness noise (repeatability), and (iii) other potential control loop errors. APS measurement errors of the warping harness settings are separately accounted under wavefront sensing This error term is the static residual figure error at the telescope calibration zenith angle and temperature, except the low order passive support errors that are changing with telescope zenith angle.
STD	**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.
SSPT	**Segment Support Print Through** includes high order surface distortions associated with the axial and lateral segment support structure. (At a given 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. An allowance is also included for M1CS equipment effects that are not polished out during IBF.
SDE	**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 those measurements 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 SRFE STD, SIPD, and SOPD.

Acronym	Definition
SIPD	**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.
SOPD	**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). , (i) edge sensor calibration and linearity errors, (ii) quasi-static wind pressure, (iii) edge sensor contamination and (v) 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. The errors in correcting M2 and M3 shapes, as well as telescope collimation by M1 are accounted for in M2RFE, M3RFE, and COLL, respectively. The APS measurement and estimation errors are separately accounted under wavefront sensing.
SDDR	**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.
M2RFE	**M2 Residual Figure Error** accounts for image degradation due to the non-perfect shape of M2, including (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, and (iv) effects of mirror warping from coating stress. These figure errors are partially compensated by M1 shape, based on a Look-Up-Table (LUT) derived from measurements made by the APS as well as on Telescope Optical Feedback System (TOFS) measurements, with the following residuals: (i) fitting errors, and (ii) increased APS wavefront measurement and estimation errors (delta above the APS measurement and estimation errors if the M2 shape were perfect). For the low (2^{nd} and 3^{rd}) order components of the surface errors, the measurement and estimation errors are determined by TOFS, instead of APS. This error term is the static residual figure error at the telescope calibration zenith angle and temperature.
M2TD	**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.
M2SDE	**M2 Shape Drift Errors** capture all the errors associated with (i) uncertainties of the M2 system state during APS measurements (LUT generation), and (ii) non-thermal M2 system state drift between measurement and observation. 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 creep or hysteresis in the deflections of the mirror or support system. It does not include errors separately addressed in M2TD, M2SPT, and M2DSR.

Acronym	Definition
M2SPT	**M2 Support Print Through** accounts for surface distortions associated with the axial and lateral support structure, including (i) fabrication and installation tolerances, and (ii) the effect of glass weight. These figure errors are partially compensated by M1 shape, based on a Look-Up-Table (LUT) derived from measurements made by the APS at multiple zenith angles as well as on TOFS measurements, with the following residuals: (i) fitting errors, and (ii) increased APS wavefront measurement and estimation errors (delta above the APS measurement and estimation errors if the M2 shape were perfect). For the low (2nd and 3rd) order components of the surface errors, the measurement and estimation errors are determined by TOFS, instead of APS. Non-repeatable support system errors are covered in M2SDE. The effect of imperfect polishing out of print through bumps at the calibration zenith angle is included in M2RFE.
M2DSR	**M2 Dynamic Shape Residual** includes residuals caused by (i) wind buffeting reacted at the support system, and (ii) equipment and microseismic vibrations.
M3RFE	**M3 Residual Figure Error** accounts for image degradation due to the non-perfect shape of M3, including (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, and (iv) effects of mirror warping from coating stress. These figure errors are partially compensated by M1 shape, based on a Look-Up-Table (LUT) derived from measurements made by the APS as well as on TOFS measurements, with the following residuals: (i) fitting errors, and (ii) increased APS wavefront measurement and estimation errors (delta above the APS measurement and estimation errors if the M3 shape were perfect). For the low (2nd and 3rd) order components of the surface errors in a particular beam footprint, the measurement and estimation errors are determined by TOFS, instead of APS. This error term is the static residual figure error at the telescope calibration zenith angle and temperature.
M3TD	**M3 Thermal Distortion** accounts for M3 shape errors due to temperature and temperature distribution differences between the time of APS measurements (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**.**
M3SDE	**M3 Shape Drift Errors** capture all the errors associated with (i) uncertainties of the M3 system state during APS measurements (LUT generation), and (ii) non-thermal M3 system state drift between measurement and observation. An example for the first type is our insufficient knowledge of the actual static wind pressure distribution above M3. An example for the second type is creep or hysteresis in the deflections of the mirror or support system. It does not include errors separately addressed in M3TD, M3SPT, and M3DSR.
M3SPT	**M3 Support Print Through** accounts for surface distortions associated with the axial and lateral support structure, including (i) fabrication and installation tolerances, and (ii) the effect of glass weight. These figure errors are partially compensated by M1 shape, based on a Look-Up-Table (LUT) derived from measurements made by the APS at multiple zenith angles as well as on TOFS measurements, with the following residuals: (i) fitting errors, and (ii) increased APS wavefront measurement and estimation errors (delta above the APS measurement and estimation errors if the M3 shape were perfect). For the low (2nd and 3rd) order components of the surface errors in a given beam footprint, the measurement and estimation errors are determined by TOFS, instead of APS. Non-repeatable support system errors are covered in M3SDE. The effect of imperfect polishing out of print through bumps at the calibration zenith angle is included in M3RFE.
M3DSR	**M3 Dynamic Shape Residual** includes residuals caused by (i) wind buffeting reacted at the support system, and (ii) equipment and microseismic vibrations.

Acronym	Definition
WFSWH	**M1 warping harness wavefront sensing** accounts for APS errors in determining first 10 WH modes. These errors include, but are not limited to: sensor noise, atmospheric residual, errors from finite spatial sampling, internal calibration errors.
WFSSP	**M1 segment phasing wavefront sensing** accounts for errors in measuring the segment piston. These errors include but are not limited to: sensor noise, atmospheric residual, errors from finite spatial sampling.
WFSLO	**Low order wavefront sensing errors** accounts for errors (from the OIWFS or APS) in estimating global Zernikes 4-15 (TBR). These errors include, but are not limited to: sensor noise, atmospheric residual, errors from finite spatial sampling, internal calibration errors.
WFSTT	**M1 segment tip/tilt wavefront sensing** accounts for errors from APS in estimating the correct tip/tilt of all M1 segments, minus global Zernikes (4-15 (TBR)) which are accounted for in the WFSLO term. Errors include but are not limited to: sensor noise, atmospheric residual, errors from finite spatial sampling, internal calibration errors
COLL	**Telescope Collimation Errors** account for the less than perfect rigid body alignment of M1 (as a whole), M2, and M3, due to gravitational and thermal deformation of the telescope structure and global mirror supports. The optical effect of this error is static image blur. The collimation errors are partially compensated by M2 positioning and M1 global shape adjustments, carried out by the Telescope Optical Feedback System, with the following residuals: (i) M1 fitting errors, (ii) M2 positioning errors. Wavefront measurement and estimation errors are accounted in WFSLO above. 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.
CN	**Image Jitter (Control Noise)** is the image jitter due to dynamic errors of the local loops controlling the rigid body positions of the mirrors. This term includes effects that are self-induced by a system, including (i)tip/tilt noise of the guide sensor, and (ii) local sensor and actuator dynamic noise (iii) self-excited motion of optical surfaces. 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. For the M2, M3 and mount control terms, the control noise allocation is limited to the image motion resulting only from self-induced disturbances e.g. the M2 term includes only M2 subsystem sources resulting in quasi-static motion of M2 and hence only requiring assessment of image motion due to M2 optical sensitivity. It does not account for image motion resulting from any external disturbances such as vibration or wind which are accounted separately in WIND and VIB. The mount control terms include the effects of azimuth and elevation cable wrap disturbances at frequencies below 5Hz. Above 5 Hz these disturbances are to be accounted for under the VIB term. The reason for this is that above 5Hz telescope structural resonances can result in significant relative motion of M1, M2 and M3.
WIND	**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).
VIB	**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).

Acronym	Definition
DBLUR	**Dynamic Blur Residual** accounts for all optical surface rigid body motions due to wind, vibration, and control noise 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 blur, this error category includes the dynamic residuals only.

6.3 Vignetting and Obscuration

Vignetting: When one of the apertures in a system (such as a lens clear aperture) limits part or all of the bundle of rays determined by the stop.

Obscuration: Anything other than a mirror aperture that gets in the way of the beam (e.g. the top end shape, M2 size, segment gaps, parts of the telescope structure including SHS). Depending on where the obscuration is, the effects can include diffraction, stray light, and thermal background as well as loss of throughput or can also lead to completely blocking part of the field of view (e.g. handrails on the ISS or the edge of M1 at high zenith angles).

6.4 Other Definitions

Nighttime: 12 hours centered around midnight.

Daytime: 12 hours centered around noon.

Steady-State (Science) Operations: the period that starts 36 (TBC) months after TMT First Light. The intervening time is considered sufficient for tuning the performance and operational procedures to the level necessary to meet requirements.

7 APPENDIX

7.1 ASTRONOMICAL FILTERS

Table 7-1: Astronomical Filters

Band	Center Wavelength (μm)	Bandwidth (μm)
U	0.3663	0.065
B	0.4361	0.089
V	0.5448	0.084
R	0.6407	0.158
I	0.798	0.154
J	1.25	0.16
H	1.635	0.29
K'	2.12	0.34
K_s	2.15	0.32
K	2.2	0.34
L	3.77	0.7
M	4.68	0.22
N	10.47	5.2
Q	20.13	7.8

Data in the table is from (RD6).

7.2 ATMOSPHERIC PARAMETERS

7.2.1 ATMOSPHERIC TRANSMISSION WINDOWS

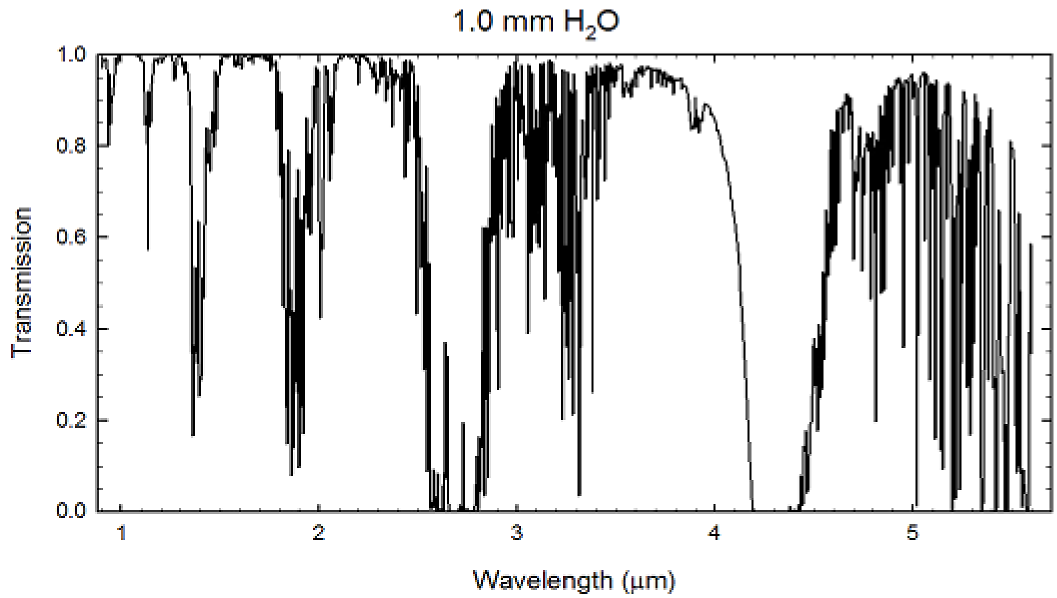

Figure 7-1: Near, mid infrared atmospheric transmission windows for 1 mm precipitable water vapor (RD7)

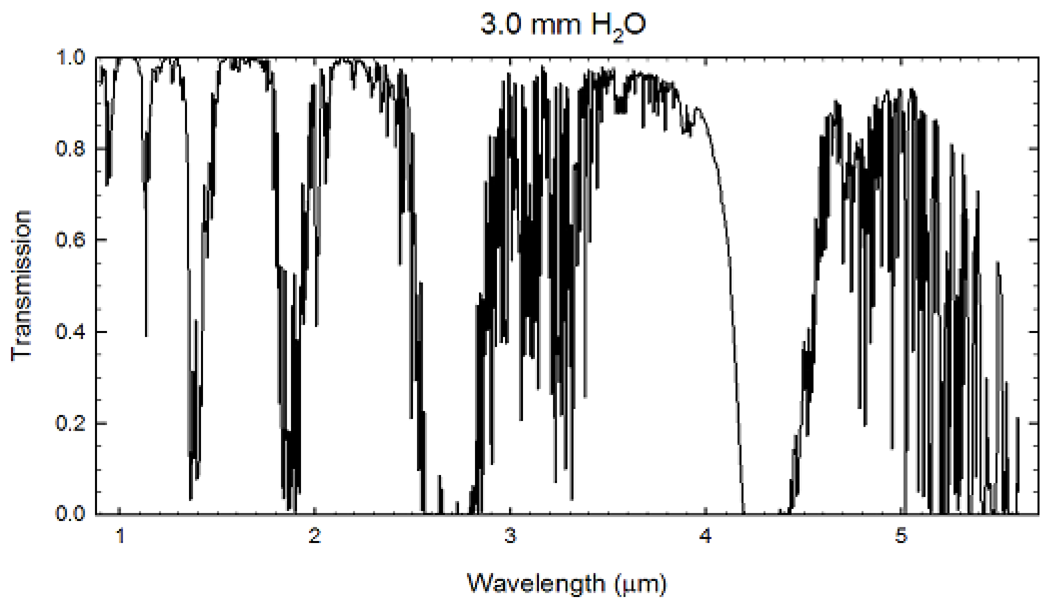

Figure 7-2: Near, mid infrared atmospheric transmission windows for 3 mm precipitable water vapor (RD7)

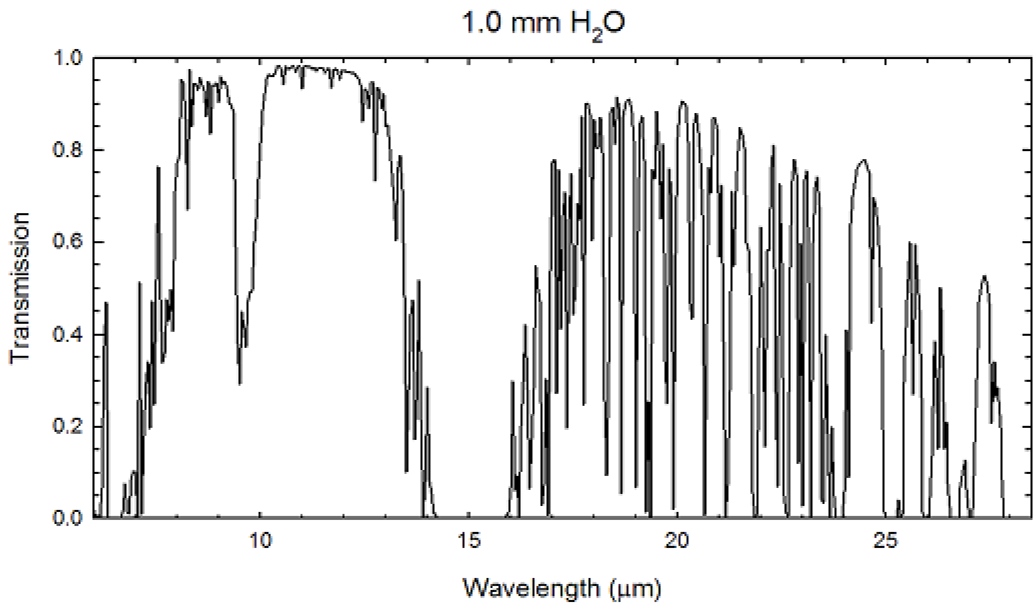

Figure 7-3: Infrared atmospheric transmission windows for 1 mm precipitable water vapor (RD7)

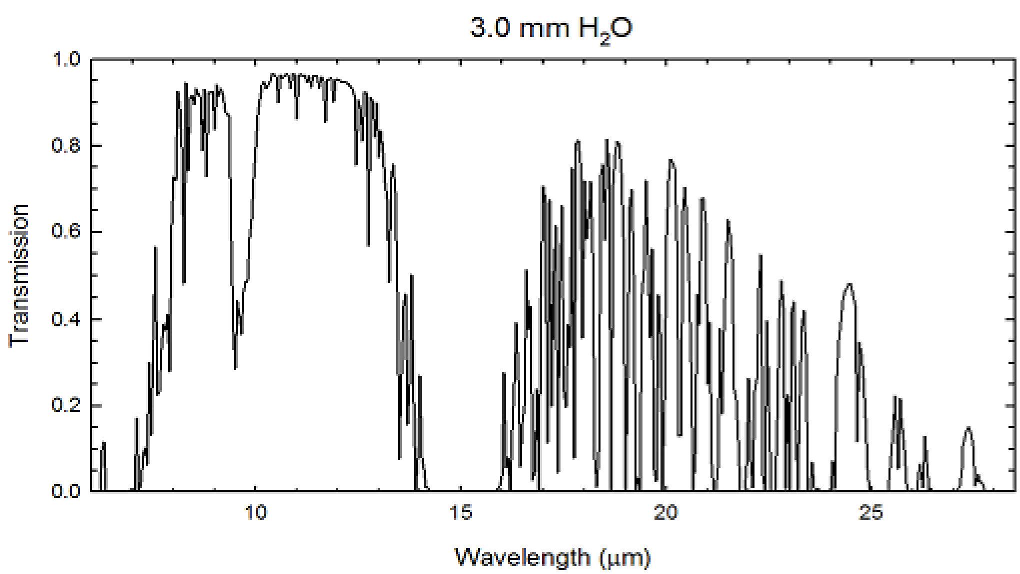

Figure 7-4: Infrared atmospheric transmission windows for 3 mm water vapor (RD7)

7.2.2 Meteorological Parameters

Precipitable H2O = 1.9 mm

7.2.3 Mesospheric Sodium Layer

The following parameters for the mesospheric sodium layer shall be used in the design of LGS AO systems for TMT:

- Centroid sodium layer altitude: 89 to 93 km above sea level (instantaneously)
- Sodium layer thickness: 7- 25 km, but with all atomic sodium >80.5 km ASL

- Column density: 3e13 ions/m2
- Sodium ion cross section: 130 photons-m2/s/W/ion
- Sodium D2 line width: 3 GHz

Based upon temporal PSDs in (RD49) [Pfrommer & Hickson A&A 2014] it is believed that focus measurements from a natural guide star must be obtained at rates of about 100 Hz to track the variations in the range to the sodium layer to the level of accuracy required for the NFIRAOS error budget. Furthermore, higher order wavefront measurements from a natural guidestar must be obtained at rates of 0.01 to 0.1 Hz to calibrate for wavefront reconstruction errors associated with changes in the shape of the sodium layer profile.

7.2.4 TURBULENCE PARAMETERS

In order to define AO performance requirements, we specify “Standard Conditions” under which the requirements should be met. These conditions are based upon the TMT site testing results taken at Mauna Kea 13N from 29th June 2005 to 1st June 2008. Three sets of standard conditions are given, identified as the 25th and 75th percentile and median conditions. These three sets were established from the 3 years of recorded profiles as follows, using a ‘NFIRAOS like’ AO system to compute residual DM fitting and servo lag errors:

- Compute the residual DM fitting error and servo lag for each profile
- Sort the profiles based on the results of step 1
- Compute the mean value of the 10% range around each profile (i.e. for 25% profile, calculate mean of the profiles between 20th and 30th percentile)

'Table 7-2: Atmospheric Turbulence Parameters' summarizes the standard values for 4 fundamental atmospheric turbulence parameters for each condition, specified at a wavelength of 0.5 µm and a zenith angle of 0 degrees. We have no measurements of L_0 so we use a generally accepted median value of 30m.

Table 7-2: Atmospheric Turbulence Parameters

Parameter	25th Percentile Conditions	Median	75th Percentile Conditions
Effective coherence diameter (r_0), m	0.27	0.2	0.13
Integrated C_n^2, $m^{1/3}$	1.30E-13	2.21E-13	4.64E-13
Isoplanatic angle (?$_0$), arc sec	2.7	2.23	1.71
Greenwood frequency (f_g), Hz	15.9	21.7	32.2
Outer scale (L_0), m	30	30	30

The values for θ_0 and f_g have been derived using the 7-layer turbulence and wind profiles from 'Table 7-3: Standard Atmospheric Cn^2dh and Windspeed Profiles'. These are also the standard profiles to be used for more detailed AO analysis and simulation.

Table 7-3: Standard Atmospheric Cn2dh and Windspeed Profiles

h, km	Cn^2dh ($m^{1/3}$) 25th Percentile Conditions	Median	75th Percentile Conditions	Median windspeed, m/s
0	4.20E-14	6.39E-14	1.07E-13	5.6
0.5	1.93E-14	3.94E-14	1.11E-13	5.8
1	6.07E-15	1.46E-14	5.72E-14	6.3
2	5.32E-15	1.73E-14	4.45E-14	7.6
4	2.03E-14	3.11E-14	5.09E-14	13.3
8	1.38E-14	2.69E-14	5.49E-14	19.1
16	2.29E-14	2.81E-14	3.83E-14	12.1

Note: The above Cn2 values are based on results taken at a height of 7m above the ground, but have been adjusted to remove turbulence between 7m and 60m to account for the height of the enclosure. 'Table 7-3: Standard atmospheric Cn^2dh and windspeed profiles' consequently does not include conditions inside the enclosure.

7.2.5 Temporal Temperature Gradients

'Table 7-4: Night time temporal temperature gradients' summarizes the night time temporal temperature gradients measured during the TMT site testing at Mauna Kea 13N from 29th June 2005 to 1st June 2008. The temperature gradients quoted are based on temperature values measured at 2 m above ground level.

Table 7-4: Night time temporal temperature gradients

Integration Time (minutes)	Min (°C/h)	2.5% (°C/h)	97.5% (°C/h)	Max (°C/h)
1	-54.1	-9.4	9.4	57.0
4	-32.0	-5.5	5.3	30.9
8	-16.9	-3.4	3.2	13.5
16	-9.8	-2.2	2.0	7.2
32	-5.8	-1.5	1.2	3.7
60	-3.7	-1.1	0.7	2.1

7.3 Acquisition

Discussion: The Preset and Acquisition Sequences for Seeing-Limited, NGSAO and LGS MCAO observing modes are defined in (RD48). Section 5.1.5 describes their subsystem time allocations.

7.4 Observatory Control Architecture

Table 7-5: 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 TOFS		
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 (Hz)
Mount	Azimuth & Elevation	2	DDL motors[3]	Tape encoder	≥ 40	~ 1	20	Pointing tests	Monthly	AGWFS[4]	1	0.1
M1	Global Tip, Tilt, Piston	3	Segment actuators	Actuator sensors	≥ 1	< 0.1[5]	0.1	Surveying	>>1 year	No outer control loop		
	Segment Tip, Tilt, Piston	1476	Segment actuators	Edge sensors	≥ 10	~ 1[5]	0.1	APS	2 to 4 weeks[6]	AGWFS[7]	0.003	0.0001
	Warping Harness	10,332	Warping harness	Strain gauge	na[8]	na[8]	na[8]	APS, but no LUT	> 1 year[8]	No outer control loop		
M2	De-center	2	Hexapod	Local encoder	≥ 10	< 1	0.1	APS/GMS[9]	See note 10	AGWFS[11]	0.003	0.0001
	Tip/Tilt	2	Hexapod	Local encoder	≥ 10	< 1	0.1	APS/GMS[9]				
	Piston	1	Hexapod	Local encoder	≥ 10	< 1	0.1	APS/GMS[9]	2 to 4 weeks	AGWFS[12]	0.003	0.0001
M3	Tilt	1	DC drive	Local encoder	≥ 10	< 1	0.1	APS & surveying	> 1 year	No outer control loop[13]		
	Piston	1	DC drive	Local encoder	≥ 10	< 1	0.1	APS & surveying	> 1 year	No outer control loop[13]		

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 sensor/encoder feedback), a middle control loop (LUT feedback), and in some cases an outer control loop (real time optical feedback, TOFS).

LUT (look up table), DOF (degrees of freedom), AGWFS (Acquisition, Guiding, and Wavefront Sensing System in the seeing limited instruments), GMS (global metrology system), TOFS (telescope Optical Feedback System).

1 In general look up tables (LUT) 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 OPD Tip/Tilt (image motion) will be corrected via the mount (guiding). In AO mode, the outer loop image feedback is not based on the AGWFS but rather via an offload of the time averaged position of the AO tip/tilt stage.

5 The global M1 control bandwidth is 1.0 Hz. The control bandwidths of the individual actuators will be 5 Hz to 10 Hz with individual update rates > 100Hz.

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, 2nd and 3rd radial order OPD modes will be corrected on the M1. In AO mode, the outer loop feedback is not based on the AGWFS 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 by APS measurement after segment exchange/installation. Infrequent calibration updates may happen, but 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.

[11] Coma will be corrected on M2 via tip/tilt, de-center, or rotation about the neutral point. 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.

7.5 Example Mirror Coating Reflectance Curves

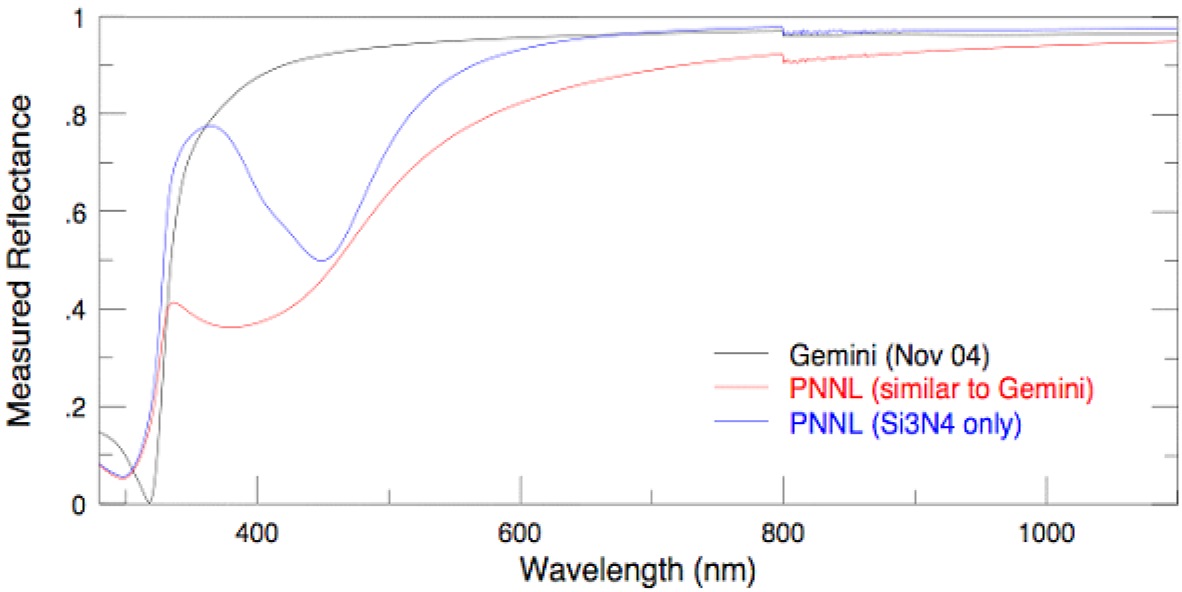

Figure 7-5: Gemini coating plus other coatings in development. Dip in reflectivity other coatings is caused by surface Plasmon resonances.

7.6 Mean Available Science Time (MAST)

Under a set of assumptions, the estimated net Mean Available Science Time (MAST) is:

Table 7-6: Mean Available Science Time (MAST)

Time	Hours Per Semester	Hours Per Year	Comments
Possible Observing per Semester	1,734	3,468	365 days per year, average 9.5 hours per night
Engineering Time	-120	-240	On-sky engineering tests
General Instrument Calibrations performed by TIO	-17	-34	SRD requirement <1% available time.
New Instrument Commissioning Time	-48	-96	Estimate 20 nights required every 2 years.
Director Discretionary Time	-30	-60	For unexpected events & adjustments to schedule
Observatory Shutdown	-24	-48	5 nights per year, average 9.5 hours per night
TOTAL AVAILABLE HOURS	1,495	2,990	
Dark Time	498	997	1/3rd of total available hours
Grey Time	498	997	1/3rd of total available hours
Bright Time	498	997	1/3rd of total available hours

The TMT Observatory is required to maximize the number of net scheduled MAST hours. The table above lists six items that are under direct TMT control, while weather is not (except in the limit that one parameter in TMT site selection is minimizing potential weather downtime). A TMT Observatory designed for robust, efficient operations and low maintenance will pay back in hours available for science observations.