THIRTY METER TELESCOPE

OBSERVATORY ARCHITECTURE DOCUMENT

TMT.SEN.DRD.05.002.CCR34

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SIGNATURE PAGE

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DOCUMENT CHANGE RECORD

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CCR31	Released per: CR216: Collection-13852 ADMIN: Update AD/RDs	S. Roberts, routing # 14195	January 30, 2017
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

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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

TABLE OF CONTENTS

1. INTRODUCTION

1.1 INTRODUCTION

This is the TMT Observatory Architecture Document (OAD). It is one of the three systems engineering level requirement documents, the others being the Operations Requirement Document (OpsRD) (RD35), and the Observatory Requirements Document (ORD) (RD34).

These three documents are the project's response to the science requirements encapsulated in the Science Requirements Document (SRD) (RD33) and the Operations Plan (OPSPlan).

Requirements flow down from the Operations Requirements Document (OpsRD) (RD35), and the Observatory Requirements Document (ORD) (RD34) into the OAD (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). These high-level requirements are contained in the OpsRD (RD35) and the ORD (RD34).

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; Superseded by RD33

AD2 DELETED; Superseded by RD34

AD3 DELETED; Superseded by RD35

AD4 DELETED; Superseded by RD37

AD5 International Building Code (IBC), International Code Council (ICC)
ICC I-CODE IBC
https://global.ihs.com/doc_detail.cfm?&rid=Z06&mid=5280&item_s_key=00410247

AD6 ICC Electrical Administrative Provisions (IEC), International Code Council (ICC)
ICC I-CODE IEC
http://publicecodes.cyberregs.com/icod/iec/index.htm

AD7 International Mechanical Code (IMC), International Code Council (ICC)
ICC I-CODE IMC
https://global.ihs.com/doc_detail.cfm?&rid=Z06&mid=5280&item_s_key=00410250&item_key_date=841231&org_code=ICC&doc_type=TSDC&origin=SMDO

AD8 International Plumbing Code (IPC), International Code Council (ICC)
ICC I-CODE IPC
https://global.ihs.com/doc_detail.cfm?&rid=Z06&mid=5280&item_s_key=00410251

AD9 International Fire Code (IFC), International Code Council (ICC)
ICC I-CODE IFC
https://global.ihs.com/doc_detail.cfm?&rid=Z06&mid=5280&item_s_key=00410249

AD10 American Society of Civil Engineers (ASCE) Standard "Minimum Design Loads for Buildings and Other Structures"
ASCE 7-98 Edition dated 1998
http://ascelibrary.org/doi/book/10.1061/9780784404454

AD11 Title 29, Code of Federal Regulations, Part 1910, Occupational Safety and Health Administration (OSHA) Standards
29 CFR Part 1910
http://www.osha.gov/pls/oshaweb/owastand.display_standard_group?p_toc_level=1&p_part_number=1910

AD12 Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment
MIL-STD-461 E
http://quicksearch.dla.mil/Analyse/ImageRedirector.aspx?token=180116.35789

AD13 Department of Defense Test Method Standard for Environmental Engineering Considerations and Laboratory Tests
MIL-STD-810 F
http://quicksearch.dla.mil/Analyse/ImageRedirector.aspx?token=431013.35978

AD14 American Institute of Steel Construction (AISC) Load and Resistance Factor Design (LRFD) Specification for Structural Steel Buildings
AISC LRFD Ed1999 pls Errata
http://user.engineering.uiowa.edu/~design1/StructuralDesignII/LRFD_Specifications12-27-99.pdf

AD15 TMT Interface N2 Diagram
TMT.SEN.TEC.05.035 CCR30
https://docushare.tmt.org/docushare/dsweb/Get/Version-80249

AD16 TMT M1S Segmentation Database
TMT.OPT.TEC.07.044 CCR15
https://docushare.tmt.org/docushare/dsweb/Get/Version-61423

AD17 Ritchey-Chrétien Baseline Design
TMT.SEN.SPE.06.001 REL04
https://docushare.tmt.org/docushare/dsweb/Get/Version-35512

AD18 Title 49, Code of Federal Regulations (CFR), Transportation
49 CFR
http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title49/49tab_02.tpl

AD19 U.S. Department of Energy Handbook on Electrical Safety, draft for R&D
DOE-HDBK-1092 Edition 2009
http://www.lanl.gov/safety/electrical/docs/09_doe_electrical_safety_handbook_rd.pdf

AD20 Functional safety of electrical/electronic/programmable electronic safety-related systems - All Parts
IEC 61508 Edition 2.0 (2010)+ Comments
https://webstore.iec.ch/publication/22273

AD21 Metallic Materials and Elements for Aerospace Vehicle Structures
MIL-HDBK-5 J
http://quicksearch.dla.mil/Analyse/ImageRedirector.aspx?token=409615.53876

AD22 Design Criteria for Controlling Stress Corrosion Cracking
TMT.OPT.TEC.12.074 REL01
MSFC-SPEC-522 B
https://docushare.tmt.org/docushare/dsweb/Get/Version-34907

AD23 Corrosion Prevention and Deterioration Control in Electronic Components and Assemblies
MIL-STD-1250 A
http://quicksearch.dla.mil/Analyse/ImageRedirector.aspx?token=47330.36168

AD24 Fasteners - General Requirements for bolts, screws, studs, and nuts
ISO 8992:1986 Edition 01
http://www.iso.org/iso/home/store/catalogue_ics/catalogue_detail_ics.htm?csnumber=16521

AD25 Standard Specification for Annular Ball Bearings for Instruments and Precision Rotation Components
ASTM F2332 Edition 06
http://www.astm.org/DATABASE.CART/HISTORICAL/F2332-06.htm

AD26 Lift Sling Design
540-PG-8719.1.1 A
http://recert.gsfc.nasa.gov/docs/540-PG-8719.1.1A.pdf

AD27 Standard Practice for Performance Testing of Shipping Containers and Systems
ASTM D4169 Edition 2014
http://www.astm.org/Standards/D4169.htm

AD28 Standard General Requirements for Safe Design and Operation of Pressurized Missile and Space Systems
MIL-STD-1522 A
http://quicksearch.dla.mil/Analyse/ImageRedirector.aspx?token=49322.36946

AD29 Standard for the Fire Protection of Information Technology Equipment
NFPA-75 Edition 2013
http://www.nfpa.org/codes-and-standards/document-information-pages?mode=code&code=75

AD30 National Fire Protection Association (NFPA) - Fire Protection Handbook
NFPA-FPH 20th Edition
http://catalog.nfpa.org/Fire-Protection-Handbook-20th-Edition-P13860.aspx?icid=D482

AD31 Safe Use of Lasers
ANSI Z136.1 Edition 2007
https://www.lia.org/PDF/Z136_1_s.pdf

AD32 National Safety Council - Accident Prevention Manual: Engineering and Technology
NSC Accident Prevention Manual Edition 13
http://shop.nsc.org/Accident-Prevention-Manual-Engineering-Technology-13th-Edition-P56.aspx

AD33 Toxic Substances Control Act (TSCA)
http://www.epw.senate.gov/tsca.pdf

AD34 DELETED; Superseded by RD16

AD35 Safety of Machinery- Functional Safety of Safety Related Electrical, Electronic and Programmable Electronic Control Systems
IEC 62061 Edition 1.0 (2005)
https://webstore.iec.ch/publication/6426

AD36 DELETED

AD37 TMT System Level Hazard Analysis
TMT.SEN.TEC.13.001 (In preparation)

AD38 Specification of Image Quality terms varying with Temperature and Zenith Angle
Document to be written (In Preparation)

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
TMT.SEN.DWG.14.003 REL01
https://docushare.tmt.org/docushare/dsweb/Get/Version-47459

AD42 TMT Telescope Structure Keep-In Space Envelope
CAD Drawing No: TMT.TEL.STR-ENV Rev C
TMT.SEN.DWG.12.012 REL04
https://docushare.tmt.org/docushare/dsweb/Get/Version-63660

AD43 TMT M1 Space Envelope
CAD Drawing No: TMT.TEL.OPT.M1S-ENV Rev A
TMT.SEN.DWG.14.001 REL01
https://docushare.tmt.org/docushare/dsweb/Get/Version-46684

AD44 TMT Telescope M2 Mirror Assembly Space Envelope
CAD Drawing No: TMT.TEL.OPT.M2-ENV Rev B
TMT.SEN.DWG.09.004 REL02
https://docushare.tmt.org/docushare/dsweb/Get/Version-49831

AD45 M2 Electronics Space Envelope
CAD Drawing No: TMT.TEL.OPT.M2.EL-ENV Rev B
TMT.SEN.DWG.15.001 REL02
https://docushare.tmt.org/docushare/dsweb/Get/Version-82795

AD46 TMT Telescope M3 Mirror Assembly Space Envelope
CAD Drawing No: TMT.TEL.OPT.M3-ENV Rev F
TMT.SEN.DWG.09.003 REL05
https://docushare.tmt.org/docushare/dsweb/Get/Version-59459

AD47 M3 Electrical Space Envelope
CAD Drawing No: TMT.TEL.OPT.M3.EL-ENV Rev B
TMT.SEN.DWG.12.011 REL02
https://docushare.tmt.org/docushare/dsweb/Get/Version-62227

AD48 Superseded by AD88

AD49 Superseded by AD88

AD50 Superseded by AD88

AD51 Superseded by AD88

AD52 Nasmyth Platform Instrument Envelope
CAD Drawing No: TMT.INS.GTY.0003 Rev A
TMT.SEN.DWG.14.004 REL01
https://docushare.tmt.org/docushare/dsweb/Get/Version-47511

AD53 Moved to RD43

AD54 TMT Telescope - APS Instrument Space Envelope
CAD Drawing No: TMT.TEL.CONT.APS-ENV Rev D
TMT.SEN.DWG.10.005 REL03
https://docushare.tmt.org/docushare/dsweb/Get/Version-79882

AD55 APS Electronics Space Envelope
CAD Drawing No: TMT.TEL.CONT.APS.EL-ENV Rev B
TMT.SEN.DWG.12.001 REL03
https://docushare.tmt.org/docushare/dsweb/Get/Version-82657

AD56 IRIS Instrument Space Envelope
CAD Drawing No: TMT.INS.INST.IRIS-ENV Rev F
TMT.SEN.DWG.10.003 REL05
https://docushare.tmt.org/docushare/dsweb/Get/Version-79311

AD57 IRIS Electronic Enclosure Space Envelope
CAD Drawing No: TMT.INS.INST.IRIS.EL-ENV Rev B
TMT.SEN.DWG.12.016 REL02
https://docushare.tmt.org/docushare/dsweb/Get/Version-78973

AD58 TMT Telescope - IRMOS Instrument Space Envelope
CAD Drawing No: TMT.INS.INST.IRMOS-ENV Rev B
TMT.SEN.DWG.10.006 REL02
https://docushare.tmt.org/docushare/dsweb/Get/Version-27503

AD59 TMT Telescope _ IRMS Instrument Space Envelope
CAD Drawing No: TMT.INS.INST.IRMS-ENV Rev C
TMT.SEN.DWG.10.004 REL03
https://docushare.tmt.org/docushare/dsweb/Get/Version-47508

AD60 TMT Telescope - MIRAO Instrument Space Envelope
CAD Drawing No: TMT.INS.INST.MIRAO-ENV Rev B
TMT.SEN.DWG.10.007 REL02
https://docushare.tmt.org/docushare/dsweb/Get/Version-27507

AD61 TMT Telescope - MIRES Instrument Space Envelope
CAD Drawing No: TMT.INS.INST.MIRES-ENV Rev B
TMT.SEN.DWG.10.008 REL02
https://docushare.tmt.org/docushare/dsweb/Get/Version-27508

AD62 TMT Telescope _ NFIRAOS Instrument Space Envelope
CAD Drawing No: TMT.INS.AO.NFIRAOS-ENV Rev D
TMT.SEN.DWG.09.002 REL04
https://docushare.tmt.org/docushare/dsweb/Get/Version-27500

AD63 TMT Telescope NFIRAOS Electronics Space Envelope
CAD Drawing No: TMT.INS.AO.NFIRAOS.EL-ENV Rev A
TMT.SEN.DWG.12.003 REL01
https://docushare.tmt.org/docushare/dsweb/Get/Version-47507

AD64 Telescope Instrument - NIRES-B Space Envelope
CAD Drawing No: TMT.INS.INST.NIRESB-ENV Rev B
TMT.SEN.DWG.10.009 REL02
https://docushare.tmt.org/docushare/dsweb/Get/Version-27512

AD65 Envelope Drawing, HROS
CAD Drawing No: TMT.INS.INST.HROS-ENV Rev B
TMT.SEN.DWG.09.006 REL02
https://docushare.tmt.org/docushare/dsweb/Get/Version-27501

AD66 TMT Telescope NFIRAOS Science Calibration Unit Space Envelope
CAD Drawing No: TMT.INS.INST.NSCU-ENV Rev B
TMT.SEN.DWG.09.005 REL02
https://docushare.tmt.org/docushare/dsweb/Get/Version-27515

AD67 Telescope Instrument - PFI Space Envelope
CAD Drawing No: TMT.INS.INST.PFI-ENV Rev B
TMT.SEN.DWG.10.010 REL02
https://docushare.tmt.org/docushare/dsweb/Get/Version-27514

AD68 TMT Telescope _ WFOS Instrument Space Envelope
CAD Drawing No: TMT.INS.INST.WFOS-ENV Rev B
TMT.SEN.DWG.10.011 REL02
https://docushare.tmt.org/docushare/dsweb/Get/Version-27516

AD69 TMT Telescope _ WFOS Electronics Space Envelope
CAD Drawing No: TMT.INS.INST.WFOS.EL-ENV Rev A
TMT.SEN.DWG.12.017 REL01
https://docushare.tmt.org/docushare/dsweb/Get/Version-35090

AD70 TMT Enclosure Stay Out Space Envelope
CAD Drawing No: TMT.FAC.ENC-ENV Rev C
TMT.SEN.DWG.12.013 REL03
https://docushare.tmt.org/docushare/dsweb/Get/Version-63675

AD71 Top End Platform Space Envelope Drawing
CAD Drawing No: TMT.FAC.ENC.TEP-ENV Rev B
TMT.SEN.DWG.14.008 REL02
https://docushare.tmt.org/docushare/dsweb/Get/Version-49742

AD72 Fixed Base Elevator Space Envelope Drawing
CAD Drawing No: TMT.FAC.SUM.ELEV-ENV Rev B
TMT.SEN.DWG.13.003 REL02
https://docushare.tmt.org/docushare/dsweb/Get/Version-47721

AD73 Light Beams for TMT Instruments
CAD Drawing No: TMT.SEN.OPTBEAM-ENV Rev A
TMT.SEN.DWG.11.003 REL01
https://docushare.tmt.org/docushare/dsweb/Get/Version-39701

AD74 Nasmyth Platform Floor Surface Area
CAD Drawing No: TMT.INS.GTY-0004 Rev A
TMT.SEN.DWG.14.005 REL01
https://docushare.tmt.org/docushare/dsweb/Get/Version-47512

AD75 TMT Enclosure - Geometry
CAD Drawing No: TMT.ENC.GTY-0001 Rev A
TMT.ENC.DWG.10.019 REL01
https://docushare.tmt.org/docushare/dsweb/Get/Version-58235

AD76 Standard for the Installation of Lightning Protection Systems
NFPA 780 Edition 2004
https://global.ihs.com/doc_detail.cfm?&rid=Z06&mid=5280&input_search_filter=NFPA&item_s_key=00140693&item_key_date=950316&input_doc_number=780&input_doc_title=&org_code=NFPA&origin=HISC

AD77 DELETED

AD78 DELETED

AD79 TMT Software Development Process
TMT.SFT.TEC.14.013 REL07
https://docushare.tmt.org/docushare/dsweb/Get/Version-50158

AD80 Environmental Safety & Health (ES&H) Hazard/Risk Assessment Processes and Guidelines
TMT.PMO.MGT.10.004 CCR08
https://docushare.tmt.org/docushare/dsweb/Get/Version-56687

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

AD82 Thermal Guidelines for Data Processing Environments
ASHRAE 90577 Edition 4 dated 2015+Errata dated 5/19/2016
http://www.techstreet.com/ashrae/standards/thermal-guidelines-for-data-processing-environments-4th-ed?ashrae_auth_token=&gateway_code=ashrae&product_id=1909403

AD83 Deleted

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
https://docushare.tmt.org/docushare/dsweb/Get/Version-70041

AD87 TMT Software Design Document Technical Architecture/Common Software -- TMT.DEOPS.OSW.CSW (Vol 2 of 2)
TMT.SFT.TEC.12.016 REL05
https://docushare.tmt.org/docushare/dsweb/Get/Version-70043

AD88 Laser Guide Star Facility System Space Envelope and Attachment Interfaces
CAD Drawing No: TMT.INS.AO.LGSF.LGSF-ENV Rev A
TMT.AOS.DWG.17.004 REL01
https://docushare.tmt.org/docushare/dsweb/Get/Version-77517

AD89 Space Envelope CRYO Cooling System
CAD Drawing No: TMT.INS.COOL.CRYO-ENV Rev A
TMT.SEN.DWG.17.004 REL01
https://docushare.tmt.org/docushare/dsweb/Get/Version-79575

1.5 REFERENCE DOCUMENTS

RD1 DELETED; Superseded by RD36

RD2 TMT Observatory Reliability and Availability Budget
TMT.SEN.TEC.07.005
https://docushare.tmt.org/docushare/dsweb/Get/Document-8087

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

TMT Image Size and Wavefront Error Budgets, Report No. 10 (V.11.0), Volume 2 of 3
TMT.OPT.TEC.07.022
https://docushare.tmt.org/docushare/dsweb/Get/Document-8823

TMT Image Size and Wavefront Error Budgets, Report No. 10 (V.11.0), Volume 3 of 3
TMT.OPT.TEC.07.023
https://docushare.tmt.org/docushare/dsweb/Get/Document-8824

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 Relationship between the Science Productivity Metric (SPM) and Normalized Point Source Sensitivity Metric (PSSn)
TMT.SEN.TEC.08.030
https://docushare.tmt.org/docushare/dsweb/Get/Document-10755

RD9 K. Vogiatzis and G.Z. Angeli, Monte Carlo simulation framework for TMT
TMT.SEN.JOU.08.002
SPIE Conference 10.1117/12.787933 (Volume 7017)
https://docushare.tmt.org/docushare/dsweb/Get/Document-9997

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 Cables Piping and Hoses to the Telescope
TMT.SEN.TEC.12.008
https://docushare.tmt.org/docushare/dsweb/Get/Document-22332

RD14 TMT Power Usage and Heat Dissipation Budgets
TMT.SEN.TEC.08.054
https://docushare.tmt.org/docushare/dsweb/Get/Document-12809

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)
TMT.SEN.TEC.09.041
SPIE Conference 10.1117/12.857722 (Volume 77380G)
https://docushare.tmt.org/docushare/dsweb/Get/Document-15972

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 Sub-Systems
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
TMT.SEN.DRD.07.026
https://docushare.tmt.org/docushare/dsweb/Get/Document-9105

RD20 TMT Observatory 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
TMT.SEN.TEC.07.028
https://docushare.tmt.org/docushare/dsweb/Get/Document-8607

RD22 Vibration Budget
TMT.SEN.TEC.14.009
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

RD24 First Decade Instrument Configuration
CAD Drawing No: TMT.INS.GTY.0002
TMT.SEN.DWG.14.014
https://docushare.tmt.org/docushare/dsweb/Get/Document-32363

RD25 Early Light Instrument Configuration
CAD Drawing No: TMT.INS.GTY-0001
TMT.SEN.DWG.14.006
https://docushare.tmt.org/docushare/dsweb/Get/Document-32099

RD26 Systems Engineering Meeting Minutes, August 11, 2009 - HROS Feed
TMT.SEN.COR.09.011
https://docushare.tmt.org/docushare/dsweb/Get/Document-15132

RD27 Systems Engineering Meeting Minutes, December 4, 2006 - Requirements Status and Dome Geometry
TMT.SEN.COR.06.033
https://docushare.tmt.org/docushare/dsweb/Get/Document-7655

RD28 30m TMT Delta Design Enclosure Geometry Selection
(based on preliminary performance results)
TMT.SEN.TEC.06.029
https://docushare.tmt.org/docushare/dsweb/Get/Document-7634

RD29 Servicing Operation: Transferring Large Components into Enclosure and to Nasmyth Platforms
TMT.SEN.TEC.11.014
https://docushare.tmt.org/docushare/dsweb/Get/Document-19673

RD30 Data elements and interchange formats -- Information interchange -- Representation of dates and times
ISO 8601:2004
http://www.iso.org/iso/home/store/catalogue_tc/catalogue_detail.htm?csnumber=40874

RD31 IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems
IEEE 1588 V2
http://standards.ieee.org/findstds/standard/1588-2008.html

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
https://docushare.tmt.org/docushare/dsweb/Get/Document-319

RD34 Observatory Requirements Document
TMT.SEN.DRD.05.001
https://docushare.tmt.org/docushare/dsweb/Get/Document-2688

RD35 Operations Requirement Document (OpsRD)
TMT.OPS.MGT.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 Moved to AD86

RD39 Moved to AD87

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 Observatory 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/ServicesLib/Document-10473/History

RD42 Environmental Safety & Health (ES&H) Hazard/Risk Assessment Processes and Guidelines
TMT.PMO.MGT.10.004
https://docushare.tmt.org/docushare/dsweb/Get/Document-17414

RD43 TMT Operations Plan
TMT.OPS.TEC.11.099
https://docushare.tmt.org/docushare/dsweb/Get/Version-35619

RD44 TMT Observation Workflow Concept Document
TMT.AOS.TEC.07.013
https://docushare.tmt.org/docushare/dsweb/Get/Document-8458

RD45 Observatory Software Operational Concept Definition Document
TMT.SFT.SPE.15.001
https://docushare.tmt.org/docushare/dsweb/Get/Document-50111

RD46 TMT Functional Safety Management Plan
TMT.CTR.SPE.17.001
https://docushare.tmt.org/docushare/dsweb/Get/Document-62522

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-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=275.3K).

2.2 OBSERVATORY SYSTEM DECOMPOSITION

The TMT System decomposition 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.

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

Table: TMT System Decomposition

System	Related WBS Element(s)
Enclosure (ENC)	TMT.FAC.ENC
Summit Facilities (SUM)	TMT.FAC.INF.SUM TMT.FAC.INF.ROAD
Observatory Headquarters (HQ)	TMT.FAC.INF.HQ
Telescope Structure (STR)	TMT.TEL.STR
M1 Optics System (M1)	TMT.TEL.OPT.M1
M2 System (M2)	TMT.TEL.OPT.M2
M3 System (M3)	TMT.TEL.OPT.M3
Optical Cleaning Systems (CLN)	TMT.TEL.OPT.CLN
Optical Coating System (COAT)	TMT.TEL.OPT.COAT
Test Instruments (TINS)	TMT.TEL.OPT.TINS TMT.TEL.OPT.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
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
NFIRAOS Science Calibration Unit (NSCU)	TMT.INS.INST.NSCU
Laser Guide Star Facility (LGSF)	TMT.INS.AO.LGSF, TMT.INS.AO.COMP.SLASR
Adaptive Optics Executive Software (AOESW)	TMT.INS.AO.AOESW
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
IRMS/MOSFIRE (IRMS)	TMT.INS.INST.IRMS TMT.INS.AO.COMP.IRCAM.IRMS
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 Enclosure (ENC)

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

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

The TMT Enclosure System is a dome structure housing the telescope. The three principal enclosure subsystems are the rotating base, cap and shutter. The base and cap are a part of a continuous spherical shell split by a plane (cap / base interface plane) inclined at 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.

2.2.1.2 Summit Facilities (SUM)

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

Associated WBS element(s): TMT.FAC.INF.SUM, 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. It also includes the lighting necessary for this area. 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 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.

2.2.1.3 Observatory Headquarters

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

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

The Observatory Headquarters house the main administrative functions of the observatory. 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.

2.2.1.4 Telescope Structure (STR)

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

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

The Telescope Structure System 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, 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 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).

2.2.1.5 M1 Optics System (M1S)

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

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

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

2.2.1.6 M2 System (M2S)

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

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

The M2 System is the telescope secondary mirror assembly. It includes the M2 Cell (weldment with axial and lateral mirror supports), the polished secondary mirror, the M2 hexapod positioner, the 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.

2.2.1.7 M3 System (M3S)

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

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

The M3 System is the telescope tertiary mirror assembly. It includes the M3 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.

2.2.1.8 Optical Cleaning Systems (CLN)

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

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

The Optical Cleaning Systems include the CO_2 snow cleaning and liquid cleaning equipment, nozzles, hoses, 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.

2.2.1.9 Optical Coating System (COAT)

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

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

The Optical Coating system includes the coating 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 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 at the side of the observatory floor. It does not include the mirror handling equipment, which is included in Optics Handling Equipment. It also does not include the coating laboratory facility equipment (air compressors, cranes, sinks, drains & sumps or fume hoods) or the utilities for the coating chamber, which are included in Summit Facilities. Safety equipment including local e-stops and any sensors and wiring that interface with the Observatory Safety System will be provided.

2.2.1.10 Test Instruments (TINS)

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

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

2.2.1.11 Optics Handling Equipment (HNDL)

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

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

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

2.2.1.12 Alignment and Phasing System (APS)

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

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

The Alignment and Phasing System (APS) is responsible for the 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.

2.2.1.13 Telescope Control System (TCS)

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

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

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

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

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

In seeing limited operation, the correction module receives and processes focus, tip/tilt, coma and low 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.

2.2.1.14 M1 Control System (M1CS)

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

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

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

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

2.2.1.15 Observatory Safety System (OSS)

[REQ-1-OAD-0185] 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, and all associated PLC software. It does not include the Local Safety Controllers, fire suppression systems, emergency lighting or the individual emergency stop buttons' wiring and mounting hardware. These are the responsibility of the individual subsystems.

2.2.1.16 Engineering Sensors (ESEN)

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

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

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

The ESEN system will include an expert user GUI.

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

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

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

NFIRAOS is a Laser Guide Star, Multi-conjugate Adaptive Optics System (LGS MCAO) system intended to provide atmospheric turbulence compensation in the near IR over a 2' FOV for up to 3 instruments working in the near IR. Near-diffraction-limited performance is provided over the central 10-30" FOV. NFIRAOS includes several optical tables, 6 LGS WFS, 1 NGS WFS, 1 TWFS, 2 DMs and a tip/tilt stage (TTS), a source simulator (for natural objects and laser beacons), rotating pupil 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. It also includes the real time computer. It also includes local e-stops and any sensors and wiring that interface with the Observatory Safety System. Instrument rotators, cable wraps, Science ADCs, on-instrument TTF WFSs, rotating lip seals and windows at NFIRAOS exit ports are included in the NFIRAOS-fed instruments and not in NFIRAOS. Also excluded are instrument wavelength and flat field calibration sources.

2.2.1.18 NFIRAOS Science Calibration Unit (NSCU)

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

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

The NFIRAOS Science Calibration Unit (NSCU) provides daytime and nighttime calibrations to NFIRAOS-fed science instruments. Four main sets of calibrations are provided by the NSCU: 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.

2.2.1.19 Laser Guide Star Facility (LGSF)

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

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

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

2.2.1.20 Adaptive Optics Executive Software (AOESW)

[REQ-1-OAD-0200] 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, IRMS, etc.)

2.2.1.21 Instrumentation Refrigerant Cooling System (REFR)

[REQ-1-OAD-0202] The Instrumentation Refrigerant Cooling System is defined as follows:

Associated WBS Element: TMT.INS.COOL.REFR

This element includes the refrigerant cooling system for TMT telescope-mounted subsystems, including all of their components in the summit facilities building and the distribution systems to the instruments/AO systems on the Telescope Structure.

The instrumentation refrigerant cooling system provides 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 M2 and LGSF systems located at the Telescope Top End, the M3 system located at the center of the M1 mirror cell, and at the M2CS location; 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.

2.2.1.22 InfraRed Imaging Spectrometer (IRIS)

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

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

2.2.1.23 Wide Field Optical Spectrometer (WFOS)

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

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

WFOS is a wide field, seeing limited multi-object spectrometer and imager. WFOS includes the entire instrument hardware, including the structure and hydrostatic bearings, atmospheric dispersion compensators, calibration unit, NGS wavefront 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.

2.2.1.24 Infrared Multiple Object Spectrograph (IRMS)

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

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

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

2.2.1.25 Common Software (CSW)

[REQ-1-OAD-0210] 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).

2.2.1.26 Communications and Information Systems (CIS)

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

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

Communications and Information Systems (CIS) 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.

2.2.1.27 Data Management System (DMS)

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

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

The Data Management System (DMS) provides the mechanisms and interfaces needed to capture, time-stamp, describe, store, 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.

2.2.1.28 Executive Software (ESW)

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

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

The 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).

2.2.1.29 Science Operations Support Systems (SOSS)

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

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

Science Operations Support Systems (SOSS) are 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.

2.2.1.30 Data Processing System (DPS)

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

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

The Data Processing System (DPS) enables the removal of atmospheric and instrument signatures from data produced by TMT science instruments, 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.

2.2.1.31 Site Conditions Monitoring System (SCMS)

[REQ-1-OAD-0227] 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

[REQ-1-OAD-0110] The interfaces between the subsystems shall be as defined in the TMT Interface N2 Diagram (AD15).

Discussion: 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

Discussion: A detailed discussion of the TMT Observatory Reliability and Availability Budget is given in (RD2).

Discussion: The maximum unscheduled technical downtime top level value of 3% flows down from the OpsRD (RD35).

[REQ-1-OAD-0300] The allowable downtime budgets for the observatory subsystems are given in 'Table: Observatory Downtime Allocation (RD2)' below (These values are preliminary, and subject to change).

Table: Observatory Downtime Allocation (RD2)

			Top Down				
Requirement Number	Budgeted Science Availability	97.00%	Downtime Allocation				
			3.00%	Level			
	System		1	2	3	4	5
[REQ-1-OAD-0310]	Enclosure		0.17%				
[REQ-1-OAD-0312]	Summit Facilities		0.02%				
	Support Facilities		N/A				
	Observatory Headquarters		N/A				
[REQ-1-OAD-0314]	Telescope Structure		0.12%				
[REQ-1-OAD-0316]	Telescope Optics		0.13%				
[REQ-1-OAD-0318]	M1 Optics System			0.03%			
[REQ-1-OAD-0320]	M2 Optics System			0.05%			
[REQ-1-OAD-0322]	M3 Optics System			0.05%			
	Optical Cleaning Systems		N/A				
	Optical Coating System		N/A				
	Test Instruments		N/A				
	Optics Handling Equipment		N/A				
[REQ-1-OAD-0324]	Telescope Control System (TCS)		0.08%				
[REQ-1-OAD-0328]	M1 Control System (M1CS)		0.73%				
[REQ-1-OAD-0330]	Sensors			0.17%			
[REQ-1-OAD-0332]	Actuators			0.48%			
[REQ-1-OAD-0334]	Control & misc			0.08%			
[REQ-1-OAD-0336]	Alignment and Phasing System (APS)		0.17%				
[REQ-1-OAD-0340]	Observatory Safety System (OSS)		0.02%				
[REQ-1-OAD-0342]	Engineering Sensors (ESEN)		N/A				
[REQ-1-OAD-0346]	AO Downtime (cf SRD 1%)		1.00%				
[REQ-1-OAD-0348]	NFIRAOS Narrow Field Near Infrared AO			0.4%			
[REQ-1-OAD-0350]	Laser Guide Star Facility (LGSF)			0.5%			
[REQ-1-OAD-0352]	Laser System				0.26%		
[REQ-1-OAD-0353]	Lasers					0.25%	
[REQ-1-OAD-0354]	Individual Lasers						0.85%
[REQ-1-OAD-0355]	Laser Service Enclosure					0.01%	
[REQ-1-OAD-0356]	BTO / LLT				0.23%		
[REQ-1-OAD-0357]	Laser Safety System				0.01%		
[REQ-1-OAD-0358]	AO Executive Software			0.1%			
[REQ-1-OAD-0360]	Instrument Downtime (cf OAD discussions 0.5%)		0.50%				
[REQ-1-OAD-0361]	NSCU			0.025%			
[REQ-1-OAD-0362]	InfraRed Imaging Spectrometer			0.475%			
[REQ-1-OAD-0364]	IRMS/MOSFIRE			0.475%			
[REQ-1-OAD-0366]	Wide Field Optical Spectrometer			0.500%			
[REQ-1-OAD-0368]	Observation Execution Software		0.12%				
[REQ-1-OAD-0370]	Data Management System			0.03%			
[REQ-1-OAD-0372]	Executive Software			0.08%			
	Science Operations Support Systems		N/A				
	Data Processing System		N/A				

3.2 HEAT DISSIPATION BUDGETS

Discussion: The peak loads listed within 'Table: Heat Dissipation and Power Consumption Budget for Equipment Located within Enclosure *(RD14)*' *and* 'Table: Heat Dissipation and Power Consumption Budget for Equipment Located within Summit Facilities Building (RD14)' *below are the sum of the individual peak loads of all subcomponents within a subsystem. This total is higher than the total allowed contribution to demand load for some subsystems, in particular, the ENC and SUM which each consist of many subcomponents whose loads are not all coincident.*

Discussion: The definition of the power types used is contained in 'Table: Power types delivered to enclosure, telescope and telescope mounted equipment and sub-systems' *below [REQ-1-OAD-4400].*

Table: Heat Dissipation and Power Consumption Budget for Equipment Located within Enclosure (RD14)

Requirement Number	Item name	Peak Load (kW)	Contribution to system Demand Load (kW)	Backup Generator Connected Load (kW)	UPS Connected Load (kW)	Nighttime power dissipated to building air (kW)	Nighttime power dissipated to water-glycol (kW)	Daytime power dissipated to building air (kW)	Daytime power dissipated to water-glycol (kW)
[REQ-1-OAD-0900]	Enclosure (ENC)	1473.2	830.5	998.6	23.4	0.8	0.0	9.0	0.0
[REQ-1-OAD-0901]	Summit Facilities (SUM)	164.1	126.1	3.0	0.0	0.0	0.0	1.3	105.7
[REQ-1-OAD-0902]	Observatory Safety System (OSS)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[REQ-1-OAD-0903]	Telescope structure (STR)	289.5	246.4	63.5	3.0	0.8	11.4	2.7	6.4
[REQ-1-OAD-0904]	M1 Optics System (M1S)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[REQ-1-OAD-0905]	M2 System (M2S)	2.6	1.8	0.0	0.0	0.6	0.0	0.0	0.0
[REQ-1-OAD-0986]	Adaptive Secondary Mirror (AM2)	11.0	11.0	1.0	1.0	1.0	0.0	1.0	0.0
[REQ-1-OAD-0906]	M3 System (M3S)	2.4	1.7	0.0	0.0	0.4	0.0	0.0	0.0
[REQ-1-OAD-0907]	Optical Cleaning Systems (CLN)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[REQ-1-OAD-0908]	Optical Coating System (COAT)	35.0	0.0	2.0	2.0	4.0	16.0	4.0	16.0
[REQ-1-OAD-0909]	Test Instruments (TINS)	0.8	0.0	0.0	0.0	0.0	0.0	0.1	0.0
[REQ-1-OAD-0910]	Optics Handling Equipment (HNDL)	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[REQ-1-OAD-0911]	Alignment and Phasing System (APS)	8.5	N/A	1.5	1.5	0.3	3.5	0.1	0.9
[REQ-1-OAD-0912]	Telescope Control System (TCS)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[REQ-1-OAD-0914]	M1 Control System (M1CS)	12.5	12.5	15.0	15.0	10.0	2.5	10.0	2.5
[REQ-1-OAD-0915]	Test Instrument Control (TINC)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[REQ-1-OAD-0916]	Engineering Sensors (ESEN)	1.1	1.0	0.7	0.7	0.6	0.0	0.6	0.0
[REQ-1-OAD-0917]	Power, Lighting, and Grounding (PL&G)	129.0	57.6	10.0	0.0	2.7	0.0	20.4	0.0
[REQ-1-OAD-0918]	Narrow Field Near Infrared On-Axis AO System (NFIRAOS)	33.1	22.6	1.5	1.5	0.2	6.6	0.1	3.2
[REQ-1-OAD-0919]	NFIRAOS Science Calibration Unit (NSCU)	1.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0
[REQ-1-OAD-0920]	Laser Guide Star Facility (LGSF)	74.0	71.5	0.0	0.0	0.9	35.2	0.1	0.0
[REQ-1-OAD-0921]	Adaptive Optics Executive Software (AOESW)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[REQ-1-OAD-0982]	Instrumentation Cryogenic Cooling (CRYO)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[REQ-1-OAD-0983]	Instrumentation Refrigerant Cooling (REFR)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[REQ-1-OAD-0923]	Infrared Imaging Spectrometer (IRIS)	6.0	6.0	3.0	3.0	0.2	3.4	0.2	2.2
[REQ-1-OAD-0924]	Wide Field Optical Spectrometer (WFOS)	3.0	3.0	3.0	3.0	0.2	2.1	0.2	1.3
[REQ-1-OAD-0925]	IRMS/MOSFIRE (IRMS)	1.9	1.9	1.9	1.9	0.1	1.4	0.1	1.2
[REQ-1-OAD-0926]	High Resolution Optical Spectrometer (HROS)	20.0	15.0	7.0	2.0	0.3	14.8	0.3	9.8
[REQ-1-OAD-0927]	Near-Infrared Multi-Object Sectrometer (IRMOS)	7.0	7.0	2.0	2.0	0.0	4.0	0.0	2.6
[REQ-1-OAD-0928]	Planet Formation Instrument (PFI)	8.0	0.0	2.0	2.0	0.3	2.1	0.3	2.1
[REQ-1-OAD-0929]	Mid-Infrared AO System (MIRAO)	1.5	1.5	1.5	1.5	0.1	0.7	0.1	0.4
[REQ-1-OAD-0930]	Mid-Infrared Echelle Spectrometer (MIRES)	2.0	2.0	2.0	2.0	0.1	0.7	0.1	0.5
[REQ-1-OAD-0931]	Near Infrared Echelle Spectrometer (NIRES-B)	1.5	1.5	1.5	1.5	0.1	0.8	0.1	0.5
[REQ-1-OAD-0932]	Near Infrared Echelle Spectrometer (NIRES-R)	1.5	1.5	1.5	1.5	0.1	0.5	0.1	0.5
[REQ-1-OAD-0933]	Wide-field Infrared Camera (WIRC)	1.9	1.9	1.9	1.9	0.1	1.4	0.1	1.2
[REQ-1-OAD-0934]	Communications and Information Systems (CIS)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[REQ-1-OAD-0935]	Common Software (CSW)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[REQ-1-OAD-0936]	Data Management System (DMS)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[REQ-1-OAD-0937]	Executive Software (ESW)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[REQ-1-OAD-0938]	Science Operations Support Systems (SOSS)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[REQ-1-OAD-0939]	Data Processing System (DPS)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[REQ-1-OAD-0940]	Site Conditions Monitoring System (SCMS)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Note:	Cells highlighted in gray indicate that the subsystem will have power dissipated to refrigerant; to be included later.								

Table: Heat Dissipation and Power Consumption Budget for Equipment Located within Summit Facilities Building (RD14)

Requirement Number	Item name	Peak Load (kW)	Contribution to system Demand Load (kW)	Backup Generator Connected Load (kW)	UPS Connected Load (kW)	Nighttime power dissipated to building air (kW)	Nighttime power dissipated to water-glycol (kW)	Daytime power dissipated to building air (kW)	Daytime power dissipated to water-glycol (kW)
[REQ-1-OAD-0941]	Enclosure (ENC)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[REQ-1-OAD-0942]	Summit Facilities (SUM)	805.6	620.4	526.6	2.0	22.9	35.1	69.0	29.1
[REQ-1-OAD-0943]	Observatory Safety System (OSS)	1.5	1.2	1.5	1.5	1.2	0.0	0.8	0.0
[REQ-1-OAD-0944]	Telescope structure (STR)	36.8	25.9	0.0	0.0	0.6	33.8	0.1	3.4
[REQ-1-OAD-0945]	M1 Optics System (M1S)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[REQ-1-OAD-0946]	M2 System (M2S)	1.5	1.2	1.5	1.5	1.2	0.0	0.6	0.0
[REQ-1-OAD-0987]	Adaptive Secondary Mirror (AM2)	3.0	2.4	3.0	3.0	1.5	0.0	0.9	0.0
[REQ-1-OAD-0947]	M3 System (M3S)	1.5	1.2	1.5	1.5	1.2	0.0	0.6	0.0
[REQ-1-OAD-0948]	Optical Cleaning Systems (CLN)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[REQ-1-OAD-0949]	Optical Coating System (COAT)	88.4	88.4	1.0	1.0	8.7	26.4	14.3	30.8
[REQ-1-OAD-0950]	Test Instruments (TINS)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[REQ-1-OAD-0951]	Optics Handling Equipment (HNDL)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[REQ-1-OAD-0952]	Alignment and Phasing System (APS)	4.2	N/A	4.2	4.2	1.0	0.0	1.0	0.0
[REQ-1-OAD-0953]	Telescope Control System (TCS)	1.5	1.2	1.5	1.5	1.2	0.0	1.2	0.0
[REQ-1-OAD-0955]	M1 Control System (M1CS)	1.5	1.2	1.5	1.5	1.2	0.0	0.8	0.0
[REQ-1-OAD-0956]	Test Instrument Control (TINC)	1.5	1.2	1.5	1.5	1.2	0.0	0.8	0.0
[REQ-1-OAD-0957]	Engineering Sensors (ESEN)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[REQ-1-OAD-0958]	Power, Lighting, and Grounding (PL&G)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[REQ-1-OAD-0959]	Narrow Field Near Infrared On-Axis AO System (NFIRAOS)	4.9	3.9	4.9	4.9	2.5	0.0	1.5	0.0
[REQ-1-OAD-0960]	NFIRAOS Science Calibration Unit (NSCU)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[REQ-1-OAD-0961]	Laser Guide Star Facility (LGSF)	6.8	5.0	2.8	2.8	3.4	0.0	0.8	0.0
[REQ-1-OAD-0962]	Adaptive Optics Executive Software (AOESW)	1.4	1.1	1.4	1.4	0.7	0.0	0.4	0.0
[REQ-1-OAD-0984]	Instrumentation Cryogenic Cooling (CRYO)	60.0	60.0	60.0	0.0	0.0	61.8	0.0	61.8
[REQ-1-OAD-0985]	Instrumentation Refrigerant Cooling (REFR)	30.0	15.0	0.0	0.0	0.8	0.0	6.7	0.0
[REQ-1-OAD-0964]	Infrared Imaging Spectrometer (IRIS)	1.5	1.2	1.5	1.5	0.8	0.0	0.5	0.0
[REQ-1-OAD-0965]	Wide Field Optical Spectrometer (WFOS)	1.5	1.2	1.5	1.5	0.8	0.0	0.5	0.0
[REQ-1-OAD-0966]	IRMS/MOSFIRE (IRMS)	1.5	1.2	1.5	1.5	0.8	0.0	0.5	0.0
[REQ-1-OAD-0967]	High Resolution Optical Spectrometer (HROS)	1.5	1.2	1.5	1.5	0.8	0.0	0.5	0.0
[REQ-1-OAD-0968]	(IRMOS)	3.0	2.4	3.0	3.0	1.5	0.0	0.9	0.0
[REQ-1-OAD-0969]	Planet Formation Instrument (PFI)	3.0	2.4	3.0	3.0	1.5	0.0	0.9	0.0
[REQ-1-OAD-0970]	Mid-Infrared AO System (MIRAO)	1.5	1.2	1.5	1.5	0.8	0.0	0.5	0.0
[REQ-1-OAD-0971]	Mid-Infrared Echelle Spectrometer (MIRES)	1.5	1.2	1.5	1.5	0.8	0.0	0.5	0.0
[REQ-1-OAD-0972]	Near Infrared Echelle Spectrometer (NIRES-B)	1.5	1.2	1.5	1.5	0.8	0.0	0.5	0.0
[REQ-1-OAD-0973]	Near Infrared Echelle Spectrometer (NIRES-R)	1.5	1.2	1.5	1.5	0.8	0.0	0.5	0.0
[REQ-1-OAD-0974]	Wide-field Infrared Camera (WIRC)	1.5	1.2	1.5	1.5	0.8	0.0	0.5	0.0
[REQ-1-OAD-0975]	Communications and Information Systems (CIS)	4.0	3.2	4.0	4.0	3.2	0.0	3.2	0.0
[REQ-1-OAD-0976]	Common Software (CSW)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[REQ-1-OAD-0977]	Data Management System (DMS)	4.0	3.2	4.0	4.0	3.2	0.0	2.4	0.0
[REQ-1-OAD-0978]	Executive Software (ESW)	6.4	5.1	6.4	6.4	4.4	0.0	4.2	0.0
[REQ-1-OAD-0979]	Science Operations Support Systems (SOSS)	1.5	1.2	1.5	1.5	1.2	0.0	0.8	0.0
[REQ-1-OAD-0980]	Data Processing System (DPS)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[REQ-1-OAD-0981]	Site Conditions Monitoring System (SCMS)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

3.3 TELESCOPE IMAGE QUALITY BUDGET

3.3.1 On-Axis Budget

Discussion: 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 = 0.2m*

The median observing temperature, or at a temperature difference of 2.5K from the APS alignment temperature.

For the allowable degradation in performance at other conditions, see 'Specification of Image Quality terms varying with Temperature and Zenith Angle' (AD38).

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).

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

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

A more detailed discussion of PSS_N *is in (RD4).*

Discussion: The error categories of the budget are explained below as Notes to 'Table: Telescope Image Quality Error Budget (RD19)' below.

*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.*

Non-repeatable support system errors are covered in SDE. Low order, gravity dependent support system fabrication and installation errors are covered in SRFE. The effect of imperfect polishing out of print through bumps at the calibration zenith angle is included in SRFE (residual polishing error).

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.*

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). These errors are the results of (i) APS measurement and estimation errors, both correlated (atmospheric residual) and* *uncorrelated (optical sensor noise), (i) edge sensor calibration and linearity errors, (ii) quasi-static wind pressure, and (iii) 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 and OIWFS measurement and estimation errors are separately accounted under wavefront sensing, but due to the inherent link between the APS measurement noise allocation included in WFSSP and the performance of M1CS, the estimation and verification of SOPD need to account for this effect.*

*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.*

*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 (2^{nd} and 3^{rd}) 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 (2^{nd} and 3^{rd}) 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 (2^{nd} and 3^{rd}) 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.*

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).*

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.*

Discussion: 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: Telescope Image Quality Error Budget (RD19)

Requirement #	Description	Error allocation					Wavefront Error Allocation after AO (NFIRAOS) Correction [nm_{RMS}]					Notes
[REQ-1-OAD-0400]	System (up to the Nasmyth Focus)	0.8500					62.0					
[REQ-1-OAD-0402]	Thermal (mirror and dome) seeing		0.9850					30.0				TS
[REQ-1-OAD-0404]	Optical surface shapes		0.8694					38.4				
[REQ-1-OAD-0406]	M1 shape			0.9203					31.8			
[REQ-1-OAD-0408]	Segment residual figure error				0.9582					21.8		SRFE
[REQ-1-OAD-0410]	Segment thermal distortion				0.9980					3.9		STD
[REQ-1-OAD-0412]	Segment support print through				0.9762					18.2		SSPT
[REQ-1-OAD-0414]	Segment drift errors				0.9999					0.5		SDE
[REQ-1-OAD-0416]	Segment in-plane displacement				0.9998					1.4		SIPD
[REQ-1-OAD-0456]	M1 gravity, thermal, installation errors					1.0000					1.0	SIPD-M1
[REQ-1-OAD-0458]	STR gravity, thermal, installation errors					0.9998					1.0	SIPD-STR
[REQ-1-OAD-0418]	Segment out-of-plane residual				0.9951					2.5		SOPD
[REQ-1-OAD-0420]	Segment dynamic displacement residual				0.9911					13.6		SDDR
[REQ-1-OAD-0422]	M2 shape			0.9823					11.4			
[REQ-1-OAD-0424]	M2 residual figure error				0.9851					11.2		M2RFE
[REQ-1-OAD-0426]	M2 thermal distortion				0.9984					0.9		M2TD
[REQ-1-OAD-0428]	M2 shape drift errors				0.9999					0.5		M2SDE
[REQ-1-OAD-0430]	M2 support print through				0.9991					1.5		M2SPT
[REQ-1-OAD-0432]	M2 dynamic shape residual				0.9998					0.6		M2DSR
[REQ-1-OAD-0434]	M3 shape			0.9846					8.9			
[REQ-1-OAD-0436]	M3 residual figure error				0.9864					8.8		M3RFE
[REQ-1-OAD-0438]	M3 thermal distortion				0.9997					0.9		M3TD
[REQ-1-OAD-0440]	M3 shape drift errors				0.9999					0.5		M3SDE
[REQ-1-OAD-0442]	M3 support print through				0.9986					0.8		M3SPT
[REQ-1-OAD-0444]	M3 dynamic shape residual				1.0000					0.0		M3DSR
[REQ-1-OAD-0460]	Wavefront Sensing			0.9768					15.9			
[REQ-1-OAD-0462]	M1 warping harness wavefront measurement error				0.9896					11.7		WFSWH
[REQ-1-OAD-0464]	M1 segment phasing wavefront measurement error				0.9970					5.8		WFSSP
[REQ-1-OAD-0466]	Low order wavefront measurement error				0.9992					0.9		WFSLO
[REQ-1-OAD-0468]	M1 segment tip/tilt wavefront measurement error				0.9908					9.0		WFSTT
[REQ-1-OAD-0446]	Optical alignment		0.9929					36.5				
[REQ-1-OAD-0448]	Telescope collimation errors			1.0000					0.0			COLL
[REQ-1-OAD-0454]	Image jitter (control noise)			0.9947					17.0			CN
[REQ-1-OAD-0470]	Guider Noise				0.9990					0.0		CN-INS
[REQ-1-OAD-0472]	Mount Control Noise				0.9980					9.0		CN-STR
[REQ-1-OAD-0474]	M2 jitter				0.9978					5.4		CN-M2
[REQ-1-OAD-0476]	M3 jitter				0.9999					13.4		CN-M3
[REQ-1-OAD-0480]	Wind jitter residual			0.9986					16.1			WJ
[REQ-1-OAD-0482]	STR wind residual				0.9986					16.0		WJ-STR
[REQ-1-OAD-0483]	M2 wind residual				1.0000					1.0		WJ-M2
[REQ-1-OAD-0484]	M3 wind residual				1.0000					1.0		WJ-M3
[REQ-1-OAD-0486]	Vibration jitter residual			0.9995					28.0			VJ
[REQ-1-OAD-0488]	Dynamic blur residual			1.0000					0.0			DBLUR
[REQ-1-OAD-0492]	Contingency		0.9997					11.8				

3.3.2 Off-Axis Budget

[REQ-1-OAD-0500] The seeing limited PSS_N at the Nasmyth focus is allowed to linearly degrade up to 5% with increasing telescope field angle. At the edge of the 20 arcminute diameter field, at 0.5μm wavelength and r_0 = 20cm in zenith direction, the allowed off-axis normalized (RD15) PSS_N is 0.8075 (0.85 on-axis allocation times 0.95).

Discussion: The image blur of an R-C optical design increases with field angle due to field dependent astigmatism inherent to the design. The corresponding PSS_N value of a perfect telescope is a function of the field angle resulting in 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).

3.3.3 Elevation Angle Dependence of the Budget

[REQ-1-OAD-0525] The total system PSSn shall be ≥0.85 at any observing zenith angle with r0 = 20cm (at zA=0) and at median wind speed and median observing temperature.

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.

[REQ-1-OAD-0526] The variation of individual terms that are dependent on zenith angle and temperature shall be consistent with the assumptions defined in 'Specification of Image Quality terms varying with Temperature and Zenith Angle' (AD38).

3.4 WAVEFRONT ERROR BUDGET FOR ADAPTIVE OPTICS OPERATIONS

3.4.1 NFIRAOS Wavefront Error Budget

Discussion: 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, over a 17” x 17” and over 30" FoV.*

TMT AO Error Budget and CBE Description (RD41) defines all the error terms and their rationales used in (RD20), summarized in 'Table: NFIRAOS LGS MCAO and IRIS RMS wavefront error budget' *and* 'Table: 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: NFIRAOS LGS MCAO and IRIS RMS wavefront error budget*' and '*Table: 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: NFIRAOS NGSAO MCAO and IRIS RMS wavefront error budget (60 x 60 actuators, m8 and m12) in nm (RD20)

		mR=8 guide star					mR=12 guide star					
REQ #	Terms	L0	L1	L1	L2	L3	L0	L1	L1	L2	L3	
REQ-0-SRD-880 REQ-0-SRD-881	NFIRAOS NGSAO and IRIS WFE	158					185					(RD41)
REQ-1-ORD-3670 REQ-1-ORD-3671	High Order Modes		149					185				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			134					174			Section 3.1.3.1
REQ-1-OAD-0274	NFIRAOS OM				51					51		Section 3.1.3.1.1
	NFIRAOS-to-Telescope misalignment					0					0	
	Uncorrectable error					35					35	
	NCPA calibration error					14					14	
	Registration Drifts after Calibration					15					15	
	Image Quality at Pyramid tip					25					25	
	Telescope pupil misregistration (Measurement error)					6					6	
	Dynamic higher order error					5					5	
	Output beam misalign					15					15	
REQ-1-OAD-0260	AO Comp: WC				51					51		Section 3.1.3.1.2
	Actuator saturation					0					0	
	Failed actuators					19					19	
	Hysteresis					20					20	
	Dynamics					11					11	
	Influence function					0					0	
	Surface flattening					42					42	
REQ-1-OAD-0275	AO Comp: PWFS WFS				38					38		Section 3.1.3.1.3
	Optical gain tracking					15					15	
	Pupil image location					12					12	
	Imperfect pyramid					16					16	
	Pupil image quality					16					16	
	CCD charge diffusion					17					17	
	Pupil image distortion					16					16	
	Modulation errors					0					0	
REQ-1-OAD-0276	AO Comp: RTC				20					20		Section 3.1.3.1.4
	Numerical precision					20					20	
REQ-1-OAD-0277	AO Architecture				105					152		Section 3.1.3.1.5
	DM fitting error					74					74	
	PWFS aliasing error					16					16	
	TMT pupil Function					14					14	
	Servo Lag					18					18	
	WFS non-linearity					64					64	
	WFS noise					0					110	
	Simulation Undersampling					26					26	
REQ-1-OAD-0264	IRIS			40					40			Section 3.1.3.3
	Design residuals				7					7		
	Chromatic aberration				14					14		
	Fabrication/installation				10					10		
	Alignment accuracy				8					8		
	Cooldown				6					6		
	Surface quality				26					26		
	Dynamic higher-order error				3					3		
	ADC effects				4					4		
	Glass inhomogeneities				12					12		
	NCPA calibration error				10					10		
	Others				14					14		
REQ-1-ORD-3669	Low Order Modes (Tip/Tilt and Focus)		29					29				Section 3.2
	Telescope											Section 3.2.1
REQ-1-OAD-0278	STR, M1, M2 and M3			22					22			Section 3.2.1.1
	Windshake tip/tilt error				2					2		
	Telescope structure vibration				21					21		
	Telescope tracking jitter				5					5		
	Instrumentation											Section 3.2.2
REQ-1-OAD-0279	NFIRAOS System			10					10			Section 3.2.2.1
REQ-1-OAD-0280	NFIRAOS OM				10					10		Section 3.2.2.1.1
	Internal NFIRAOS vibration					10					10	
REQ-1-OAD-0281	AO Comp: WC				0					0		Section 3.2.2.1.2
	TTS/DM dynamics					0					0	
	DM hysteresis					0					0	
REQ-1-OAD-0282	AO Comp: RTC/RPG				0					0		Section 3.2.2.1.3
	RTC/RPG implementation					0					0	
REQ-1-OAD-0283	AO Architecture				2					2		Section 3.2.2.1.4
	Turbulence tip/tilt					2					2	
REQ-1-OAD-0272	IRIS			16					16			Section 3.2.2.2
	NFIRAOS to IRIS vibration				10					10		
	OIWFS to Imager vibration				10					10		
	Internal IRIS imager vibration				7					7		
	WFS (OIWFS/ODGW)				0					0		
	Contingency		45					0				

Table: NFIRAOS LGS MCAO and IRIS RMS wavefront error budget (60 x 60 actuators, on axis, 17"x17", 30") in nm (RD20)

		On axis					17"x17"					30" Diameter					
	Terms	L0	L1	L1	L2	L3	L0	L1	L1	L2	L3	L0	L1	L1	L2	L3	
REQ #	NFIRAOS LGS MCAO and IRIS WFE	187					191					203					(RD41)
REQ-0-SRD-0820 REQ-1-ORD-3530 REQ-1-ORD-3532	High Order Modes		173					190					190				Section 2.1
	Telescope																Section 2.1.1
REQ-1-OAD-0251	TCS			6					6					6			Section 2.1.1.1
	Pupil misregistration (Control)				6					6					6		Section 2.1.1.1.1
REQ-1-OAD-0252	M1S			29					29					29			Section 2.1.1.2
	M1 static shape				29					29					29		
REQ-1-OAD-0253	M1CS			14					14					14			Section 2.1.1.3
	Segment dynamic misalignment				14					14					14		
REQ-1-OAD-0254	M2S			13					14					16			Section 2.1.1.4
	M2 Static Shape				11					11					11		
	Focal Plane Tilt				0					6					10		
	Pupil misregistration (M2 actuators)				6					6					6		
REQ-1-OAD-0255	M3S			11					11					11			Section 2.1.1.5
	M3 Static Shape				9					9					9		
	Pupil misregistration (M3 actuators)				6					6					6		
REQ-1-OAD-0256	APS			16					16					16			Section 2.1.1.6
	M1 shape calibration				16					16					16		
	Facilities																Section 2.1.2
REQ-1-OAD-0257	ENC			30					30					30			Section 2.1.2.1
	Dome Seeing				22					22					22		
	Mirror Seeing				20					20					20		
	Instrumentation																Section 2.1.3
REQ-1-OAD-0258	NFIRAOS SYSTEM			157					176					176			Section 2.1.3.1
REQ-1-OAD-0259	NFIRAOS OM				50					58					60		Section 2.1.3.1.1
	NFIRAOS-to-Telescope misalignment					0					20					20	
	Uncorrectable error					35					35					35	
	NCPA calibration error					25					33					35	
	DM/WFS pupil distortion					12					12					12	
	DM/WFS pupil misregistration					16					16					16	
	Telescope pupil misregistration (Measurement error)					6					6					6	
	Dynamic higher order error					5					5					5	
	Output beam misalign					15					15					15	
REQ-1-OAD-0260	AO Comp: WC				51					51					51		Section 2.1.3.1.2
	Actuator saturation					0					0					0	
	Failed actuators					19					19					19	
	Hysteresis					20					20					20	
	Dynamics					11					11					11	
	Influence function					0					0					0	
	Surface flattening					42					42					42	
REQ-1-OAD-0261	AO Comp: LGSWFS				44					44					44		Section 2.1.3.1.3
	Offset/gain calibration					14					14					14	
	Na layer range tracking					12					12					12	
	Pt. src tomographic approx					0					0					0	
	Rayleigh fratricide					4					4					4	
	Signal variability					23					23					23	
	Diff. atmospheric refractive index					17					17					17	
	Chromatic anisoplanatism					0					0					0	
	Lenslet throughput and aberrations					28					28					28	
REQ-1-OAD-0262	AO Comp: RTC				28					28					28		Section 2.1.3.1.4
	Numerical precision					20					20					20	
	Cn2 Profile					20					20					20	
REQ-1-OAD-0263	AO Architecture				130					148					148		Section 2.1.3.1.5
	DM fitting error					74					74					74	
	DM projection error					48					85					85	
	LGS WFS aliasing error					26					26					26	
	Tomography Error					48					53					53	
	TMT pupil Function					14					4					4	
	Servo Lag					18					17					17	
	LGS WFS non-linearity					19					23					23	
	LGS WFS noise					51					53					53	
	Simulation Undersampling					48					48					48	
REQ-1-OAD-0264	IRIS			40					40					40			Section 2.1.3.2
	Design residuals				7					7					7		
	Chromatic aberration				14					14					14		
	Fabrication/installation				10					10					10		
	Alignment accuracy				8					8					8		
	Cooldown				6					6					6		
	Surface quality				26					26					26		
	Dynamic higher-order error				3					3					3		
	ADC effects				4					4					4		
	Glass inhomogeneities				12					12					12		
	NCPA calibration error				10					10					10		
	Others				14					14					14		
REQ-1-OAD-0265	LGSF			34					34					34			Section 2.1.3.3
	Surface roughness				30					30					30		
	Alignment and Fabrication				15					15					15		
REQ-0-SRD-0850 REQ-1-ORD-2730	Low order Modes (Tip/tilt, Focus and Plate Scale)		68					68					68				Section 2.2
	Telescope																Section 2.2.1
REQ-1-OAD-0266	STR, M1, M2 and M3			37					37					37			Section 2.2.1.1
	Windshake tip/tilt error				16					16					16		
	Windshake plate scale error				5					5					5		
	Telescope structure vibration				28					28					28		
	Telescope tracking jitter				17					17					17		
	Instrumentation																Section 2.2.2
REQ-1-OAD-0267	NFIRAOS System			54					54					54			Section 2.2.2.1
REQ-1-OAD-0268	NFIRAOS OM				22					22					22		Section 2.2.2.1.1
	Internal NFIRAOS vibration					10					10					10	
	Field dependent WFE					20					20					20	
REQ-1-OAD-0269	AO Comp: WC				0					0					0		Section 2.2.2.1.2
	TTS/DM dynamics					0					0					0	
	DM hysteresis					0					0					0	
REQ-1-OAD-0270	AO Comp: RTC/RPG				0					0					0		Section 2.2.2.1.3
	RTC/RPG implementation					0					0					0	
REQ-1-OAD-0271	AO Architecture				50					50					50		Section 2.2.2.1.4
	Turbulence tip/tilt					32					32					32	
	Turbulence plate scale					38					38					38	
REQ-1-OAD-0272	IRIS			16					16					16			Section 2.2.2.2
	NFIRAOS to IRIS vibration				10					10					10		
	OIWFS to Imager vibration				10					10					10		
	Internal IRIS imager vibration				7					7					7		
	WFS (OIWFS/ODGW)				0					0					0		
	Contingency		20					0					22				

*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 a second-order high-pass filter with damping ζ = 0.7 and natural frequency ω0 = 15 Hz*2*π. 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. This rejection transfer function is too optimistic by ignoring integrator overshoot. 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.

3.4.2 Elevation Angle Dependence of the Budget

[REQ-1-OAD-0595] The residual telescope error budget [REQ-1-OAD-0556] is allowed to degrade the same way as the atmospheric seeing does, i.e. $W_{RMS} \propto \sqrt{\sec z}$ (RD33).

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

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

3.4.3 Wavefront Corrector Stroke Allocation

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

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

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

Discussion: The tip/tilt/piston removed RMS OPD due to atmospheric turbulence is about 1.5 [2.1] microns for an r_0 of 15 [10] cm and a 30 meter outer scale. Each NFIRAOS DM will provide a total stroke +/- 10 microns of wavefront correction. Treating all wavefront error sources as normally distributed, zero-mean random numbers, we find that the additional wavefront error due to DM saturation is about 6 [24] nm RMS if the observatory wavefront errors are no larger than 2 um RMS. See (RD10).

3.5 POINTING ERROR BUDGET

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

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

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

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

Telescope pointing error budget in arcsec:

The pointing error is the result of statistically independent azimuth and elevation errors.

Table: Pointing Error Budget

Telescope		1.0
[REQ-1-OAD-0660]	Residual astrometry	0.2
[REQ-1-OAD-0666]	Structure/M1 (alignment of elevation/azimuth axes, encoder etc.) not including thermal or temporal drift	0.6
[REQ-1-OAD-0667]	Structure/M1 thermal drift	0.5
[REQ-1-OAD-0668]	Structure/M1 temporal drift (over 1 month)	0.3
[REQ-1-OAD-0669]	M2 alignment (relative to M1)	0.4
[REQ-1-OAD-0672]	M3 alignment (relative to M1)	0.4
[REQ-1-OAD-0675]	Pointing camera location (relative to M1)	0.2

3.6 PUPIL SHIFT BUDGET

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

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

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

3.7 PLATE SCALE STABILITY BUDGET

Discussion: This budget controls the stability of positions in the telescope field of view, to meet the requirement of [REQ-1-ORD-2850]. This budget is elaborated in more detail in (RD12).

Table: 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. (RD12)

Requirement Number	Item	Maximum Image Motion (mas)
[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
	Total	**60**

3.8 MASS BUDGET

Table: Mass Budget for Telescope Mounted Sub-systems (RD21)

Requirement	Subsystem Decompostion		Mass (not to exceed)			
	Abbrev-iation	Description	Elevation (tonnes)	Azimuth (tonnes)	Sub-total (tonnes)	Subsystem Total (tonnes)
[REQ-1-OAD-0740]	STR	Telescope Structure				2130.3
		Elev. Structure	1091.6		1091.6	
		Az. Structure		831.4	831.4	
		Inst. Support Structures		72.6	72.6	
		Utility Service Lines	9.1	36.5	45.6	
		Mount Control System	8.9	80.3	89.3	
[REQ-1-OAD-0742]	M1S	M1 System	135.0		135.0	135.0
[REQ-1-OAD-0744]	M2S	M2 System	6.5		6.5	6.5
[REQ-1-OAD-0745]	AM2	Adaptive Secondary Mirror System	8.5		8.5	8.5
[REQ-1-OAD-0746]	M3S	M3 System	12.3		12.3	12.3
[REQ-1-OAD-0748]	TINS	Test Instruments	0.3		0.3	0.3
[REQ-1-OAD-0750]	APS	Alignment and Phasing System				6.0
		Instrument (early light)		5.6	5.6	
		Instrument (first decade)		5.6	5.6	
		Electronics+misc Nasmyth (early light)		0.4	0.4	
		Electronics+misc Nasmyth (first decade)		0.4	0.4	
[REQ-1-OAD-0754]	M1CS	M1 Control System	29.1		29.1	29.1
[REQ-1-OAD-0756]	TINC	Test Instrument Controls				0.1
[REQ-1-OAD-0758]	OSS	Telescope Safety System		0.1	0.1	0.1
[REQ-1-OAD-0760]	ESEN	Engineering Sensors	0.8	0.8	1.6	1.6
[REQ-1-OAD-0764]	NFIRAOS	NFIRAOS				49.5
		Instrument		46.8	46.8	
		Electronics + misc Nasmyth		2.7	2.7	
[REQ-1-OAD-0766]	LGSF	Laser guide star facility				14.4
		LGSF laser system	9.3		9.3	
		LGSF BTO Optical Path	3.0		3.0	
		LGSF Top End	2.1		2.1	
[REQ-1-OAD-0781]	CRYO	Cryogenic Coolant System		20.5	20.5	20.5
[REQ-1-OAD-0783]	REFR	Refrigerant Cooling System		1.3	1.3	1.3
[REQ-1-OAD-0768]	IRIS	IRIS				10.5
		Instrument		6.8	6.8	
		Cable Wrap		2.8	2.8	
		Electronics + misc Nasmyth		0.9	0.9	
[REQ-1-OAD-0770]	IRMS	IRMS				6.8
		Instrument + elec		6.8	6.8	
[REQ-1-OAD-0772]	MIRES	MIRES + MIRAO				7.2
		Instrument (MIRAO)		2.6	2.6	
		Instrument (MIRES)		3.6	3.6	
		Electronics + misc Nasmyth		1.0	1.0	
[REQ-1-OAD-0774]	PFI	PFI				5.7
		Instrument		4.5	4.5	
		Electronics + misc Nasmyth		1.3	1.3	

Requirement	Subsystem Decompostion		Mass (not to exceed)			
	Abbrev-iation	Description	Elevation (tonnes)	Azimuth (tonnes)	Sub-total (tonnes)	Subsystem Total (tonnes)
[REQ-1-OAD-0776]	NIRES-B	NIRES				7.4
		Instrument		6.4	6.4	
		Electronics + misc Nasmyth		1.0	1.0	
[REQ-1-OAD-0777]	NIRES-R	NIRES				7.4
		Instrument		6.4	6.4	
		Electronics + misc Nasmyth		1.0	1.0	
[REQ-1-OAD-0778]	WIRC	WIRC				6.1
		Instrument		5.1	5.1	
		Electronics + misc Nasmyth		1.0	1.0	
[REQ-1-OAD-0780]	WFOS	WFOS				42.0
		Instrument		41.0	41.0	
		Electronics + misc Nasmyth		1.0	1.0	
[REQ-1-OAD-0782]	HROS	HROS				49.7
		Instrument		47.4	47.4	
		Electronics + misc Nasmyth		2.3	2.3	
[REQ-1-OAD-0784]	IRMOS	IRMOS				19.3
		Instrument		16.6	16.6	
		Electronics + misc Nasmyth		2.7	2.7	
[REQ-1-OAD-0785]	NSCU			2.6	2.6	2.6
[REQ-1-OAD-0786]	Misc. Nasmyth	Misc. Nasmyth				20.0
		+X Side		10.0	10.0	
		-X Side		10.0	10.0	
		Mass Sums	**1308.0**	**1277.6**	**2585.6**	

3.9 OTHER PERFORMANCE BUDGETS

3.9.1 M1CS Actuator Range of Travel Budget

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

Table: M1CS Actuator Range of Travel Budget.

Requirement Number	Component	Actuator Travel Allowance
[REQ-1-OAD-0800]	Gravity deflection of Telescope Elevation Structure and M1 Optics System	1.80 mm
[REQ-1-OAD-0802]	Thermal deflection of Telescope Elevation Structure and M1 Optics System	0.42 mm
[REQ-1-OAD-0804]	M1 Subcell installation errors	0.20 mm
[REQ-1-OAD-0806]	Added range for actuator diagnostics	0.25 mm
[REQ-1-OAD-0807]	End of Travel Margin	0.20mm
	Margin	2.13 mm
[REQ-1-OAD-0808]	Total required M1CS Actuator travel	5.00 mm

3.9.2 Equipment Vibration Budget

Discussion: 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-0540] (M1 contribution) and [REQ-1-OAD-0572] (Image Jitter contribution).

*This results in the following allocations of vibration contributions to system AO WFE among subsystems in '*Table: Equipment 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.*

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.

Table: Equipment Vibration Budget (RD22)

Requirement Number	Subsystem	Subcomponent	Estimated sensitivity value (nm/N)	Estimated allowable force (N rms)	Estimated subcomponent contribution to AO WFE (nm)	Subsystem aggregate allowable AO WFE impact (nm)
	Observatory Total					**30.0**
	Contingency					**5.0**
	On Telescope					**26.1**
REQ-1-OAD-1120	Telescope structure (STR)					12.0
		Azimuth drives	0.7	1.0	0.7	
		Elevation drives	1.9	1.0	1.9	
		Azimuth cable wrap	0.5	1.0	0.5	
		Elevation cable wrap	1.3	1.0	1.3	
		HSB oil distribution	0.7	1.0	0.7	
		Telescope Utility Services	7.6	1.4	10.7	
		Other	4.7	1.0	4.7	
REQ-1-OAD-1121	M1 Optics System (M1)					0.0
REQ-1-OAD-1122	M2 System (M2)					5.8
		M2 cell	27.5	0.2	5.5	
		M2 electronics	3.9	0.5	1.9	
REQ-1-OAD-1123	M3 System (M3)		4.7	0.5	2.4	2.4
REQ-1-OAD-1124	Optical Cleaning Systems (CLN)			0.0	0.0	0.0
REQ-1-OAD-1125	Test Instruments (TINS)			0.0	0.0	0.0
REQ-1-OAD-1126	Optics Handling Equipment (HNDL)			0.0	0.0	0.0
REQ-1-OAD-1127	Alignment and Phasing System (APS)		7.6	0.0	0.0	0.0
REQ-1-OAD-1128	Telescope Control System (TCS)			0.0	0.0	0.0
REQ-1-OAD-1129	M1 Control System (M1CS)		4.7	0.5	2.4	2.4
REQ-1-OAD-1130	Test Instrument Control (TINC)			0.0	0.0	0.0
REQ-1-OAD-1131	Observatory Safety System (OSS)			0.0	0.0	0.0

Requirement Number	Subsystem	Subcomponent	Estimated sensitivity value (nm/N)	Estimated allowable force (N rms)	Estimated subcomponent contribution to AO WFE (nm)	Subsystem aggregate allowable AO WFE impact (nm)
REQ-1-OAD-1132	Engineering Sensors (ESEN)		27.5	0.0	0.0	0.0
REQ-1-OAD-1133	Narrow Field Near Infrared On-Axis AO System (NFIRAOS)		7.6	1.0	7.6	7.6
REQ-1-OAD-1134	NFIRAOS Science Calibration Unit (NSCU)		7.6	0.0	0.0	0.0
REQ-1-OAD-1135	Laser Guide Star Facility (LGSF)					11.1
		Top-end	27.5	0.2	5.5	
		BTO	7.6	0.5	3.8	
		Lasers	3.9	0.5	1.9	
		Laser electronics	17.3	0.5	8.7	
REQ-1-OAD-1136	Communications and Information Systems (CIS)		7.6	0.5	3.8	3.8
	Instrumentation Cooling (CRYO/REFR)					
REQ-1-OAD-1137		Cryocooling	7.6	1.0	7.6	7.6
REQ-1-OAD-1197		Refrigerant cooling	7.6	1.0	7.6	7.6
REQ-1-OAD-1138	Infrared Imaging Spectrometer (IRIS)		7.6	0.5	3.8	3.8
REQ-1-OAD-1139	Wide Field Optical Spectrometer (WFOS)		7.6	0.8	6.1	6.1
REQ-1-OAD-1140	IRMS/MOSFIRE (IRMS)		7.6	0.5	3.8	3.8
	First Decade Instruments					**10.7**
REQ-1-OAD-1141	High Resolution Optical Spectrometer (HROS)		7.6	0.5	3.8	3.8
REQ-1-OAD-1142	Near-Infrared Multi-Object Spectrometer (IRMOS)		7.6	0.5	3.8	3.8
REQ-1-OAD-1143	Planet Formation Instrument (PFI)		7.6	0.5	3.8	3.8
REQ-1-OAD-1144	Mid-Infrared AO System (MIRAO)		7.6	0.5	3.8	3.8
REQ-1-OAD-1145	Mid-Infrared Echelle Spectrometer (MIRES)		7.6	0.5	3.8	3.8
REQ-1-OAD-1146	Near Infrared Echelle Spectrometer (NIRES-B)		7.6	0.5	3.8	3.8
REQ-1-OAD-1147	Near Infrared Echelle Spectrometer (NIRES-R)		7.6	0.5	3.8	3.8
REQ-1-OAD-1148	Wide-field Infrared Camera (WIRC)		7.6	0.5	3.8	3.8

Requirement Number	Subsystem	Subcomponent	Estimated sensitivity value (nm/N)	Estimated allowable force (N rms)	Estimated subcomponent contribution to AO WFE (nm)	Subsystem aggregate allowable AO WFE impact (nm)
	Within Enclosure					**10.8**
REQ-1-OAD-1149	Enclosure (ENC)		0.15	50.0	7.3	7.3
REQ-1-OAD-1150	Summit Facilities (SUM)		0.73	10.0	7.3	7.3
REQ-1-OAD-1151	Telescope structure (STR)		0.15	10.0	1.5	1.5
REQ-1-OAD-1152	Optical Cleaning Systems (CLN)		0.15	10.0	1.5	1.5
REQ-1-OAD-1153	Optical Coating System (COAT)		0.15	10.0	1.5	1.5
REQ-1-OAD-1154	Test Instruments (TINS)		0.15	1.0	0.1	0.1
REQ-1-OAD-1155	Optics Handling Equipment (HNDL)		0.15	10.0	1.5	1.5
REQ-1-OAD-1156	Test Instrument Control (TINC)		0.15	1.0	0.1	0.1
REQ-1-OAD-1157	Observatory Safety System (OSS)		0.15	1.0	0.1	0.1
REQ-1-OAD-1158	Engineering Sensors (ESEN)		0.15	10.0	1.5	1.5
REQ-1-OAD-1159	Communications and Information Systems (CIS)		0.15	1.0	0.1	0.1
	Inside Support Building					8.9
REQ-1-OAD-1160	Summit Facilities (SUM)		0.07	100.0	7.3	7.3
REQ-1-OAD-1161	Telescope structure (STR)		0.07	50.0	3.7	3.7
REQ-1-OAD-1162	M2 System (M2)		0.07	1.0	0.1	0.1
REQ-1-OAD-1163	M3 System (M3)		0.07	1.0	0.1	0.1
REQ-1-OAD-1164	Optical Cleaning Systems (CLN)		0.07	10.0	0.7	0.7
REQ-1-OAD-1165	Optical Coating System (COAT)		0.07	20.0	1.5	1.5
REQ-1-OAD-1166	Test Instruments (TINS)		0.07	5.0	0.4	0.4
REQ-1-OAD-1167	Optics Handling Equipment (HNDL)		0.07	1.0	0.1	0.1
REQ-1-OAD-1168	Alignment and Phasing System (APS)		0.07	5.0	0.4	0.4
REQ-1-OAD-1169	Telescope Control System (TCS)		0.07	5.0	0.4	0.4
REQ-1-OAD-1170	M1 Control System (M1CS)		0.07	5.0	0.4	0.4

Requirement Number	Subsystem	Subcomponent	Estimated sensitivity value (nm/N)	Estimated allowable force (N rms)	Estimated subcomponent contribution to AO WFE (nm)	Subsystem aggregate allowable AO WFE impact (nm)
REQ-1-OAD-1171	Test Instrument Control (TINC)		0.07	5.0	0.4	0.4
REQ-1-OAD-1172	Observatory Safety System (OSS)		0.07	5.0	0.4	0.4
REQ-1-OAD-1173	Engineering Sensors (ESEN)		0.07	5.0	0.4	0.4
REQ-1-OAD-1174	Narrow Field Near Infrared On-Axis AO System (NFIRAOS)		0.07	5.0	0.4	0.4
REQ-1-OAD-1175	NFIRAOS Science Calibration Unit (NSCU)		0.07	1.0	0.1	0.1
REQ-1-OAD-1176	Laser Guide Star Facility (LGSF)		0.07	10.0	0.7	0.7
REQ-1-OAD-1177	Adaptive Optics Executive Software (AOESW)		0.07	10.0	0.7	0.7
REQ-1-OAD-1178	Instrumentation Cryogenic Cooling (CRYO)		0.07	20.0	1.5	1.5
REQ-1-OAD-1198	Instrumentation Refrigerant Cooling (REFR)		0.07	20.0	1.5	1.5
REQ-1-OAD-1179	Infrared Imaging Spectrometer (IRIS)		0.07	5.0	0.4	0.4
REQ-1-OAD-1180	Wide Field Optical Spectrometer (WFOS)		0.07	5.0	0.4	0.4
REQ-1-OAD-1181	IRMS/MOSFIRE (IRMS)		0.07	5.0	0.4	0.4
REQ-1-OAD-1182	High Resolution Optical Spectrometer (HROS)		0.07	5.0	0.4	0.4
REQ-1-OAD-1183	Near-Infrared Multi-Object Sectrometer (IRMOS)		0.07	5.0	0.4	0.4
REQ-1-OAD-1184	Planet Formation Instrument (PFI)		0.07	5.0	0.4	0.4
REQ-1-OAD-1185	Mid-Infrared AO System (MIRAO)		0.07	5.0	0.4	0.4
REQ-1-OAD-1186	Mid-Infrared Echelle Spectrometer (MIRES)		0.07	5.0	0.4	0.4
REQ-1-OAD-1187	Near Infrared Echelle Spectrometer (NIRES-B)		0.07	5.0	0.4	0.4
REQ-1-OAD-1188	Near Infrared Echelle Spectrometer (NIRES-R)		0.07	5.0	0.4	0.4
REQ-1-OAD-1189	Wide-field Infrared Camera (WIRC)		0.07	5.0	0.4	0.4
REQ-1-OAD-1190	Communications and Information Systems (CIS)		0.07	5.0	0.4	0.4
REQ-1-OAD-1191	Common Software (CSW)		0.07	5.0	0.4	0.4
REQ-1-OAD-1192	Data Management System (DMS)		0.07	5.0	0.4	0.4
REQ-1-OAD-1193	Executive Software (ESW)		0.07	5.0	0.4	0.4
REQ-1-OAD-1194	Science Operations Support Systems (SOSS)		0.07	5.0	0.4	0.4
REQ-1-OAD-1195	Data Processing System (DPS)		0.07	5.0	0.4	0.4
REQ-1-OAD-1196	Site Conditions Monitoring System (SCMS)		0.07	5.0	0.4	0.4

3.9.3 M1S Warping Harness Stroke Budget

Discussion: 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: M1S Warping Harness Stroke Budget

Requirement Number	Effect	% Warping Harness Stroke Allocated
REQ-1-OAD-1980	M1 Polishing	20
REQ-1-OAD-1981	M1 segment installation errors	5
REQ-1-OAD-1982	Surface change due to coating stress	3
REQ-1-OAD-1983	Segment thermal distortion	2
REQ-1-OAD-1984	Segment assembly and manufacturing tolerances and errors	10
REQ-1-OAD-1991	Segment thermal clocking and translation errors	2
REQ-1-OAD-1986	M2 shape tolerances	7
REQ-1-OAD-1987	M2 low and mid frequency polishing errors	5
REQ-1-OAD-1988	M3 polishing errors	1
REQ-1-OAD-1989	Small Terms	3
	Contingency	42

4. SYSTEM SPECIFICATION

4.1 GENERAL SYSTEM REQUIREMENTS

4.1.1 Environmental and Lifetime Requirements

Discussion: 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.*

4.1.2 Environmental Requirements Applying to All Sub-systems

4.1.2.1.1 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.

4.1.2.1.2 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.

4.1.2.2 Environmental Conditions for Enclosure and other Unprotected Equipment

Discussion: "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'.

4.1.2.2.1 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.

4.1.2.2.2 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.

4.1.2.2.3 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.

4.1.2.2.4 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 AD10, wind speeds should be considered using the air density resulting from the lowest temperature and lowest pressure for the conditions.

4.1.2.2.5 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.

4.1.2.2.6 Lightning

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

4.1.2.2.7 Snow and Ice

4.1.2.2.7.1 Snow and Ice Operational Requirements

[REQ-1-OAD-1222] The Summit Facilities and Enclosure shall be fully operational with up to 150 kg/m^2 snow and ice load (vertical projection) after removal of ice and snow from critical areas.

4.1.2.2.7.2 Snow and Ice Survival Requirements

[REQ-1-OAD-1223] The Summit Facilities and Enclosure shall be able to support snow loads up to 150kg/m^2.

[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.

4.1.2.2.8 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.

4.1.2.3 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.

4.1.2.3.1 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.

4.1.2.3.2 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% values defined in *Table: 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 maximum level stated in *Table: Temporal Temperature Gradients Inside and Outside Enclosure*.

Table: Temporal Temperature Gradients Inside and Outside Enclosure

Integration time (minutes)	99.9% Conditions (°C/h)	Maximum (°C/h)
1	TBD	57.0
4	TBD	32.0
8	TBD	16.9
16	TBD	9.8
32	TBD	5.8
60	TBD	3.7

4.1.2.3.3 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-1221). 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

4.1.2.3.4 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: Wind speeds inside enclosure*.

Table: Wind speeds inside enclosure

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

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.

4.1.2.3.5 Humidity

[REQ-1-OAD-1238] The sub-systems inside the enclosure shall meet their Observing, Facility Performance, and Component Functional requirements when relative humidity is between 0 and 95% at temperatures between -10 to +13°C.

[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: Humidity data from MK shows that 100% humidity conditions occur between - 10 and +10°C.

4.1.2.3.6 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: Median dust levels at Mauna Kea Site*.

Table: 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 x 10^3	4.5 x 10^3	912	417	54	5.8 x 10^3
No. of particles/m^3	918 x 10^3	159 x 10^3	32 x 10^3	14.7 x 10^3	1.9 x 10^3	207 x 10^3

4.1.2.4 Environmental Requirements Inside Utility Room

[REQ-1-OAD-1251] The Summit Facilities Utility Room temperature shall be maintained between 0 and 30°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%.

4.1.2.5 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.

4.1.2.6 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°

4.1.2.7 Miscellaneous General Environmental Requirements

[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.

4.1.3 Other General Requirements

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

[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-1102] The telescope design shall support interchangeable conventional and adaptive secondary mirror subsystems.

*Discussion: The mass allowance for AM2 is contained in the mass budget ('*Table: - Mass Budget for Telescope Mounted Sub-systems *(RD21)' in section 3). The increased mass of the AM2 is not to be considered in the design of the M2 hexapod, it only affects the design of the telescope structure and the interface between the structure and the M2S It is not planned to mass load the top end to the higher number at first light - in the future, if the AOM2 is heavier than the conventional M2 cell assembly, counterbalance mass will be added to the lower tube.*

Discussion: APS is only expected to be able to perform limited alignment of AM2 due to the inability to distinguish between errors on M1 and M2.

[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

4.2.1 Optical Design

Discussion: The optical design flows from requirements in the ORD (RD34), and is documented in (AD17).

[REQ-1-OAD-1000] The telescope optical design shall be a Ritchey Chrétien (R-C) configuration. See '*Figure: Optical Configuration of the telescope* (AD17)' below.

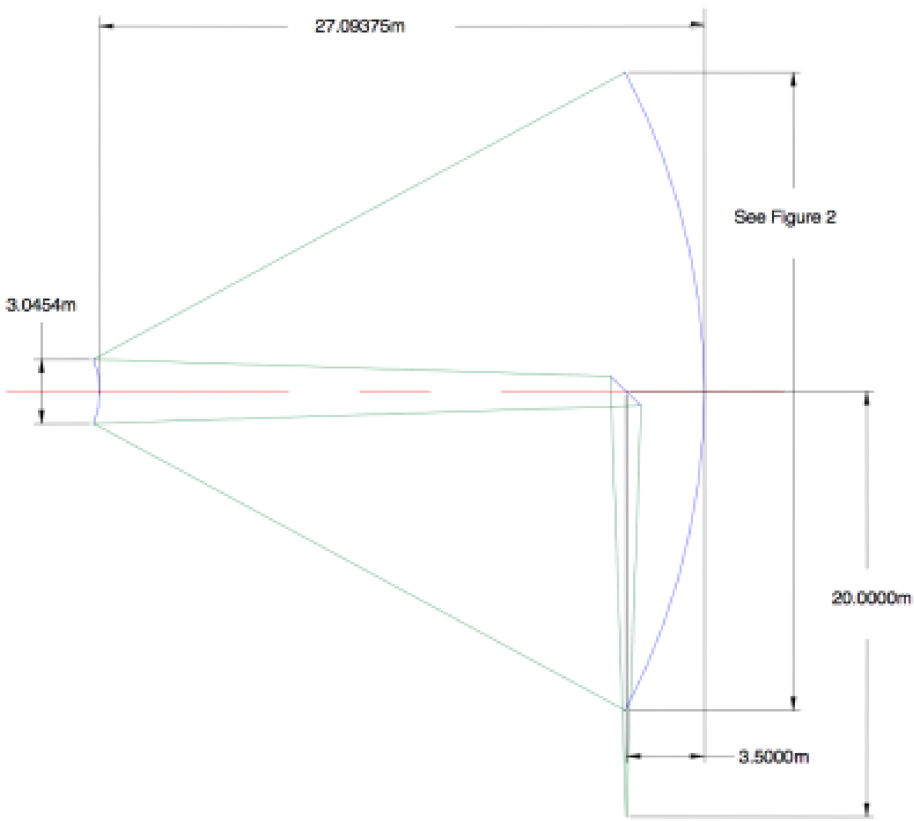


Figure: Optical Configuration of the telescope (AD17)

Discussion: The mirror spacings defined in the above figure are based on the optical design values and do not imply alignment tolerances.

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

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

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

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

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

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

[REQ-1-OAD-1025] Stray light control shall be provided 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 pupil obscuration pattern of the telescope shall be as shown in '*Figure: Pupil obscuration pattern* (AD41)' below. (TBR)

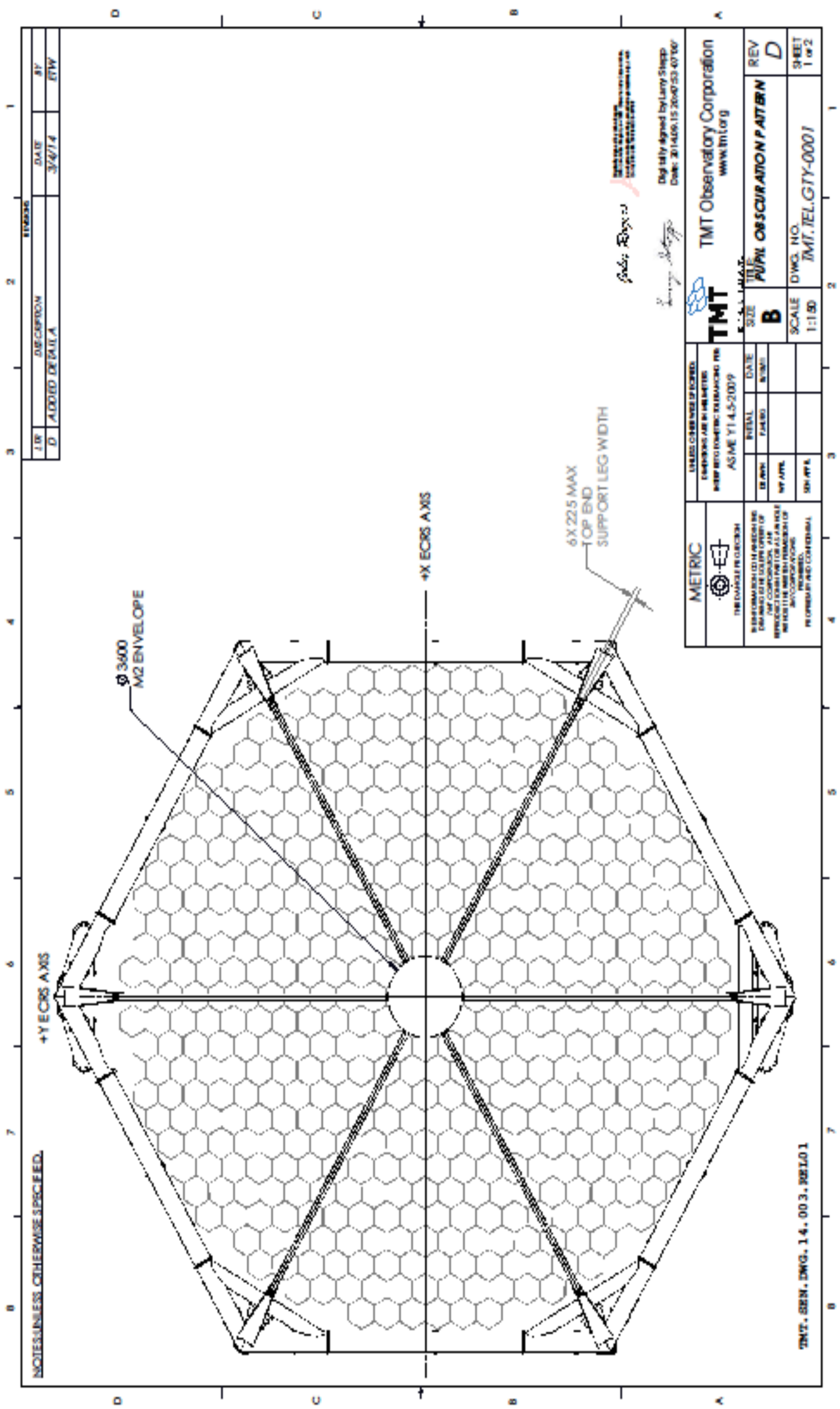


Figure: Pupil obscuration pattern (AD41) (page 1 of 2 is shown above)

Table: Summary of the optical design

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

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

4.2.2 Aerothermal Considerations

[REQ-1-OAD-1080] The transverse cross sectional area of the telescope above a plane perpendicular to the optical axis and 14.4m above the elevation axis shall be less than the values defined in the table below. The allocations to M2 and LGS 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: Maximum Allowable Cross Sectional Area of Telescope Top End

Requirement Number	**Sub-System**	**Maximum Transverse cross sectional area (m²)**	
REQ-1-OAD-1090	M2S	4.0	
REQ-1-OAD-1092	LGSF Top End	4.0	
REQ-1-OAD-1094	LGSF Beam Transfer Tube	6.0	
REQ-1-OAD-1096	Telescope Structure	Area projected onto ECRS XZ plane	Area projected onto ECRS YZ plane
		45.0	70.0

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

4.2.3 Telescope Structure

4.2.3.1 General

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

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

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

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

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

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

[REQ-1-OAD-1220] It shall be possible to position the telescope elevation axis at any zenith angle between 0 and 90 degrees.

Discussion: Other OAD requirements dictate the pointing accuracy required over the observing zenith angles. The accuracy of positioning outside these ranges is to be specified at the STR DRD level and in ICDs.

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

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

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

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

[REQ-1-OAD-1245] 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 above requirement in conjunction with [REQ-1-OAD-5150] ensure a 0.5m gap between the telescope and enclosure.

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

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

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

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

[REQ-1-OAD-1270] Except when observing or when necessary in servicing and maintenance mode, the telescope shall be parked in a horizon pointing orientation at an azimuth angle of 0 degrees in TCRS coordinates (pointing South).

Discussion: It may be desirable to vary this azimuth position slightly (+/-5 (TBC) 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-1280] The telescope structure shall be instrumented with temperature and wind speed sensors to enable configuration of the enclosure vents to manage the local seeing effects.

[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 equipment listed in '*Table: Sub-system equipment mounted to telescope structure (excluding instruments)*' below and instruments listed in '*Table: Instrument Volumes and Associated Electronics'* below [REQ-1-OAD-1425].

Table: Sub-system equipment mounted to telescope structure (excluding instruments)

Sub-System	Equipment	Location (see space envelope drawing for details)	Space Envelope Reference	Services Required*	Notes
M1 System	M1 segment, segment support, actuators and sensors	M1 Cell	TMT.TEL.OPT.M1S-ENV (AD43)	None	
M2 System	M2 Mirror and Positioner	Elevation Structure, top end	TMT.TEL.OPT.M2-ENV (AD44)	L1C	
	M2 Electronics	Elevation structure	TMT.TEL.OPT.M2.EL-ENV (AD45)	L1C Refrigerant	
M3 System	M3 Mirror and Positioner	Elevation Structure, M3 Support Tower	TMT.TEL.OPT.M3-ENV (AD46)	L1C	
	M3 Electronics	Elevation Structure, Mirror Cell	TMT.TEL.OPT.M3.EL-ENV (AD47)	L1C Refrigerant	
Test Instruments	Global Metrology System	Elevation Structure	TBD	L1C	
CRYO System	Compressors and Tanks	Azimuth Structure	TMT.INS.COOL.CRYO-ENV (AD89)	TBD	
M1 Control System	Node Boxes and associated equipment	Elevation Structure, Mirror Cell	Defined in ICD	L3CUG Compressed air	Compressed air distributed to sensors. Compressed air supply is responsibility of M1CS and is separate from supply to LGSF, NFIRAOS. Telescope to provide provision for routing only.
Laser Guide Star Facility	Laser System, Beam Transfer Optics and the Laser Launch Telescope System, and the Laser Safety System.	Elevation Structure, -X Laser Platform, Top End	TMT.INS.AO.LGSF.LGSF-ENV (AD88)	L3C, H3D, Fixed temperature water/glycol, L1C, Compressed air, Variable temperature water/glycol, refrigerant	

4.2.3.1.1 Seismic Accelerations

[REQ-1-OAD-1287] Under all operating conditions and configurations, the telescope structure shall limit the seismic accelerations transferred to the instruments and sub-systems which are mounted on it to the levels defined in '*Table: Seismic limits on telescope structure*' below:

Table: Seismic Limits on Telescope Structure

Subsystems	**Maximum Acceleration (g)**	
	200-year return period	1000-year return period
M1 System, LGSF Lasers	1.8	3.0
M2 System, LGSF Top End Equipment	3.0	5.0
M3 System	1.8	3.0
Science Instruments, NFIRAOS and APS	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).

Discussion: This requirement is intended to set a general requirement on the telescope structure that can be used for verification of the seismic performance. More detailed requirements for specific seismic loading of telescope mounted sub-systems 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).

Discussion: When actual 10-year return period time histories are not available for analysis, a factor of 0.28 can be 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.

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 in the azimuth coordinate reference system (ACRS).

Discussion: 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 azimuth coordinate reference 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-1295] The height of azimuth journal above ground shall be 3.5 meters.

[REQ-1-OAD-1297] A man lift shall be mounted on the azimuth structure to enable personnel to access to M3 mirror during removal 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-1305] Power and services shall be routed to the telescope elevation mounted systems through a trailing cable train located below the elevation axis.

[REQ-1-OAD-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.

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

[REQ-1-OAD-1321] The maximum deflections of the interface planes between the telescope and the M2S and LGSF laser launch telescope shall not exceed the values given in '*Table: 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: Maximum allowable deflection of the telescope top end

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

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

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

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

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

[REQ-1-OAD-1334] A fixed walkway with outside radius not exceeding 20.4m shall be provided around the perimeter of the telescope pier.

[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.

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

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

[REQ-1-OAD-1345] The cable wraps 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 (RD13).

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

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

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

[REQ-1-OAD-1360] The cable wrap system shall implement sufficient monitoring to detect faults and potentially hazardous conditions and shall communicate these to the OSS via interlock request signals.

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

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

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

4.2.3.6 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: 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.*

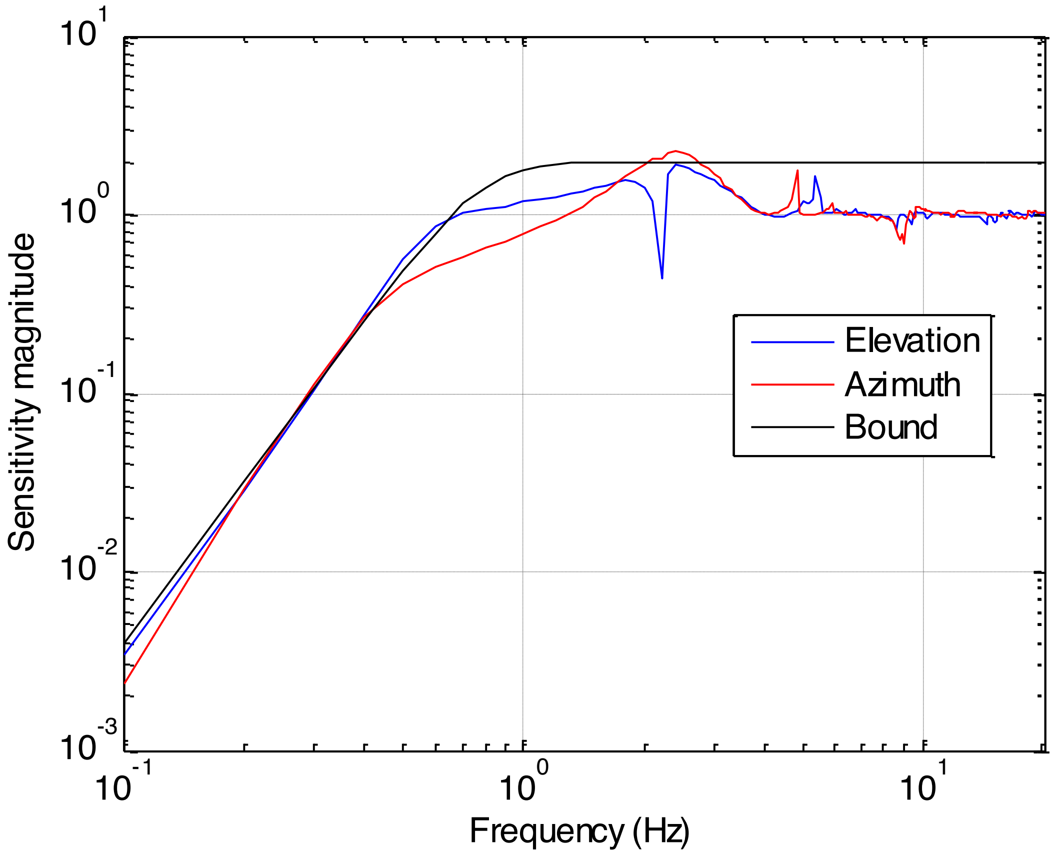


Figure: Bound on mount control torque rejection with respect to open-loop. The mount control rejection achieved with the current design is shown for comparison.

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) & Adaptive Optics (AO)

4.2.3.6.3.1 Accuracy Allocation

Discussion: 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: Sub-allocation of accuracy requirements for Seeing Limited Acquisition and Guider Offsets:

Requirement Number	Move Distance	Mode	Telescope Accuracy	M3 Allocation	STR Azimuth Allocation	STR Elevation Allocation
REQ-1-OAD-1113	< 10 arcseconds	Guider	0.05 arcsec RMS	0.0 arcsec RMS (0% in RSS)	0.041 arcsec RMS (2/3 in RSS)	0.029 arcsec RMS (1/3 in RSS)
REQ-1-OAD-1101	>= 10, <=30 arcseconds	Guider	0.05 arcsec RMS	0.035 arcsec RMS (50% in RSS)	0.027 arcsec RMS (30% in RSS)	0.022 arcsec RMS (20% in RSS)
REQ-1-OAD-1114	Up to 0.1 degree	Offset (no Guider)	0.5 arcsec RMS	0.354 arcsec RMS (1/2 in RSS)	0.289 arcsec RMS (1/3 in RSS)	0.204 arcsec RMS (1/6 in RSS)
REQ-1-OAD-1103	Up to 1.0 degree	Offset (no Guider)	0.5 arcsec RMS	0.354 arcsec RMS (1/2 in RSS)	0.289 arcsec RMS (1/3 in RSS)	0.204 arcsec RMS (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 M3 mirror shall not be moved during offsets of 10 arc-seconds or less on the sky.

4.2.3.6.3.2 Time to Move

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

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

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: Allowable image jitter as seen by an instrument mounted on the Nasmyth Platform*' below.

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

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

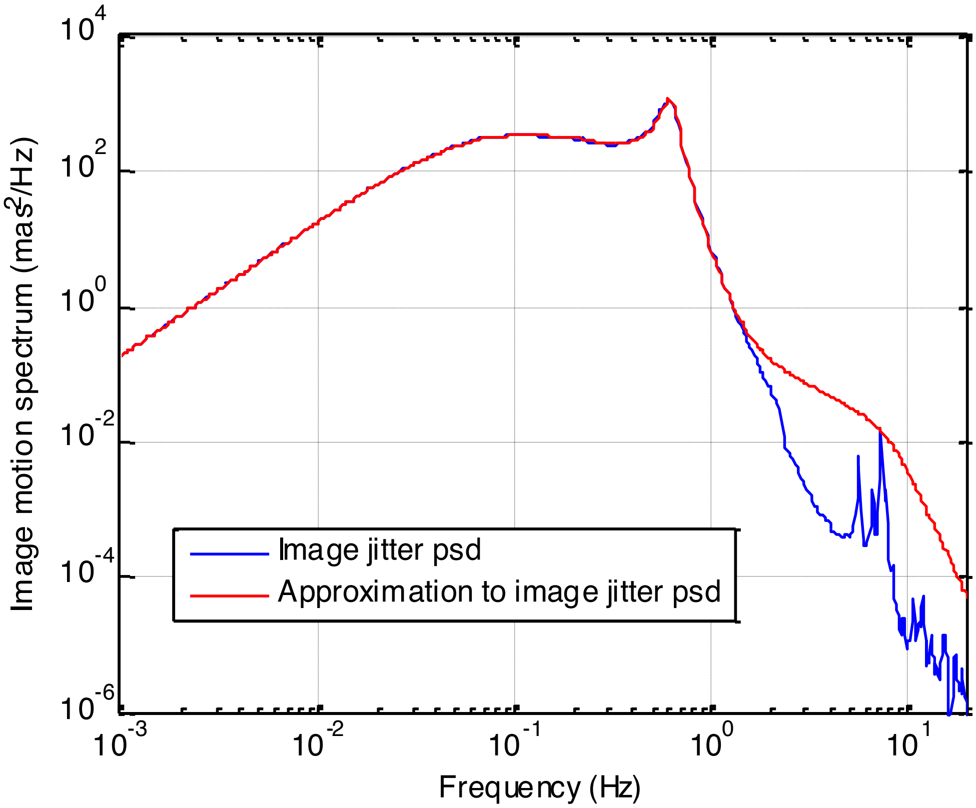


Figure: Allowable image jitter as seen by an instrument mounted on the Nasmyth Platform

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

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

where k is chosen to scale the overall amplitude. For the 75th percentile wind and upwind (0° azimuth, 30° zenith) orientation used to generate the above spectrum, then f_0 = 0.105 Hz, f_1 = 0.625 Hz, f_2 = 1.5 Hz, f_3 = 8 Hz and 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 90mas 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 'Figure: Pupil Obscuration Pattern'.

[REQ-1-OAD-1398] The STR 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.

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

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

[REQ-1-OAD-1410] At early light, the Nasmyth Platforms shall provide support for the following instruments as defined in the ORD (RD34), each at their own foci: NFIRAOS with the NSCU, feeding IRIS and IRMS, at the 174.5 degree position on the -X platform, WFOS at the 0 degree position on the +X platform, and APS at the 180 degree position on-axis and beside NFIRAOS. The location of these instruments is shown in '*Figure: Nasmyth Platform Reference Instrument Layout (NFIRAOS, IRIS, IRMS and APS at left, WFOS at right) (RD25)*' later in this section.

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 counter clockwise as viewed from above.

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

[REQ-1-OAD-1415] The Nasmyth Platforms shall be designed to be upgradeable to additionally support the following second and future generation instruments, as defined in the ORD (RD34), each at their own foci and with their required field of view: IRMOS, MIRES, PFI, NIRES, HROS, and WIRC.

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

*Discussion: The instrument locations for the full SAC instrument suite (early light plus future instrumentation) on the Nasmyth Platforms shall be as shown in '*Figure: Full SAC Instrument Layout *(RD24)' in the Appendix (Section 7.4).*

[REQ-1-OAD-1425] Instruments shall not exceed the volumes, and shall meet the focal plane position requirements listed in '*Table: Instrument Volumes and Associated Electronics' below*.

*Discussion: These volumes and focal plane positions are required to meet the instrument arrangement as shown in '*Figure: Nasmyth Platform Reference Instrument Layout (NFIRAOS, IRIS, IRMS and APS at left, WFOS at right) (RD25)'*' later in this section.*

Table: Instrument Volumes and Associated Electronics

Instrument	Space Envelope Definition					Notes
	Shape	Width or Dia (m)	Height (m)	Depth (m)	Focal Plane Position	
APS	See drawing TMT.TEL.CONT.APS-ENV (AD54)					
APS Electronics	See drawing TMT.TEL.CONT.APS.EL-ENV (AD55)					
HROS	See drawing TMT.INS.HROS-ENV (AD65)					
IRIS	See drawing TMT.INS.INST.IRIS-ENV (AD56)					Mounted on NFIRAOS bottom port
IRIS Electronics	See drawing TMT.INS.INST.IRIS.EL-ENV (AD57)					
IRMOS	See drawing TMT.INS.INST.IRMOS-ENV (AD58)					
IRMS	See drawing TMT.INS.INST.IRMS-ENV (AD59)					Mounted on NFIRAOS top port. Dimensions based on Keck Mosfire requirements. No separate allocation for electronics
MIRAO	See drawing TMT.INS.INST.MIRAO-ENV (AD60)					
MIRES	See drawing TMT.INS.INST.MIRES-ENV (AD61)					
NFIRAOS	See drawing TMT.INS.AO.NFIRAOS-ENV (AD62)					
NFIRAOS Electronics	See drawing TMT.INS.AO.NFIRAOS.EL-ENV (AD63)					
NIRES-B	See drawing TMT.INS.INST.NIRESB-ENV (AD64)					Mounted on NFIRAOS side port
NIRES-R	Cylinder	1	1.5		0.5m inside, on axis	Fed by MIRAO
NSCU	See drawing TMT.INS.NSCU-ENV (AD66)					
PFI	See drawing TMT.INS.INST.PFI-ENV (AD67)					
WIRC	Cylinder	2		3.7	Focal plane position as per that defined for IRIS	Mounted on NFIRAOS top port. Volume doesn't include protrusion into NFIRAOS
WFOS	See drawing TMT.INS.INST.WFOS-ENV (AD68)					
WFOS Electronics	See drawing TMT.INS.INST.WFOS.EL-ENV (AD69)					

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 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] One or more elevators shall be provided to lift personnel and pieces of equipment up to 1.5 x 1.5 x 1.5 m and 500 kg to the Nasmyth platforms.

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

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

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

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

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

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

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

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

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

Discussion: Crane and hoist working volumes are defined in Section 4.6.1 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 provide a pathway at the Nasmyth platform level, at least 1.5 m wide and 2.5 m high, for personnel and equipment to transit between the +Y and -Y ends of the Nasmyth areas.

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

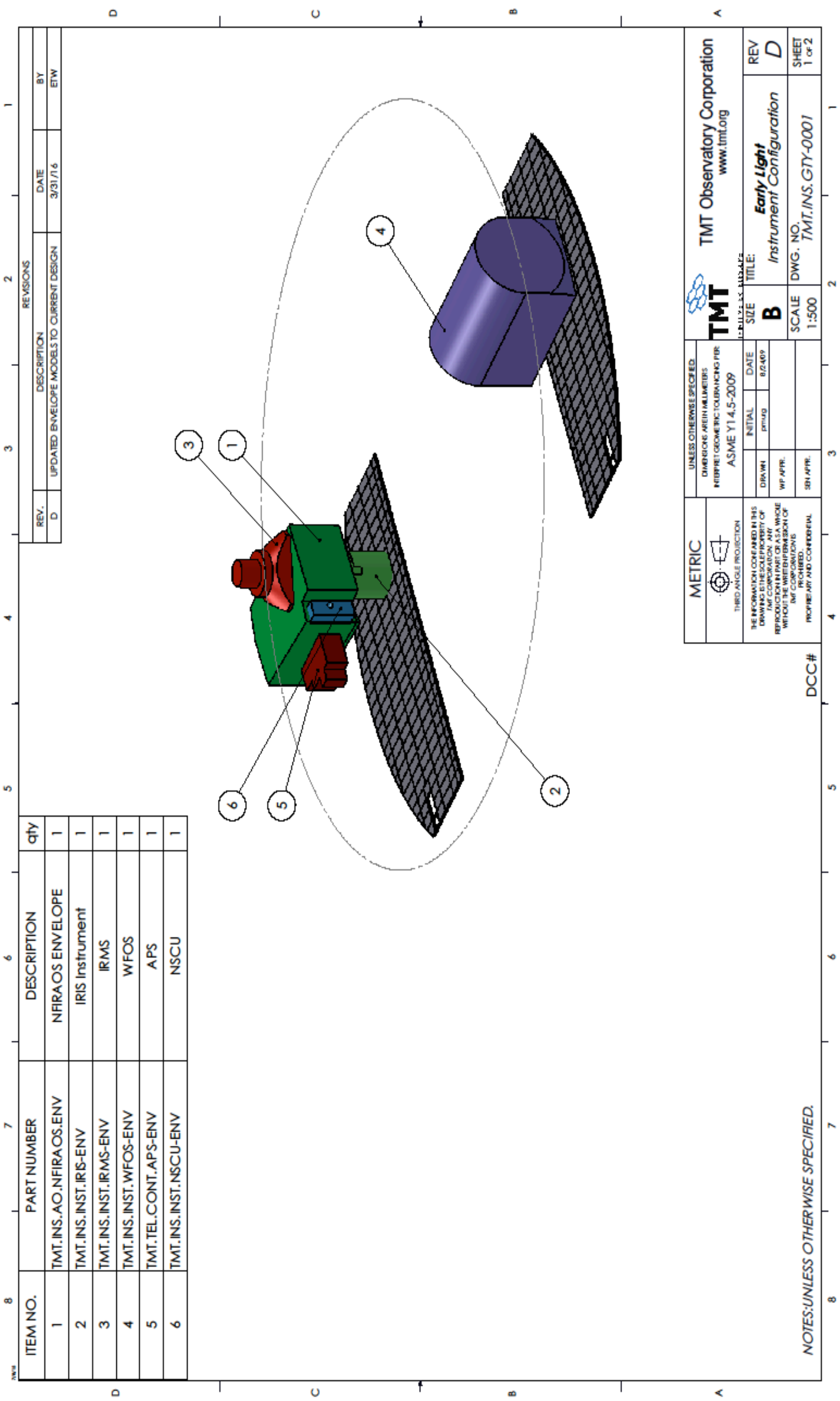


Figure: Nasmyth Platform Reference Instrument Layout (NFIRAOS, IRIS, IRMS and APS at left, WFOS at right) (RD25)

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 must be provided between the -X and +X Nasmyth platforms. The walkway must be accessible at all telescope elevation angles.

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

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

4.2.3.7.8 Instrument Handling, Installation and Removal

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

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

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

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

[REQ-1-OAD-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 the figure below to be lifted from the floor to the Nasmyth platforms.

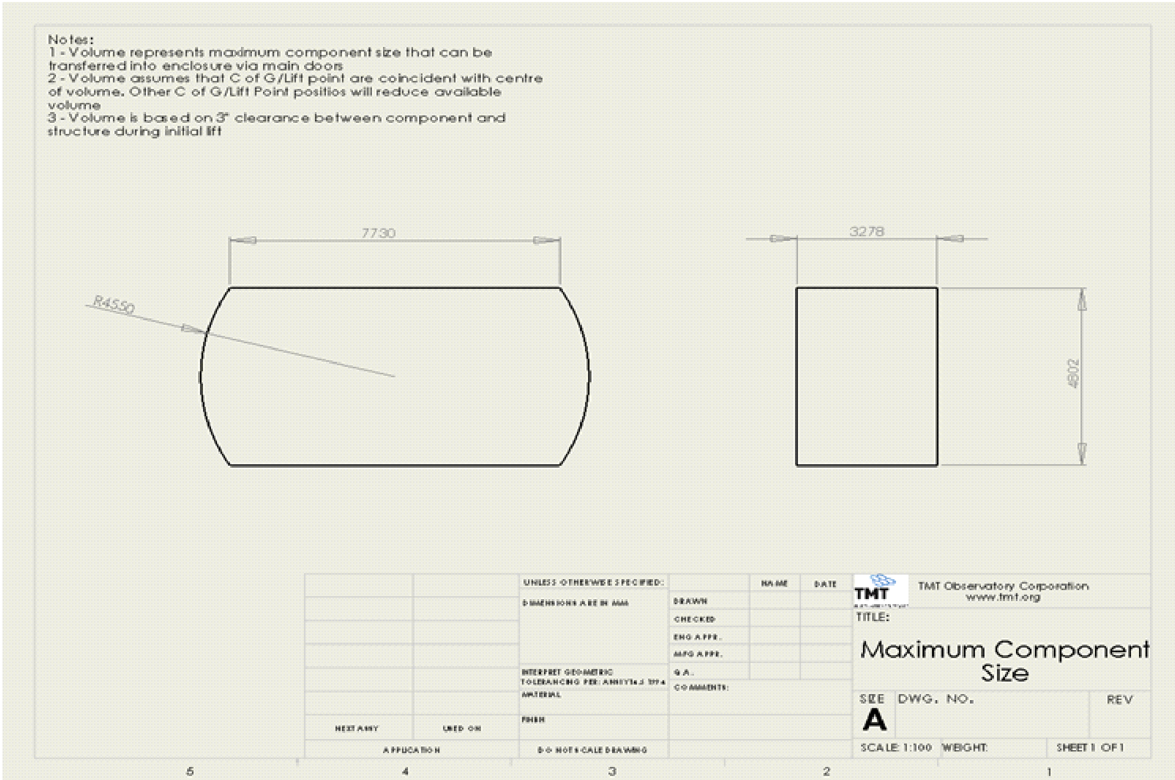


Figure: Maximum component size to be lifted from enclosure floor to Nasmyth Platform

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

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

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

4.2.3.7.9 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-1575] As a goal, a personnel refuge and rest area shall be provided on each of the +X and -X Nasmyth platforms.

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

Discussion: See [REQ-1-ORD-7005] for the hierarchy of allowable safety system precedence. This requirement states that safety must be achieved by either item 1 or 2 of this requirement, and that achieving safety through warning devices, or procedures and training (items 3 or 4 of the ORD requirement (RD34)) is not acceptable. For example, this prohibits the elevator from sweeping out an area of the observing floor at a level that could crush a person against portable equipment that might be placed there. The elevator is a high use item that has the potential of a high risk to personnel safety, so an extremely safe system is required.

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

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

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

[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 M1 segment handling system (M1 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 SHS 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 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. This process is described in RDTBD.

[REQ-1-OAD-1612] The M1 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 M1 SHS shall enable the installation and removal of any 10 primary mirror segments per 10-hour day.

[REQ-1-OAD-1618] The M1 SHS duty cycle includes 2000 installation or removal operations during construction, 10 routine segment exchanges during a single 8 hour day, once every two weeks for fifty years (13,000 segment exchanges), and a proof test (at two times rated load) every six months for 50 years.

[REQ-1-OAD-1620] The M1 SHS shall be able to access, install and remove any of the 492 segments in the primary mirror.

[REQ-1-OAD-1622] The M1 SHS shall be placed in a stowed position when the telescope is used for observing. In its stowed position, no component of the M1 SHS shall vignette the field of view of any of the science instruments.

[REQ-1-OAD-1624] In its stowed position, the M1 SHS shall not increase the obscuration of the telescope aperture by more than 2 square meters, evaluated for any point in a telescope field of view of 30 arcseconds radius.

> *Discussion: In determining the increase in obscuration it is possible to hide portions of the M1 SHS below the secondary mirror support legs. Non-symmetrical spokes on the secondary mirror support system will cause a more complex diffraction pattern. This specification should be followed-up with image analysis to make sure that the result doesn't adversely affect the telescope performance.*

[REQ-1-OAD-1626] Any increase in obscuration of the telescope aperture by the stowed M1 SHS shall have a simple geometry that can be easily masked in an instrument pupil plane, and should avoid obscuring the edges of segments as viewed by the alignment and phasing system.

[REQ-1-OAD-1628] In its stowed position, the M1 SHS shall not produce any acoustic noise or structural vibration when the telescope zenith angle varies from -1 to 90 degrees.

> *Discussion: For example, any cables must be tensioned so they do not sway or rattle, and any joints within the mechanisms must be preloaded to prevent transient vibration as the gravity vector changes.*

[REQ-1-OAD-1630] The M1 SHS shall enable MSAs to be raised and lowered directly to a segment handling cart on the observatory floor.

[REQ-1-OAD-1632] The M1 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 M1 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.*

[REQ-1-OAD-1636] If the M1 SHS is stowed when an earthquake up to the level of a very infrequent earthquake occurs, the M1 SHS shall not damage any telescope mirror or any science instrument.

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

[REQ-1-OAD-1639] If the M1 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 M1 SHS shall not allow damage to the MSA being moved.

[REQ-1-OAD-1640] The M1 SHS shall strictly minimize any contaminants which might be deposited onto the surface of the primary mirror or tertiary mirror, including dust, debris or 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 in a dusty environment.*

[REQ-1-OAD-1641] In its stowed position, the M1 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 M1 segment handling system (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 SHS should minimize the potential damage to the segment which is in the process of being engaged during a seismic condition or operational failure.

4.2.4 Telescope Mirror Optical Coating Requirements

Discussion: 'Table: 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. These requirements are based on what is achievable with existing coatings (see example coating plots in the Appendix 7.5).*

Table: Requirements for M1, M2 and M3 Optical Coatings

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

4.2.5 M1 Optics System

4.2.5.1 General

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

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

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

[REQ-1-OAD-1655] The optical surfaces of the M1 segments shall have a smooth specular surface finish that scatters less than 0.15 % of the light at the shortest observing wavelength specified in Section 3.3.2 of the ORD (RD34).

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

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

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

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

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

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

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

[REQ-1-OAD-1685] The segment and the portions of the SSA that will stay with it in the coating chamber 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-0418] for periods of at least 30 days without updates from the APS.

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

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

4.2.5.2 Segmentation

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

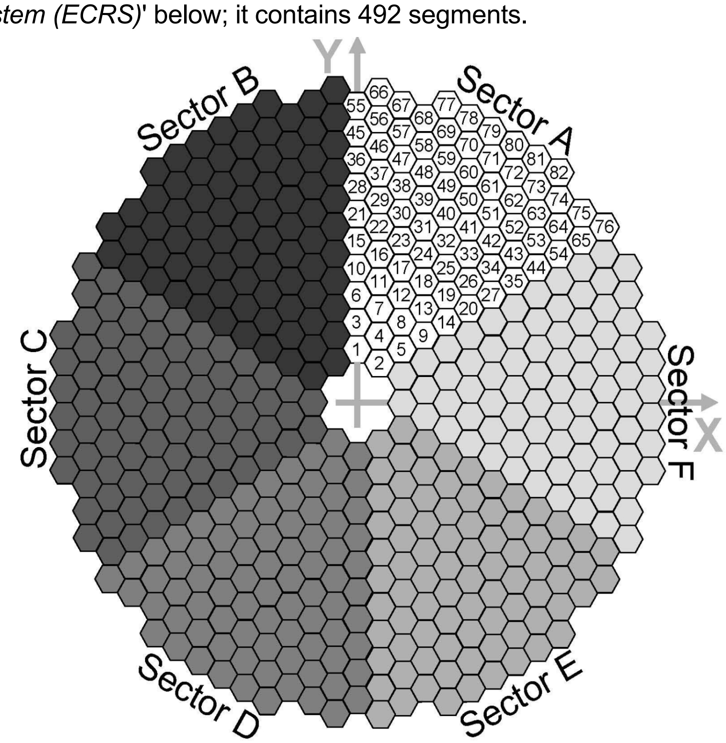


Figure: Layout of the segmented primary mirror, as projected on the X-Y plane of the Elevation Coordinate System (ECRS). The capital letters denote identical sectors rotated by 60 degrees relative to each other.

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

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

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

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

[REQ-1-OAD-1720] The primary segment assembly shall be compatible with an actuator stroke range as specified in [REQ-1-OAD-0808].

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

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

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

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

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

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

Case	Temperature	No. Failed Actuators	Earthquake	Zenith Angle
Nominal Operation	2°C	0	No	All
Low temp, failed actuator	-14°C	1	No	All
Survival Low temperature	-18°C	0	No	All
10 year earthquake	-5°C	1	10 year	All
200 year earthquake	-5°C	0	200 year	All
1000 year earthquake	-5°C	0	1000 year	All
Jacking	-5°C	0	No	Zenith Pointing

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

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

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

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-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).

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

4.2.5.3 Positioning

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

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

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

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

4.2.6 M2 System

4.2.6.1 General

[REQ-1-OAD-1805] The M2 System shall be designed to be compatible with the Laser Launch Telescope. No component of the M2 Assembly shall extend beyond a plane perpendicular to the M1 optical axis located 1.6 meters behind the vertex of the M2.

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

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

4.2.6.2 Removal, Cleaning and Coating

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

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

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

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

4.2.6.3 Control

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

[REQ-1-OAD-1860] In addition to any other motion requirements, the mechanical range of motion of the M2 system shall be sufficient to accommodate any combination of the telescope top end deflections as specified in '*Table: Maximum allowable deflection of the telescope top end*' below requirement [REQ-1-OAD-1321].

[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-1890] The M2 System shall include a low level control system to control the M2 positioner. The M2 positioner control system shall be able to operate successfully in the absence of the M2 Cell Assembly, for example, when the conventional M2 has been replaced with an adaptive M2.

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

4.2.6.4 Optical Quality

[REQ-1-OAD-1910] The optical surface of the secondary mirror shall have a smooth specular surface finish that scatters less than 0.15 % of the light at the shortest observing wavelength specified in Section 3.3.2 of the ORD (RD34).

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

4.2.7 M3 System

4.2.7.1 General

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

Discussion: The intersection of the M3 rotation and tilt axes is coincident with the intersection of the telescope elevation and azimuth axes.

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

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

[REQ-1-OAD-1958] During specific servicing operations, it shall be possible to lock M3 into a configuration that ensures all components are within the 'SHS deployment' volume defined in TMT.TEL.OPT.M3-ENV (AD46).

Discussion: This configuration will be used during deployment and operation of the SHS bridge and is required to prevent any collision between SHS equipment and M3.

4.2.7.2 Removal, Cleaning and Coating

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

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

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

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

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

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

[REQ-1-OAD-1995] The M3 assembly shall be serviceable 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. The cable wraps shall leave adequate room for this access.

4.2.7.3 Control

[REQ-1-OAD-2000] The M3 System shall provide two degree of freedom motion of the tertiary mirror relative to the telescope structure. The required mechanical range of motion shall be sufficient to redirect a beam of light from the secondary mirror towards the Nasmyth platform instrument locations as shown in '*Figure: Nasmyth positions addressed by the M3 mirror (ECRS axes shown with telescope zenith pointing)*' below. 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.

Discussion: The location of the HROS focal plane and optical feed is currently under study (RD26). The resulting position may lie above the plane described above.

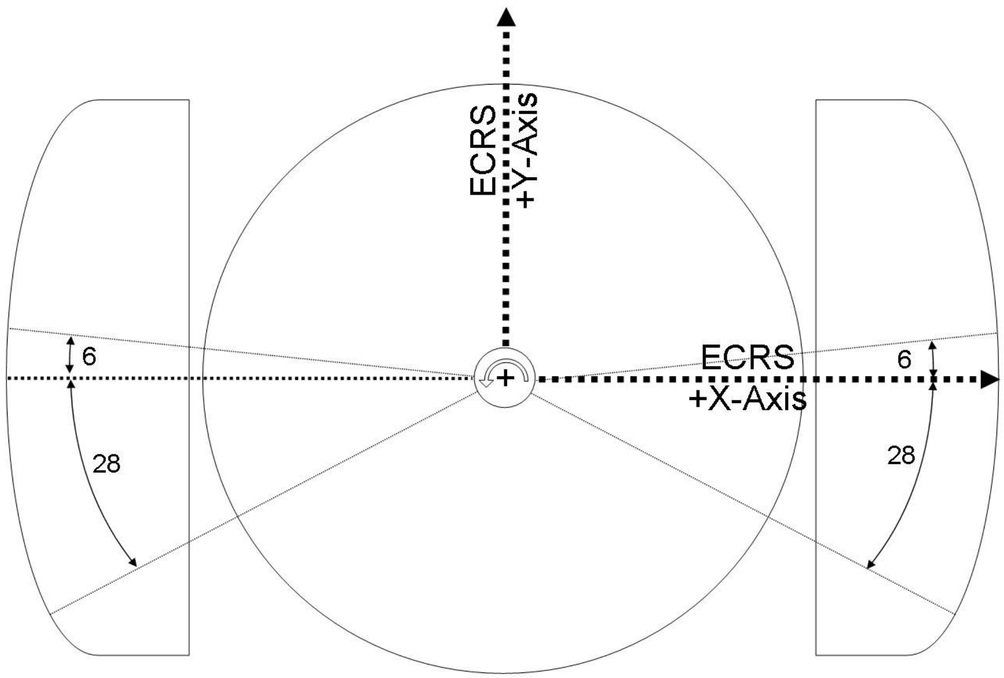


Figure: Nasmyth positions addressed by the M3 mirror (ECRS axes shown with telescope zenith pointing)

[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.

[REQ-1-OAD-2050] The M3 System shall include a low level control system to control the M3 positioner. The M3 positioner control system shall be able to operate successfully in the absence of the M3 Cell Assembly.

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

4.2.7.4 Optical Quality

[REQ-1-OAD-2070] The optical surface of the tertiary mirror shall have a smooth specular surface finish that scatters less than 0.15% of the light at the shortest observing wavelength specified in Section 3.3.2 of the ORD (RD34).

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. The allowable image motion and image blur on M1 due to wind is addressed in section TBD. 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)

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

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

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

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

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

[REQ-1-OAD-2210] The APS shall provide a location for mounting a Low Order Wavefront Sensor (LOWFS), similar in functionality to the one used in the seeing limited instruments.

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

[REQ-1-OAD-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 position the pupil using M3 tip and tilt to an accuracy of TBD% of diameter of the pupil.

[REQ-1-OAD-2255] In alignment maintenance mode the initial M1, M2 and M3 optics shall not exceed the error shown in '*Table: Alignment maintenance mode capture range*' below.

Table: Alignment maintenance mode capture range

	Optical Element	Maximum Error	Units
[REQ-1-OAD-2260]	M1 segment tip/tilt	+/- 1	arcseconds in one dimension on the sky
[REQ-1-OAD-2262]	M1 segment piston	+/- 110	nm (surface)
[REQ-1-OAD-2264]	M1 surface shape	+/- 0.25	arcseconds relative in one dimension on the sky between Shack-Hartmann subapertures 20cm apart.
[REQ-1-OAD-2266]	M2 tip/tilt	+/- 30	arcseconds in one dimension on the sky
[REQ-1-OAD-2268]	M2 piston	+/- 2	mm (surface)
[REQ-1-OAD-2270]	M2 X/Y decenter	+/- 100	microns
[REQ-1-OAD-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 Observatory System shall meet all performance requirements for periods of no less than four weeks without calibration by the APS.

[REQ-1-OAD-2285] In post-segment exchange mode the initial M1, M2 and M3 optics shall not exceed the error shown in 'Table: Post-segment exchange mode capture range' below.

Table: Post-segment exchange mode capture range

	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 on-axis alignment in less than 120 minutes when all optics are within the post-segment exchange specifications.

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

[REQ-1-OAD-9821] The TMT software system shall be capable of transporting an APS technical data stream at a rate of 100 MBytes (100 MB) per second for a 5 second burst, every 30 seconds.

Discussion: Technical data needs further definition, including definition of the wavefront sensor image data stream. This is a very specific requirement; it is acknowledged that there is a broader set of requirements that need to be added in the future.

4.2.10 Servicing and Maintenance

4.2.10.1 Telescope Structure

[REQ-1-OAD-2400] The telescope structure shall be designed to be consistent with the servicing and replacement intervals and scenarios shown in '*Table: Telescope structure Servicing Requirements*' below.

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

Table: Telescope structure Servicing Requirements

TBD

4.2.10.2 Telescope Optics

[REQ-1-OAD-2500] The telescope optics shall be designed to be consistent with the servicing and replacement intervals and scenarios shown in '*Table: Telescope Optics Servicing Requirements' below*.

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

Table: Telescope Optics Servicing Requirements

TBD

4.2.10.3 Telescope Controls

[REQ-1-OAD-2600] The telescope controls shall be designed to be consistent with the servicing and replacement intervals and scenarios shown in '*Table: Telescope Controls Servicing Requirements*' below.

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

Table: Telescope Controls Servicing Requirements

TBD

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 (TBC) arcseconds RMS.

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

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

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

[REQ-1-OAD-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 and science instruments (specifically NFIRAOS, NSCU, IRIS, IRMS, 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.

4.3.2 Facility AO System

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

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

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

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

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

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

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

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

[REQ-1-OAD-2745] The facility AO system shall be upgradeable to meet all of the specifications for the narrow- and moderate-field AO systems as listed in the ORD (RD34).

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

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

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

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

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

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

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

[REQ-1-OAD-2765] The facility AO system shall operate off-null in order to compensate non-common path aberrations in science instruments, with a maximum offset of 0.350 arcsec slope on each wavefront sensing subaperture.

[REQ-1-OAD-2766] The worst case defined in [REQ-1-OAD-2766] for slope errors in the non-common path wavefront between the LGS WFS and the Science Instrument shall be as defined in '*Table: Non-common path slope error allocation' below*.

Table: Non-common path slope error allocation

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

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

4.3.3 NFIRAOS

4.3.3.1 General

[REQ-1-OAD-2800] NFIRAOS AO system shall have 2 deformable mirrors conjugate to 0 km and 11.2 km.

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

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

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

[REQ-1-OAD-2811] The NFIRAOS System throughput shall exceed 60% over 0.84 to 1.0 microns and 80% over the 1.0-2.4 micron wavelength range.

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

[REQ-1-OAD-2822] NFIRAOS shall provide a common mechanical, thermal and optical interface at each of its three instrument interface ports.

[REQ-1-OAD-2823] NFIRAOS shall be designed to accommodate instruments with a mass of up to 6800kg at any of its three instrument interface ports.

Discussion: The intent of these requirements is to allow any on the NFIRAOS client instruments to be mounted to any of the three output ports without significant modification to either NFIRAOS or the instrument. 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-2825] NFIRAOS System shall be designed to be upgradeable to a higher order AO system that interfaces to a wider-field near infra-red science instruments.

Discussion: The early light implementation of NFIRAOS provides acceptable image quality for the early light adaptive optics instrument suite, IRIS and IRMS. However, an upgrade of this instrument will be required to meet the full SRD (RD33) performance requirements for these two instruments and additional first decade instrumentation.

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

[REQ-1-OAD-2842] Night time calibration of NFIRAOS shall consume no more than 0.7% of its scheduled observing time.

4.3.3.2 Servicing and Maintenance

[REQ-1-OAD-2845] NFIRAOS shall be designed to be consistent with the servicing and replacement intervals and scenarios shown in '*Table: NFIRAOS Servicing Requirements*' below.

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

Table: NFIRAOS Servicing Requirements

TBD

4.3.4 LGSF

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

[REQ-1-OAD-2905]The LGSF shall project NFIRAOS asterism and be upgradeable to other asterisms as required by the AO modes described herein with up to 9 LGS and radii varying from 5 arcsec to 450 arcsec (TBC) as shown in '*Figure: LGSF asterisms supporting different AO modes*' below. As a goal, this functionality shall be available at early light.

*Discussion: The asterisms for the early light and first decade AO systems have been defined and are summarized in '*Figure: LGSF asterisms supporting different AO modes*' below:*

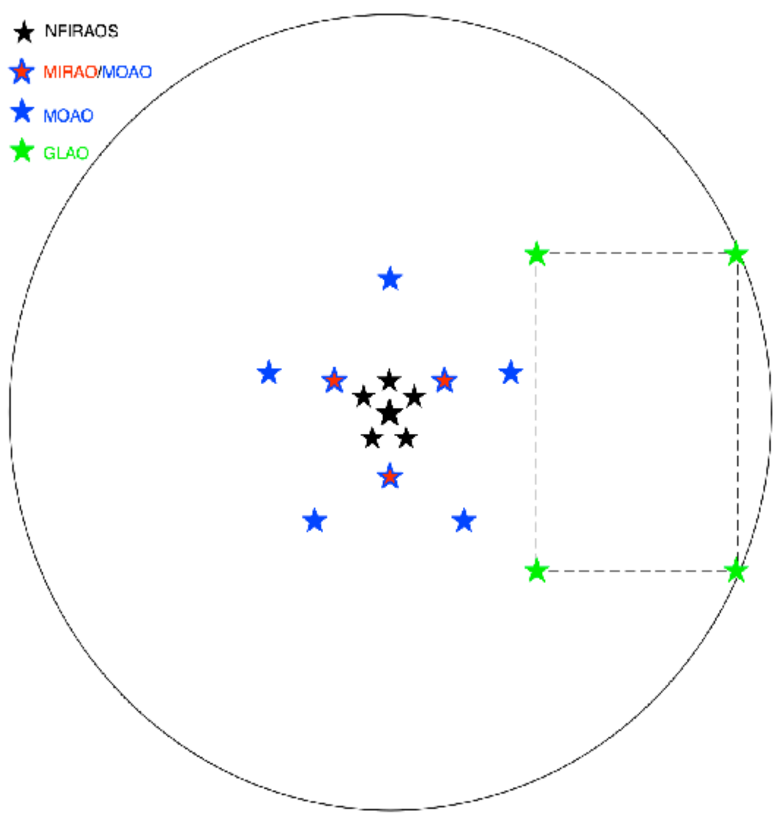


*Figure: LGSF asterisms supporting different AO modes: **NFIRAOS** (black) 1 on axis, 5 on a 35 arcsec radius; **MIRAO** (red) 3 on a 70 arcsec radius; **MOAO** (blue) 3 on a 70 arcsec radius, 5 on a 150 arcsec radius; **GLAO** (green) 4 on a 240 arcsec by 360 arcsec rectangle offset by 288 arcsec (TBC).*

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

[REQ-1-OAD-2915] The baseline LGSF shall generate Laser Guide Stars with a signal level and image quality consistent with the first light NFIRAOS wavefront error budget defined in section 3.4.1

Discussion: NFIRAOS first light system will deliver images with an RMS wavefront error of 187 nm on axis, 191nm over a 17"x17" FOV, 203nm over a 30" diameter FOV. Based on current modeling, a total laser power of 150 W or 120W with D2b repumping is appropriate to satisfy the NFIRAOS error budget during times with low sodium column density, i.e. 25 W (or 20W) per beacon. This signal level may be reduced by ~65% if a laser pulse format that enables dynamic refocusing (in order to eliminate LGS elongation) is utilized.

[REQ-1-OAD-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 589nm solid state lasers with either a continuous wave (CW) or mode locked CW pulse format.

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

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

[REQ-1-OAD-2937] In addition to any other motion requirements, the LGSF shall be capable of correcting for any combination of the deflections at the telescope top end as specified in '*Table: Maximum allowable deflection of Telescope Top end*' below [REQ-1-OAD-1321].

[REQ-1-OAD-2940] The Laser System of the early light LGSF system shall be mounted on the inside of the -X ECRS elevation journal.

[REQ-1-OAD-2941] Space shall be provided 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 early light and future 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. 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 as defined in TMT.INS.AO.LGSF.LGSF-ENV (AD88).

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

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

[REQ-1-OAD-2955] The LGSF system shall be upgradeable to provide Laser Guide Stars with the signal level and image quality consistent with the wavefront error budget of an upgraded version of NFIRAOS as defined in the ORD (RD34).

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] Night time calibration of the LGSF shall consume no more than 0.3% of its scheduled observing time.

4.3.4.1 Servicing and Maintenance

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

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

Table: LGSF Servicing Requirements

TBD

[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.

4.3.5 Adaptive Optics Executive Software (AOESW)

4.3.5.1 General

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

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

[REQ-1-OAD-3005] The AO Sequencer shall be upgradeable to control the first decade AO system upgrades as defined in the ORD (RD34).

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

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

Discussion: This corresponds to the "offload router" functionality described in section 3.1.4.

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

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

4.3.5.2 Servicing and Maintenance

[REQ-1-OAD-3050] The AOESW shall be designed to be consistent with the servicing and replacement intervals and scenarios shown in '*Table: AOESW Servicing Requirements*' below.

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

Table: AOESW Servicing Requirements

TBD

4.3.6 IRIS

4.3.6.1 General

[REQ-1-OAD-3060] IRIS shall provide diffraction-limited moderate spectral resolution (~ R=4000) NIR spectra using an integral field unit (IFU), and images over a small field of view.

[REQ-1-OAD-3061] IRIS shall allow simultaneous operation of the imager and spectrograph.

Discussion: This is expected to be the normal operating mode of IRIS and images and spectra will be stored for each observation.

[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 4 configurable on detector guide windows.

[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 shall be up to 3 arcsec in one spatial direction for integral field mode. This applies to the coarsest scale.

[REQ-1-OAD-3076] IRIS minimum field of view in imaging mode shall be 16x16 arcsec.

[REQ-1-OAD-3078] IRIS detector sampling shall be 0.004 arcsec per pixel (Nyquist sampled (λ/2D)) over 4096 pixels for IFU).

[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 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 5% (TBC) over the sum of: inter-OH sky, telescope and NFIRAOS background.

[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 2000s.

4.3.6.2 Servicing and Maintenance

[REQ-1-OAD-3150] The maximum scheduled maintenance time for IRIS shall be <person 40 hours/year averaged over the required instrument lifetime.

> *Discussion: This does not include the time required for the planned instrument refurbishment.*

4.3.7 IRMS

4.3.7.1 General

> *Discussion: IRMS is an early light instrument, a near infrared multiple slit spectrometer, that provides some of the science capability envisioned for IRMOS. To the maximum extent possible, the IRMS instrument will be a clone of the Keck MOSFIRE instrument for cost and ease of implementation reasons.*

[REQ-1-OAD-3202] IRMS shall be fed an adaptive optics corrected beam from the NFIRAOS adaptive optics system.

[REQ-1-OAD-3203] The IRMS OIWFS sensors shall provide pixel intensities to NFIRAOS.

[REQ-1-OAD-3204] IRMS shall include one NGS wavefront sensor to provide guide star position feedback.

[REQ-1-OAD-3205] As a goal, the interfaces and components of the IRMS wavefront sensor shall be common with those of the IRIS WFS.

> *Discussion: Although the NGS OIWFS hardware will be the same, the precision and stability requirements of IRMS are relaxed compared to IRIS, so requirements and tested performance can be relaxed. IRMS may be side mounted for example, which would add gravity deflections to guider motions.*

[REQ-1-OAD-3206] The IRMS to NFIRAOS interface shall permit instrument rotation to provide field derotation.

[REQ-1-OAD-3208] IRMS shall provide a pupil mask that can rotate to match the telescope pupil.

[REQ-1-OAD-3210] The IRMS wavefront sensor shall be designed to minimize vignetting, especially in the central 1/3 of the field where slits will be located.

[REQ-1-OAD-3212] IRMS shall have a wavelength range of 0.95 - 2.40 µm.

[REQ-1-OAD-3214] IRMS shall have a wavelength coverage of an entire band at a time.

[REQ-1-OAD-3216] IRMS, in Spectroscopic Mode, shall have an image quality >80% ensquared energy in 0.12” by 0.16” box.

[REQ-1-OAD-3217] IRMS, in Direct Imaging mode, shall have rms image diameters <0.07” over full bandwidth without re-focus.

[REQ-1-OAD-3218] IRMS shall have a 2.0 arcmin diameter unvignetted field of view with AO correction by NFIRAOS.

[REQ-1-OAD-3220] IRMS Spatial Sampling shall be 0.060 arcsec/pixel in the spatial direction and 0.08 arcsec/pixel in the dispersion direction.

[REQ-1-OAD-3221] IRMS shall have a field of view of at least 2.05 arcmin x 2.05 arcmin at the sampling given in [REQ-1-OAD-3220].

[REQ-1-OAD-3222] IRMS shall have a Spectral Resolution R>3270 with 3 pixel slit (0.24 arcsec)

[REQ-1-OAD-3224] IRMS shall have a Spectral Resolution R>4660 with 2 pixel slit (0.16 arcsec)

[REQ-1-OAD-3228] IRMS throughput shall be >40% for imaging; >30% on order blaze in each band, not including telescope or NFIRAOS.

[REQ-1-OAD-3230] IRMS shall image the entire NFIRAOS 2 arcmin field of view with 0.06 arcsec sampling.

[REQ-1-OAD-3232] IRMS background shall not increase the inter-OH background by more than 10% over the natural sky + telescope + AO system background.

[REQ-1-OAD-3233] IRMS spectroscopic observations shall be background-limited for any exposure > 60 seconds.

[REQ-1-OAD-3234] IRMS shall have at least 46 adjustable cryogenic slits with a total slit length of up to 120 arcsec.

4.3.7.2 Servicing and Maintenance

[REQ-1-OAD-3250] IRMS shall be designed to be consistent with the servicing and replacement intervals and scenarios shown in '*Table: IRMS Servicing Requirements*' below.

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

Table: IRMS Servicing Requirements

TBD

4.3.8 WFOS

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

4.3.8.1 General

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

Discussion: The ORD [REQ-1-ORD-2720] (RD34) allocates a total of 50mas RMS image motion for guiding and field de-rotation. This is interpreted as also including the effects of jitter due to wind and vibration. The telescope image quality budget includes allocations for control noise, wind and vibration, the total allowable telescope jitter resulting from these allocations is 31mas. Allocating 33mas for the instrument rotator leaves a contingency of 21mas 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 a tip-tilt-focus WFS/guider for each sub-field of the instrument.

> *Discussion: It is anticipated that the WFOS field will not be contiguous. A guider is required in each field to ensure slit transmission in each sub-field.*

[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 WFS can serve as a guider for one of the fields.*

[REQ-1-OAD-3322] WFOS shall provide internal baffling.

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

[REQ-1-OAD-3326] WFOS, in Imaging Mode, shall have an image quality ≤ 0.2 arcsec FWHM over any 0.1µm wavelength interval (not including contributions from the telescope or the atmosphere).

[REQ-1-OAD-3328] WFOS, in Spectroscopy Mode, shall have an image quality ≤ 0.2 arcsec FWHM at every wavelength.

[REQ-1-OAD-3330] The WFOS Field of View shall be >40.5 arcmin^2. The field need not be contiguous.

[REQ-1-OAD-3332] The WFOS total Slit Length shall be ≥ 500 arcseconds.

[REQ-1-OAD-3334] WFOS shall have a Spatial Sampling < 0.15 arc-sec per pixel, goal < 0.1 arc-sec.

[REQ-1-OAD-3336] WFOS shall have a spectral resolution R = 500-5000 for a 0.75 arc-sec slit, 150-7500 (goal).

[REQ-1-OAD-3338] WFOS, in Spectroscopy Mode, shall have a throughput of ≥ 30% from 0.31 - 1.0µm, not including the telescope.

[REQ-1-OAD-3340] WFOS spectra shall be photon noise limited for all exposure times >60 sec.

[REQ-1-OAD-3341] WFOS background subtraction systematics shall be negligible (TBD) compared to photon noise for total exposure times as long as 100 Ksec.

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

[REQ-1-OAD-3342] WFOS shall have a gravity flexure due to instrument rotation at a level less than 0.15 arc-sec at the detector.

[REQ-1-OAD-3344] WFOS shall support short (< 3 minutes once telescope is in position) field acquisition for multi-slit masks.

[REQ-1-OAD-3346] WFOS shall support fast (< 1 min) acquisition of single targets onto a long slit.

4.3.8.2 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.

4.3.8.3 Servicing and Maintenance

[REQ-1-OAD-3350] WFOS shall be designed to be consistent with the servicing and replacement intervals and scenarios shown in '*Table: WFOS Servicing Requirements*' below.

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

Table: WFOS Servicing Requirements

TBD

4.4 SERVICES

4.4.1 Power, Lighting and Grounding

4.4.1.1 General

[REQ-1-OAD-4400] Electrical power shall be distributed to the summit facilities, enclosure, telescope and sub-systems as defined in '*Table: Power types delivered to enclosure, telescope and telescope mounted equipment and sub-systems*' below.

Table: Power types delivered to enclosure, telescope and telescope mounted equipment and sub-systems.

ID	Voltage	Power Conditioning*	Phase	Back Up Type	Location			
					Summit Facilities Fixed Base	Azimuth Structure	Elevation Structure	Enclosure (above slip ring)
H3D	480Y277V	None	3	None	Yes	Yes	No	No
H3DG	480Y277V	None	3	Generator	Yes	Yes	No	Yes
H3CUG	480Y277V	None	3	UPS	No	No	No	Yes
L3D	208Y120V	None	3	None	Yes	Yes	Yes	No
L3DG	208Y120V	None	3	Generator	Yes	Yes	Yes	No
L3C	208Y120V	Clean	3	None	Yes	Yes	Yes	No
L3CUG	208Y120V	Clean	3	UPS	Yes	Yes	Yes	No
L1C	120V	Clean	1	None	Yes	Yes*	Yes*	Yes
L1CUG	120V	Clean	1	UPS	Yes	Yes*	Yes*	No

*See discussion for explanation

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.

The full list of which sub-systems and equipment are connected to which power type is defined in the TMT Power and Cooling Budget (RD14).

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.

[REQ-1-OAD-4405] Color coded general purpose single phase 120V 'clean' and 'dirty' power outlets shall be provided throughout the observatory.

Discussion: The power available at these outlets will not be backed up by either the generator or UPS. Three phase power will be available as spare capacity at nearby junction boxes rather than as actual three phase outlets. The need for both 'clean' and 'dirty' power outlets is to be reviewed, and depending on the expected types of connected loads, this requirement may change to define power outlets providing only a single type of conditioned power.

[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 following loads:

- 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

Discussion: The comprehensive list of equipment to be supported by the backup generator is defined in the TMT Power and Cooling Budget (RD14).

[REQ-1-OAD-4430] A centralized UPS shall be provided to cover a period of one minute (TBC) 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. The list of equipment that is connected to the UPS is defined in the TMT Power and Cooling Budget (RD14).

[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-4500] The power, lighting and grounding system shall distribute the electrical power types on the telescope structure as described in '*Table: Power types delivered to enclosure, telescope and telescope mounted equipment and sub-systems*' above.

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

4.4.1.2 Lighting Requirements

[REQ-1-OAD-4590] General Illumination within the enclosure shall be provided at the following levels:

- Illumination of floor at 100 lux
- Illumination of Nasmyth platforms at 100 lux
- Illumination of walkways at 300 lux

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

4.4.1.3 Grounding Requirements

4.4.2 Coolant

[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' as per '*Table: Observatory Chilled Water Supply*' above.

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 Chilled Water

[REQ-1-OAD-4660] Chilled water shall be supplied to the observatory at the temperatures defined in '*Table: Observatory Chilled Water Supply*' below:

Table: Observatory Chilled Water Supply

Description	Temperature	Comments	Anticipated Uses
Fixed temperature facility chilled water	+7 +/-ºC	Chosen at operating temperature for standard chiller equipment	Majority of facility cooling including computer room, mirror coating equipment
Variable temperature chilled water	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.	Majority of electronic equipment located on telescope
Air handler fixed low temperature chilled water	-15 +/-ºC		Enclosure air handlers and hydrostatic bearing system (tbc)

Discussion: The term 'chilled water' is used to refer to a water/glycol mixture appropriate to prevent freezing over the range of site temperatures.

Discussion: For full definition of which equipment is connected to each supply, refer to the TMT Power and Cooling Budget (RD14).

[REQ-1-OAD-4670] The normal operating pressure of the chilled water supplies listed in '*Table: 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-4700] Variable temperature chilled water shall be provided to the telescope Azimuth structure for removal of heat from instrumentation, telescope drives, and other electronics.

[REQ-1-OAD-4715] Liquid refrigerant shall be provided to the telescope Elevation structure for removal of electronics heat from the LGSF Top End and the M2 and M3 control electronics via phase-change cooling.

[REQ-1-OAD-4720] Variable Temperature Chilled Water shall be provided to the telescope Laser Platform on the Elevation structure for removal of heat from the lasers, laser electronics, and BTO electronics.

4.4.2.2 Refrigerant

[REQ-1-OAD-4705] Liquid refrigerant shall be provided to the telescope Nasmyth areas for removal of heat from instrumentation and instrument electronics via phase-change cooling.

[REQ-1-OAD-4740] For Nasmyth instrument cooled enclosures, the gaseous return pressure shall be regulated to maintain the refrigerant boiling point at either -35°C +/- 1°C (TBC) or -43°C +/- 1°C (TBC).

[REQ-1-OAD-4741] For electronics cooling, the gaseous return pressure shall be regulated to maintain the refrigerant boiling point within 2°C of the ambient enclosure cooling set point.

Discussion: The ambient enclosure cooling set point will be 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 will never be set to a value below the local frost/dew point.

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

4.4.3 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 distrubution 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*

4.4.3.1 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-4830] All CIS equipment shall be connected to UPS systems.

[REQ-1-OAD-4835] All CIS equipment shall be able to return to service after a loss in less than 5 (TBC) minutes.

[REQ-1-OAD-4840] The CIS shall have multiple redundant physical connections between wiring centers and service points so it's possible to switch between physical connections rapidly.

[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.).

4.4.3.2 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-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.

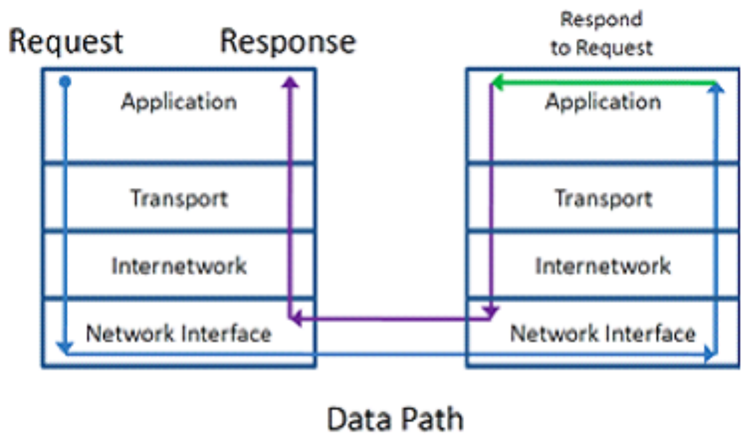
[REQ-1-OAD-4883] The CIS CNET shall accommodate a bandwidth of at least 24.0575 Gbps to the Computer Room.

[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: Latency for Subsystems Terminating in a CIS or Subsystem Switch.

Table: Latency for Subsystems Terminating in a CIS or Subsystem Switch

	CIS Switch (CNET/ENET/SNET)	Internal Subsystem Switch (PNET)
CIS Components	33 µs	3 µs
CSW Based Components	4967 µs	4997 µs

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, telemtry).



4.4.3.3 CIS Security

[REQ-1-OAD-4888] The CIS shall provide physical access control systems on areas identified as controlled spaces.

[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.

4.5 FACILITIES

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 (reference availability requirements).

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

[REQ-1-OAD-5065] The enclosure 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-5075] The enclosure design shall incorporate vibration mitigation to manage the generation and transmission of vibrations to the telescope, instruments, adaptive optics, alignment & phasing, and calibration subsystems (reference error budget).

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

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

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

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

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

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

TBD

Figure: Allowable enclosure vibration PSD

[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).

> *Discussion: The above requirement in conjunction with [REQ-1-OAD-1245] ensures a 0.5 meter gap between the telescope and enclosure. This gap may be bridged at particular places in order to provide access to various areas of the telescope, like the Nasmyth platform. Such bridges may create pinch points, which must be addressed by the Observatory Safety System.*

[REQ-1-OAD-5155] The plane of contact between the enclosure azimuth track and the summit facility fixed base mounted bogey wheels shall be 5.43 m above the X-Y plane of the ACRS.

> *Discussion: This plane defines the height of the enclosure fixed base above the ACRS. The interface between the summit facilities and fixed base and enclosure rotating base is below this level, at the mounting surface for the bogey assemblies.*

[REQ-1-OAD-5156] Below the level of the lower vent doors no part of the enclosure shall be closer than 26.8m from the *ACRS* z axis (excluding stairways necessary to transfer from fixed enclosure walkway to rotating vent walkway).

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

[REQ-1-OAD-5161] The size of the clear aperture opening shall be 31.25 m diameter at the external radius as shown in the TMT Enclosure Geometry Drawing TMT.ENC.GTY-0001 (AD75) in Appendix (see section 7.5).

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.

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.

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.

[REQ-1-OAD-5166] When operating in conditions outside the range of Observing Performance Conditions, the enclosure base axis moves, including settling time, shall be completed sooner than those calculated for the same distance using a reference trapezoidal velocity profile with acceleration and deceleration rates of 0.05 degrees/s^2 and a maximum velocity of 1.15 degrees/sec, were assumed.

Discussion: This requirement relaxes the slewing rate in order for the enclosure to operate under higher winds, with crane loads, or with snow or ice imbalance loading.

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.

[REQ-1-OAD-5172] When operating in conditions outside the range of Observing Performance Conditions, the enclosure cap axis moves, including settling time, shall be completed within the time it would take to complete the same moves if a trapezoidal velocity profile, with acceleration and deceleration rates of 0.05 degrees/s^2 and a maximum velocity of 1.15 degrees/sec, were assumed.

Discussion: This requirement relaxes the slewing rate in order for the enclosure to operate under higher winds, with crane loads, or with snow or ice imbalance loading.

4.5.1.4 Wind, Thermal and Environmental Management

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

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

[REQ-1-OAD-5185] The enclosure vent assemblies shall 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-5190] The enclosure design shall include vent openings with a minimum total vent area of 1500m2. The shape and location of the vent openings is defined in the TMT Enclosure Geometry Drawing TMT.ENC.GTY-0001 (AD75) in Appendix (see section 7.5).

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 m²).

[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.

Discussion: The one exception is the shutter motor drives which will dissipate to ambient air for a TBD period after shutter opening.

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

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

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

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

Discussion: This is an observatory architecture decision to enable a smaller sized enclosure, as per System Engineering Meeting Minutes TMT.SEN.COR.06.033 (RD27), with a supporting technical note TMT.SEN.TEC.06.029 (RD28). Aperture flaps increase the effective diameter of the enclosure for protection of the telescope top end from wind buffeting.

[REQ-1-OAD-5208] The enclosure shall incorporate aperture flaps with geometry as per the TMT Enclosure Geometry Drawing TMT.ENC.GTY-0001 (AD75) in Appendix (see section 7.5).

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

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

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

[REQ-1-OAD-5247] The outside diameter of the pier shall be 36.4m.

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

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

[REQ-1-OAD-5257] The observing floor shall be flat and continuous in the area from the central pier to the interior of the enclosure fixed base at radial distances between 18.2 meters and 29.4 meters.

Discussion: This requirement specifies the floor only and excludes obstructions such as stairways, air handlers, mirror storage etc.

[REQ-1-OAD-5258] The enclosure floor shall be kept free from obstructions at the following locations:

- Sector extending 22.5º counterclockwise from main enclosure door
- Sector extending 60º clockwise from main enclosure door (excluding air handler and protrusion of M2/M3 coating chamber into fixed enclosure)

- Sector extending TBDº counterclockwise from entrance from summit facilities building to fixed base (excluding air handlers and stairways)

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-5259] The inner radius of the fixed enclosure walkway shall be greater than 26.8m.

[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 4.88m 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 1m wide by 2m 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 space adjacent to the mirror coating area for the storage of equipment used for optics handling equipment.

[REQ-1-OAD-5287] The Summit Facilities shall include 12 regularly spaced monuments embedded in the observatory floor at a radius of 25.5m from the observatory azimuth axis. These shall be placed at 30 degree intervals with targets located on the OFCRS +X/-X (East/West) and +Y/-Y axes (North South).

Discussion: These monuments should be surveyed relative to the azimuth track, pintle bearing and other features in the foundation during construction to establish a datum frame of reference for the observatory floor relative to these features.

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

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

[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-5334] The top end platform shall accommodate TBD persons.

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

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

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

4.5.1.7 Survival Loads

[REQ-1-OAD-5301] The enclosure shall meet the environmental constrain survival conditions as specified in the ORD (RD34).

[REQ-1-OAD-5305] In addition to the ORD (RD34) requirements for survival, the enclosure shall withstand seismic events of up to TBD g lateral ground acceleration, with minor damage (meaning a resumption of full functionality within 1 week of event occurrence).

[REQ-1-OAD-5310] In addition to the ORD (RD34) requirements for survival, the enclosure shall withstand ice loads of up to 76 mm, without sustaining any damage.

[REQ-1-OAD-5316] In addition to the ORD (RD34) requirements for survival, the enclosure shall withstand snow loads of up to 150 kg/m^2, without sustaining any damage.

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

- 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 TBD 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

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

[REQ-1-OAD-5355] The enclosure shall be designed to be consistent with the servicing and replacement intervals and scenarios shown in '*Table: Enclosure Servicing Requirements*' below.

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

Table: Enclosure Servicing Requirements

TBD

4.5.2 Summit Facilities

4.5.2.1 General

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

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

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

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

[REQ-1-OAD-5500] The summit facilities control room shall be equipped with heating, cooling and humidity controls.

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

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

[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-5517] The M2 and M3 mirror coating chamber shall be located in an area that will allow a temporary clean environment to be constructed during mirror stripping and coating activities.

Discussion: During early operations, it is expected that significant time will be devoted to developing the M2 and M3 mirror coating process. Any temporary clean environment required for this shall be designed so as not to obstruct regular observatory operation and maintenance.

[REQ-1-OAD-5520] A storage facility for the spare quantity of M1 mirror segments shall be provided 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] An air conditioned 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 AD82) 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-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 RD14 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 air conditioning shall be capable of providing a total flow of 23.6m^3/s at the following operating points with 80% of air being re-circulated:

Case	Target Temperature	Nozzle Temperature	Temperature Difference (outside temperature to nozzle temperature)
Minimum Nozzle Temperature	-5°C	-7°C	11°C
Maximum temperature difference (external to dome air)	-0.5°C	7°C	17°C

[REQ-1-OAD-5635] An exhaust to remove heat from the summit facilities mechanical plant shall be located on the northwest corner of the summit facilities building with the outlet directed to the north.

[REQ-1-OAD-5637] The maximum outlet temperature of the summit facilities exhaust shall not exceed 10°C above the ambient nighttime temperature at the exit of the vent.

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

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

[REQ-1-OAD-5685] The external lightning protection system shall comply with the National Fire Protection Association Standard for Installation of Lightning Protection Systems NFPA 780 Edition 2004 (AD76).

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 summit facility shall incorporate video and audio systems to allow operations staff to monitor the enclosure environment.

4.5.2.12 Summit Facility Servicing and Maintenance

[REQ-1-OAD-5700] The summit facility shall be designed to be consistent with the servicing and replacement intervals and scenarios shown in '*Table: Summit Facility Servicing Requirements*' below.

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

Table: Summit Facility Servicing Requirements

TBD

4.5.3 Headquarters

Discussion: This section has been added following the site selection, and contains only requirements for facilities that were previously part of the summit support facilities. It is expected that these requirements will be reviewed and updated once operational scenarios specific to Hawaii are developed.

4.5.3.1 General

[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.

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

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

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

[REQ-1-OAD-5820] The headquarters mechanical and engineering workshops 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 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 Mechanical Plant

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

Discussion: This includes support facility heating, air conditioning, domestic water and waste and any plumbed in services to the lab and shop spaces and mask cutting facilities.

4.5.3.8 Electrical Plant

[REQ-1-OAD-5860] An electrical plant shall be provided to supply the electrical services required at the headquarters.

[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.

4.5.3.9 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

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

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

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

- The maximum reach shall be no less than R 17.0 m to R 25.7 m relative to the TCRS z-axis.
- The maximum hook height shall be at least 34.5 m above the TCRS XY plane.
- 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 6.5m (between R 23.25m to R 29.0 m relative to the TCRS z-axis)
- The maximum hook height shall be at least 24.5 m above the TCRS XY plane
- 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 primary mirror segment assemblies is 210 kg and 150 kg for the lifting talon.

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

Discussion: Mass estimate for azimuth bogies is 2000 kg.

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

Discussion: Mass estimate for azimuth bogies is 440 kg.

[REQ-1-OAD-6240] There shall be a crane, 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-6250] A mobile platform lift (500 kg capacity and 9 meters reach) shall be available to provide access to instruments.

[REQ-1-OAD-6255] There shall be a mobile crane, with 2 tonne capacity, and 24 meters reach, located on the observatory floor.

Overhead cranes shall be available in the following places:

[REQ-1-OAD-6260] Freight and delivery 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] M1 Mirror coating area: bridge crane with 1 ton 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 and oil shields.

[REQ-1-OAD-6271] M1 Mirror segment maintenance area: monorail crane with 1 ton (TBC) 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 and oil shields.

Discussion: A movable crane can be shared between the coating area and stripping area.

[REQ-1-OAD-6272] The mirror segment storage area shall be accessible by a crane or other lifting equipment with a capacity of 1 ton and capable of lifting segments to and from the segment storage cabinets.

Discussion: Further details of requirements for handling equipment in the mirror segment storage area are TBD.

[REQ-1-OAD-6274] The engineering lab: monorail crane with 5t 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] Mechanical workshops: 3 tonnes capacity bridge crane, 2-speed electric hoist with slow speed about 30 cm per minute, and oil shields.

[REQ-1-OAD-6276] Utility Room: monorail crane with 1 ton 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.

4.7 ENVIRONMENTAL, SAFETY AND HEALTH REQUIREMENTS

Discussion: Top level safety requirements are in the ORD (RD34).

Discussion: 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.

The figure 'Functional Safety Architecture' below illustrates the OSS and Functional Safety Architecture

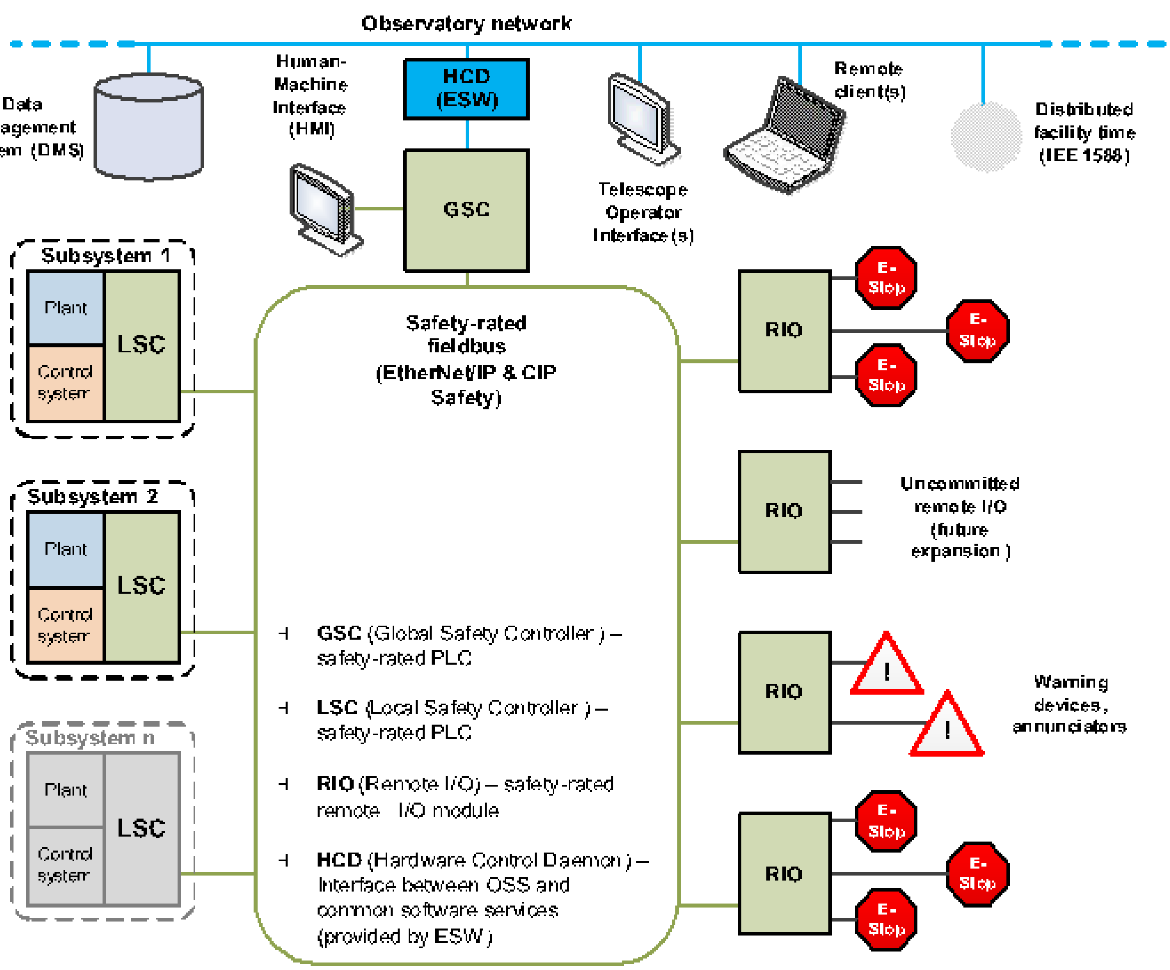


Figure: Functional Safety Architecture.

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.

[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 (AD35).

Discussion: AD35 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 AD35. 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 (AD35) shall provide a Local Safety Controller to implement the SRCF.

Discussion: (AD35) 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: Observatory 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: Illustration of the components that comprise a local safety controller*' below*

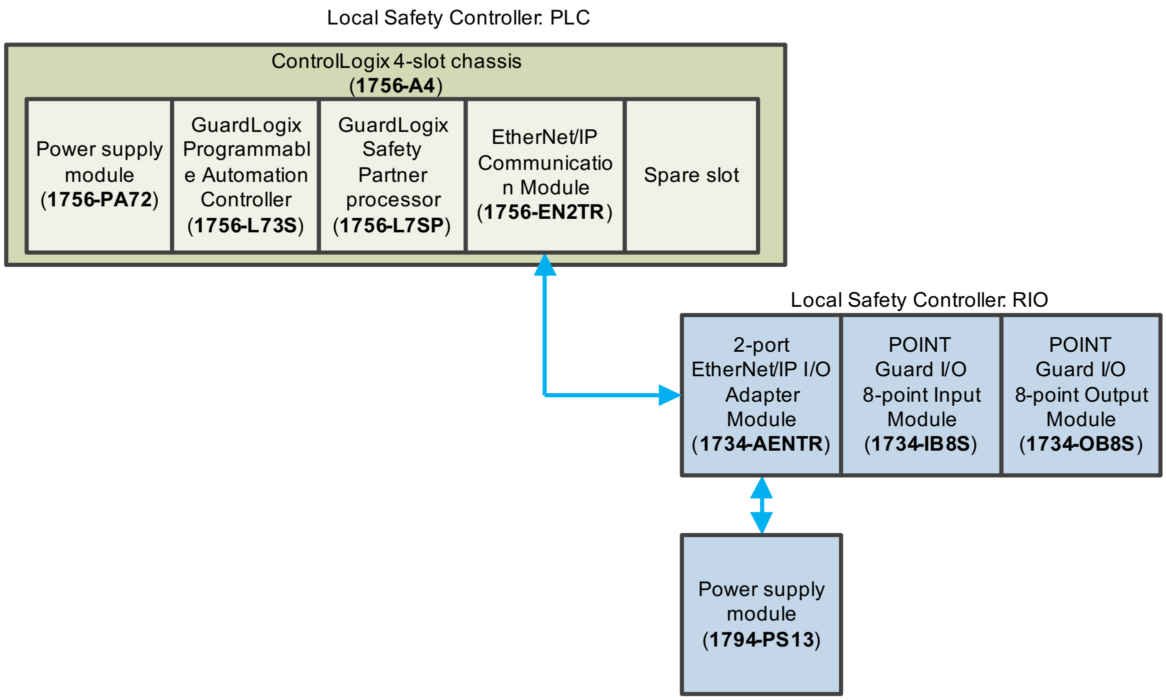


Figure: Illustration of the components that comprise a local safety controller

[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-6911] 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 Environmental Requirements

4.7.1.2.1 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

Discussion: 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.

[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.

[REQ-1-OAD-7088] Maintenance and checkout of the OSS shall require no more than 20 hours per year.

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 sub-system.

[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 will initiate action via the OSS to place all sub-systems 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 switches shall be conveniently and appropriately located throughout the summit facility as necessary to ensure adequate coverage and access in the event of an emergency.

Discussion: Emergency stop switches 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 stop switches 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] It is the responsibility of each subsystem to provide any emergency stop switches mounted at its location(s), and to connect them to the nearest interface to the OSS.

Discussion: The OSS will provide sufficient remote I/O modules at suitable locations to ensure that all emergency stops can be connected to it. The ICD between the OSS and subsystem will define the electrical interface and the requirements on the type and appearance of the switch. The subsystem will provide the switch(es), the mounting hardware and the necessary cabling and connectors to make the interface at the nearest remote I/O module.

[REQ-1-OAD-7113] E-stop switches associated with the OSS shall adhere to the relevant industry standards and be easily distinguished from equipment e-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 be able to immediately identify and report the location of any triggered emergency stop switch.

Discussion: To speed fault recovery, the OSS will report the location of any triggered emergency stop switch(es). It will correctly identify the triggered switches and report their location even when more than one switch has been activated.

4.7.3 Telescope Safety

4.7.3.1 General

[REQ-1-OAD-7200] The elevation structure of the telescope shall be physically restrained to inhibit motion or damage even under Infrequent Earthquake Conditions, for any servicing or maintenance operation that involves more than 10000 (TBC) kg-m mass imbalance of the elevation axis.

[REQ-1-OAD-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 as defined in the ORD (RD34).

[REQ-1-OAD-7210] The telescope shall provide a secondary emergency means of egress for personnel from the Nasmyth platforms that is available at any telescope azimuth position.

[REQ-1-OAD-7215] There shall be a secondary emergency means of egress for personnel from all permanent walkways within the summit facility.

[REQ-1-OAD-7220] In an emergency situation, it shall take no longer than 2 minutes (TBC) to exit the summit facility from any regularly accessed location.

[REQ-1-OAD-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: 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
2.5	1.25	0.75	0.098

[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: 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
2.00	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 document (RDX).

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.

[REQ-1-OAD-8010] The system shall establish the alignment of the telescope and instrument foci relative to the sky primarily by means of mount actuators setting the telescope azimuth and elevation angles, and the tertiary mirror steering the beam to the instrument foci.

Discussion: The mount actuators consist of the elevation and azimuth drives with the corresponding position encoders and possibly rate sensors for local mechanical feedback. There are several instrument foci on the Nasmyth platforms that are selected by steering the tertiary mirror in azimuth and elevation.

[REQ-1-OAD-8015] The 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 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: 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.

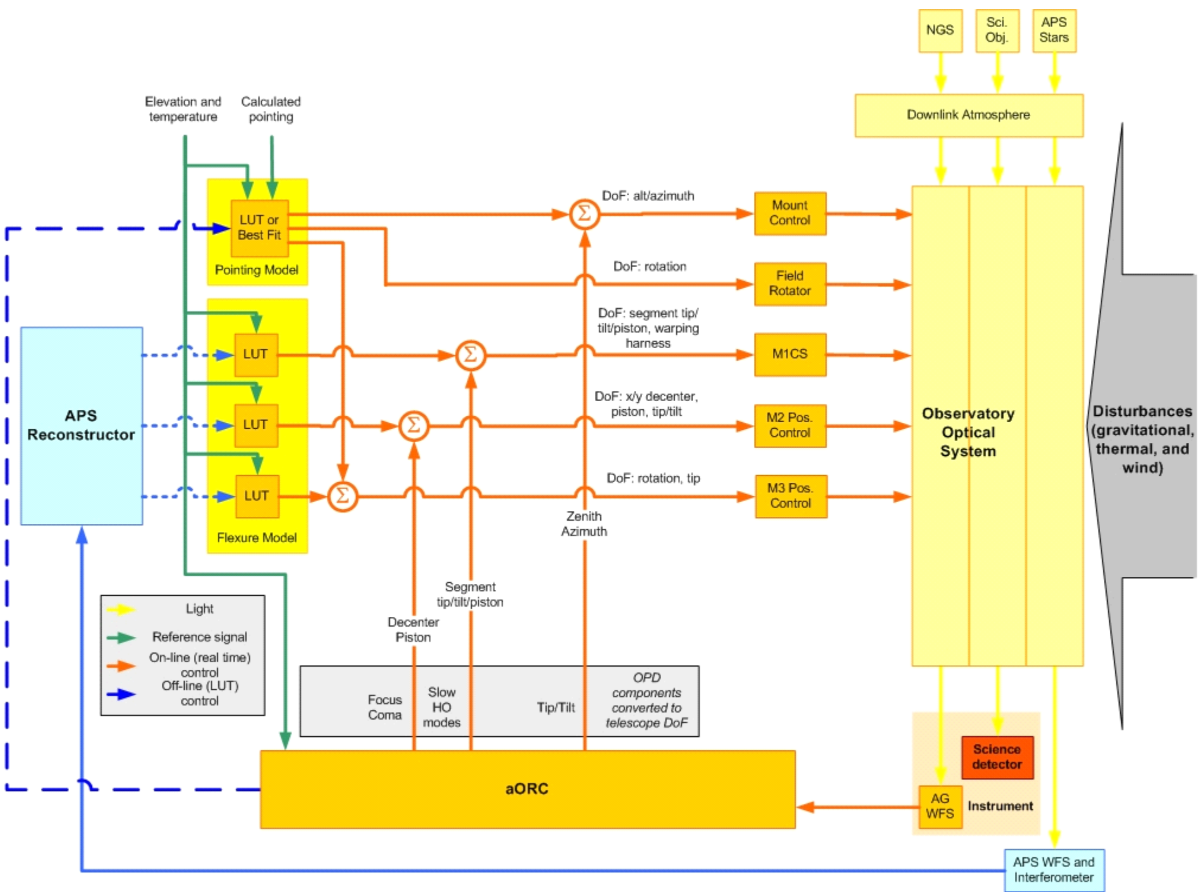


Figure: Control architecture for seeing limited observations.

[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: Control Architecture for adaptive optics observations*' below).

[REQ-1-OAD-8040] OPD information from guiders shall be scaled and rotated into telescope modes (degrees of freedoms) that are transferred to the Telescope Control System.

[REQ-1-OAD-8045] The guiding NGS WFS(s) shall be either adjacent to the entrance window of the instrument, or preferably located inside the instrument.

[REQ-1-OAD-8050] The telescope control system (TCS) shall control NGS WFS probe positioning in coordination with the mount to perform non-sidereal tracking, dithering, and differential refraction compensation.

[REQ-1-OAD-8055] During dithering, the coordinated trajectories of the mount and the NGS WFS probes shall be complementary to within 0.5 (TBC) arcseconds.

Discussion: The intent is to stay within the capture range of WFSs and to limit transients induced onto tip-tilt mirrors during AO guiding.

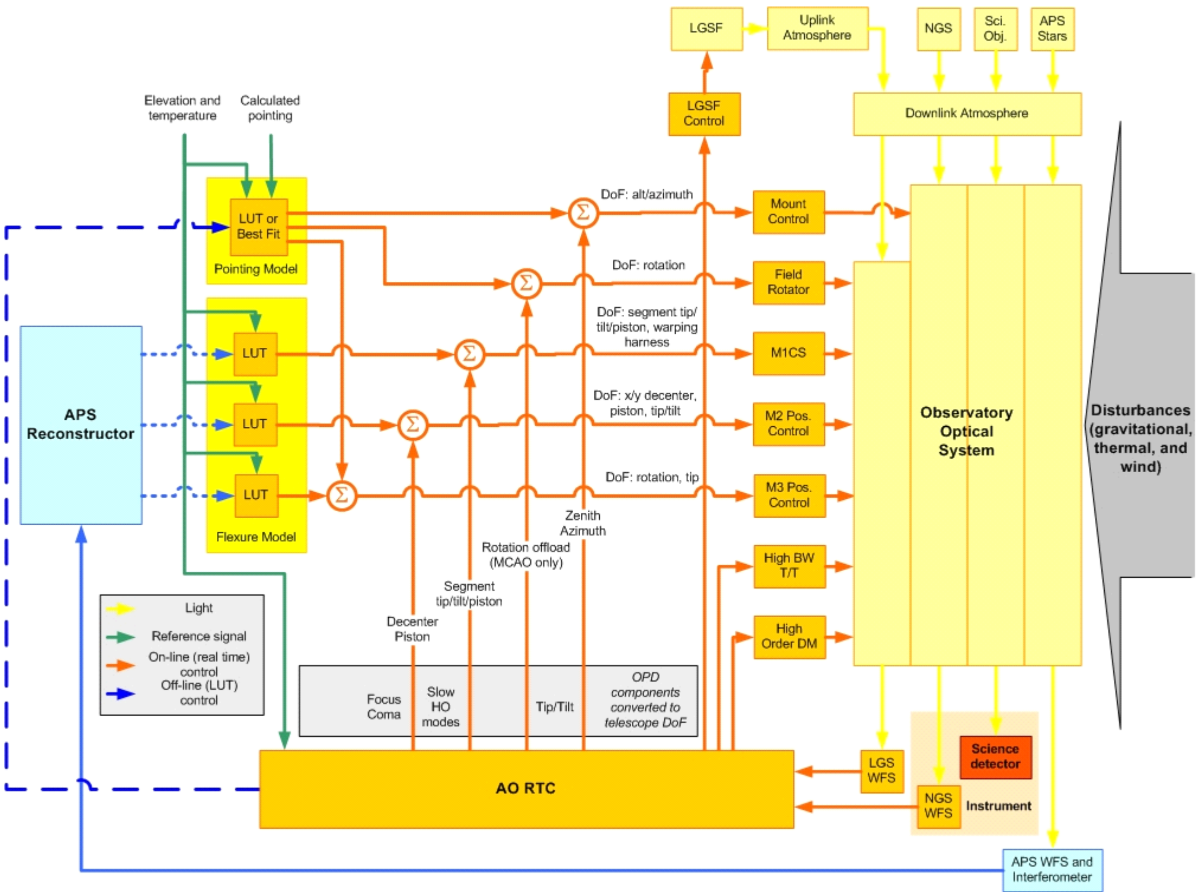


Figure: Control Architecture for adaptive optics observations

[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: Control architecture for seeing limited observations*' and '*Figure: 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] Atmospheric dispersion compensation commands shall be "blind" i.e. open optical loop operation calculated by the pointing model. This pointing model shall be the responsibility of the telescope control system (TCS).

[REQ-1-OAD-8210] The accuracy of the atmospheric dispersion correction shall be determined by the requirements for the particular system configuration.

5.1.4 Active and Adaptive Optics Control Architecture

5.1.4.1 General

[REQ-1-OAD-8300] The system shall maintain the shape of the 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: Control architecture for seeing limited observations*' and '*Figure: 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 system shall be able to validate wavefront control independent of an instrument

Discussion: Instruments and AO systems are integral parts of the pointing and wavefront control architecture, in that they provide acquisition and guiding cameras, and wavefront feedback to the system. This requirement mandates that there be another system, independent of science instruments and AO systems, that provides components and interfaces that enable validation of these functions.

[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 and TBD% for HROS at the galactic pole.

Discussion: The WFOS requirement is inferred from the MOBIE OCDD.

[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

Discussion: The active optics system may rely on local mechanical feedback loops to stiffen up and linearize the actuators described in this section. The local feedback loops may utilize mechanical measurements, like position (encoder), force (strain gauge), and possibly acceleration.

[REQ-1-OAD-8400] The active optics system shall adjust M1 segment position in 3 DoF (tip, tilt, piston) by means of 3 piston actuators per segment.

[REQ-1-OAD-8405] The active optics system shall adjust M1 global position in 3 DoF (tip, tilt, piston) by means of 3 piston actuators per segment.

[REQ-1-OAD-8410] The active optics system shall adjust M1 segment shape by means of 21 warping harness actuators for each segment.

[REQ-1-OAD-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: 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
Quadrafoil ($Z_{4,+4}$)	14	423	306	4.1
Quadrafoil ($Z_{4,-4}$)	15	421	306	4.1

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-8615] The bandwidth for the Telescope Optical Feedback System (TOFS) loop feeding OPD focus back to M2 piston shall be 0.0001 Hz.

[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: 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 both seeing limited and adaptive optics operations the OPD information shall be scaled and rotated into telescope modes (degrees of freedom) that are transferred to the Telescope Control System.

[REQ-1-OAD-8645] OPD Zernike modes up to the 6th radial order (TBC) shall be reconstructed into M1 mirror modes.

[REQ-1-OAD-8650] 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: 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 Acquisition

Definition: Acquisition is the process of (i) locking the telescope to the sky (guide star acquisition), and (ii) establishing proper alignment of the science target with the instrument (science target acquisition).

[REQ-1-OAD-8700] Both guide star and science target acquisition shall be coordinated by the Executive Software.

[REQ-1-OAD-8705] TMT instrumentation shall provide their sensors for acquisition and guiding.

Discussion: There shall be no facility acquisition and guiding system. Nevertheless, there are standard procedures detailed below that all AO systems and instruments shall support.

5.1.5.1 Acquisition Process

[REQ-1-OAD-8710] Each system configuration (instrument/AO combination) shall provide reliable means for both guide star and science target acquisition by implementing one of the following two general procedures:

- If it is feasible to design the field of view of the guide WFS large enough to accommodate telescope pointing repeatability (1 arcsec), the acquisition can be made in a single pointing step. Even in this case though, it may be necessary to re-align the wavefront sensors relative to the instrument after the initial acquisition.
- If it is technically or financially not feasible to use large enough FOV guide WFS, the instrument shall provide an at least 20 arcsec acquisition camera. After acquiring the guide star on the camera, telescope blind offset places the guide star on the WFS.

Discussion: In order to accommodate the second acquisition option, the telescope need to be able to offset without optical feedback up to 1 arcmin with 50 mas repeatability (1 sigma), as specified in the ORD (RD34). It is understood that this high precision offset is meaningful only with high order (laser guide star) adaptive optics corrections reducing image blur to the level commensurate to the FOV of the WFS. It is also understood that this offset requirement includes a blind tracking component due to the finite time of the offset operation.

Although the WFS pick-off positions are supposed to be set so that they ensure appropriate target positioning on the science detector or slit, it may be necessary to test and correct this condition with collecting and analyzing actual science data.

[REQ-1-OAD-8715] Early light instruments choosing the option of not having an acquisition camera shall provide provisions for dependable acquisition in the commissioning phase when the pointing precision of the telescope may not meet the pointing requirement.

[REQ-1-OAD-8720] As a goal, the acquisition camera shall have the same spectral sensitivity as the WFS in order to prevent long integration time and consequently time consuming acquisition process.

[REQ-1-OAD-8725] For acquisition, the positions of the NGS WFSs shall be commanded by the pointing model in the Telescope Control system.

5.1.5.2 Acquisition Sequences for Different System Configurations

Discussion: Appendix 7 illustrates some example acquisition sequences for seeing limited and adaptive optics modes of the observatory. These are for illustration purposes, and are not requirements on the system.

5.2 OBSERVATORY SOFTWARE ARCHITECTURE

Discussion: 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.

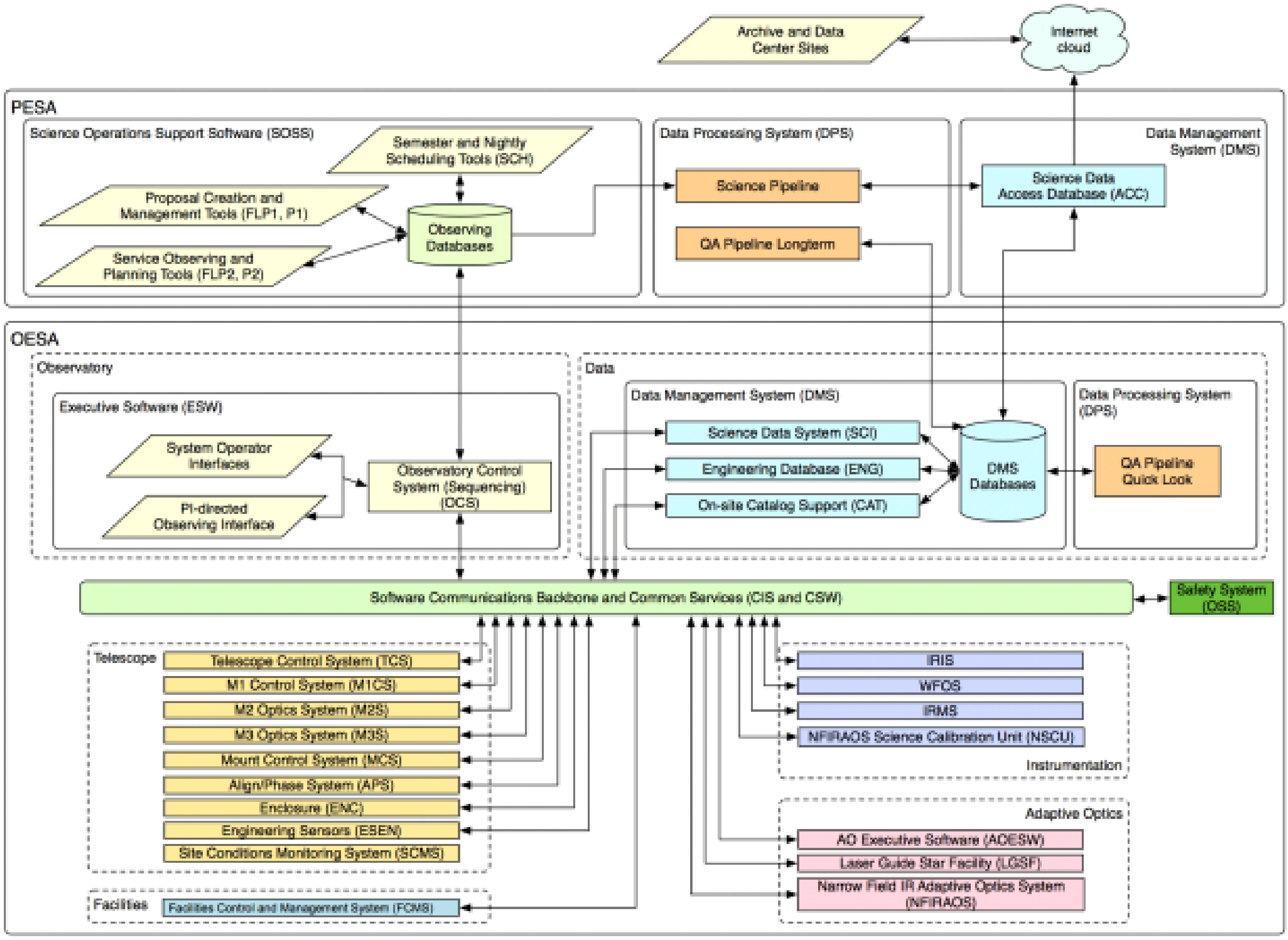


Figure: Observatory Software Architecture (OSA) Subsystem Decomposition

*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: OSA partitions software subsystems into Principal Software Systems*' below and '*Figure: Observatory Software Architecture (OSA) Subsystem Decomposition*' above. The observatory subsystems that implement these functions are called out in '*Table: OSA subsystem allocation into Principal Software Systems*'.*

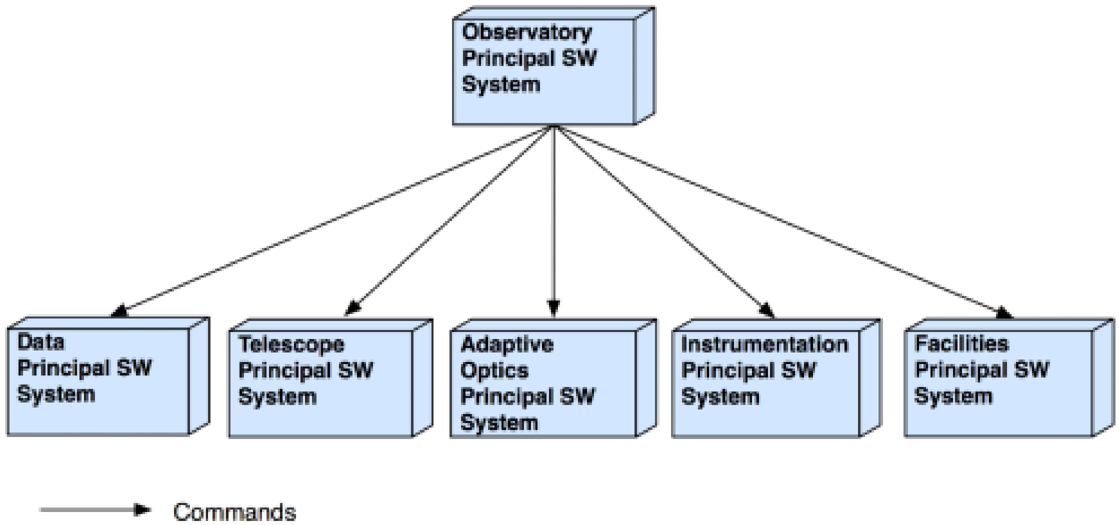


Figure: OSA partitions software subsystems into Principal Software Systems

[REQ-1-OAD-9351] The OSA principal systems shall be implemented per the Observatory Subsystem Allocation subsystem elements as shown in '*Table: OSA subsystem allocation into Principal Software Systems*' and '*Figure: Observatory Software Architecture (OSA) Subsystem Decomposition*'.

Table: 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)	Adaptive Optics	OESA
NFIRAOS Science Calibration Unit (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
Infrared Multi-Slit Spectrometer (IRMS)	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: 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 PI-Directed Observing Mode ("classical").

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 PI-Directed observers. OSW provides tools for planning observations prior to arrival at this telescope. The planning tools are available for PI-Directed observers, but they are not required to use them. PI-Directed 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 PI-Directed observer's program. The created science data flows to the local data storage system and is available via a data access web site. The data may also flow directly to TMT remote observing site for immediate analysis by a remote observer.

[REQ-1-OAD-9852] The OSA shall include all software necessary to implement the first light observing mode called Pre-planned Service Queue Observing Mode.

Discussion: Pre-planned queue observations are executed by TMT Science Operations Staff on behalf of PIs from a combined list of observation descriptions from all partners via a fixed pre-planned six-month schedule.

Discussion: OSW provides software tools that support the proposal process for Pre-planned Queue observers. OSW provides tools for planning observations prior to arrival at this telescope. The planning tools are required for Pre-planned Queue 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 Pre-planned Queue 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 design consideration for future support of an observing mode called Adaptive Queue Observing Mode to ensure that this mode is available without significant re-design.

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 Pre-planned Queue Observing and Pi-Directed 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 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.

[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: 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)

Discussion: 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: 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: Standardized software components for subsystems with hardware and software*' below.*

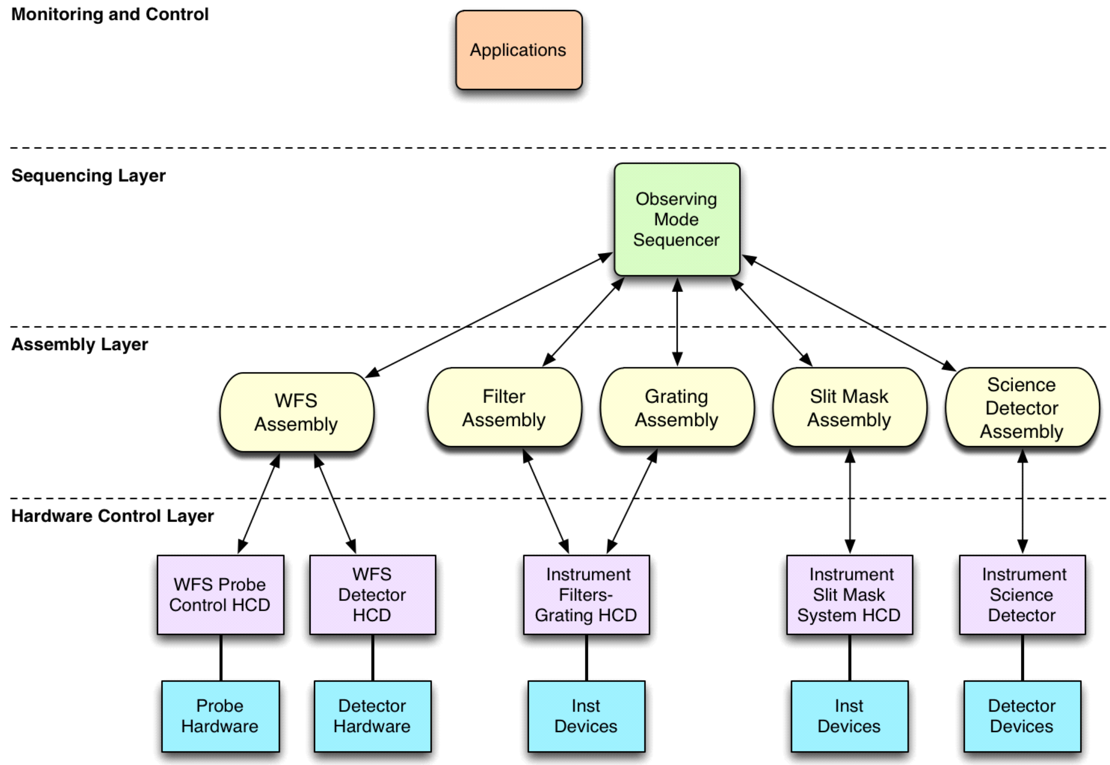


Figure: Standardized software components for subsystems with hardware and software

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: 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: Software subsystem user types*' below.

Table: 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: 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.

5.2.2 Program Execution System Architecture (PESA)

Discussion: 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.

Discussion: 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

Discussion: The reference design for the Observatory Database Architecture is shown in 'Figure: Observatory database architecture'.

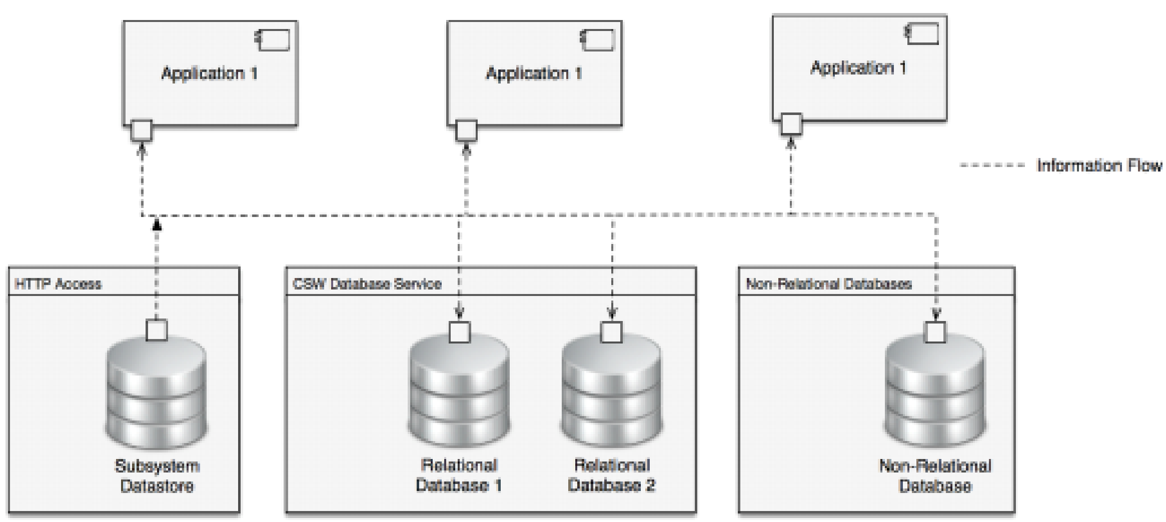


Figure: Observatory Database Architecture

[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: Observatory Database Architecture*'.

Discussion: The Observatory Database Architecture can be composed of one or more databases. 'Figure: 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: Observatory Database Use Cases*'.

Table: 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: 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 (DEOPS)

5.4.1 Common Software

Discussion: 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.

[REQ-1-OAD-9706] The TMT Common Software shall include (but be 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-9342] CSW shall provide the OESA reusable components for development teams that allow implementation of the software structures of [REQ-1-OAD-9365].

> *Discussion: To take advantage of common component reuse, TMT must develop and deliver these components to the project. This requirement may need features of Common Software as well.*

[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-9840] CSW shall provide support that allows an OESA software subsystem or component to initialize itself with a default configuration to support [REQ-1-OAD-9309].

[REQ-1-OAD-9200] The CSW shall include the set of software communication and integration services listed in '*Table: 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: 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: 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 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 Event 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-9235] The Health Service supports and enables the publication of a software process or component's health, e.g. GOOD, ILL, BAD, UNKNOWN.

Discussion: Health service capability may be a subset of general event service capability and hence redundant based on the system design.

[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-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-OCD-4130].

[REQ-1-OAD-9250] The Time Service shall provide software components and processes with access to precise and accurate time based on PTP IEEE 1588 V2 (RD31) 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 Event Services enable the publication of messages indicating a change of state, completion of task etc. and the subscription to events from specific registered processes. Event Services provide support for telemetry, alarms, events and event streams.

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-9255] On initialization, subsystem software components shall publish initial values for event streams and telemetry.

Discussion: Dependent systems subscribing to events are dependent on getting initial values for event streams.

[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 stream to a newly subscribing component.

Discussion: Dependent systems subscribing to events are dependent on getting initial values for event streams.

[REQ-2-OAD-9259] When an event stream publisher has not yet published an event stream value because it has not initialized, the CSW event service shall enable a subscribing component to determine that the publisher is not currently available.

Discussion: This enables the subscribing system to determine how to proceed with their initialization when event stream publishers have not yet initialized.

5.4.2 Executive Software Subsystem

Discussion: 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.

Discussion: 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: 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: 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.

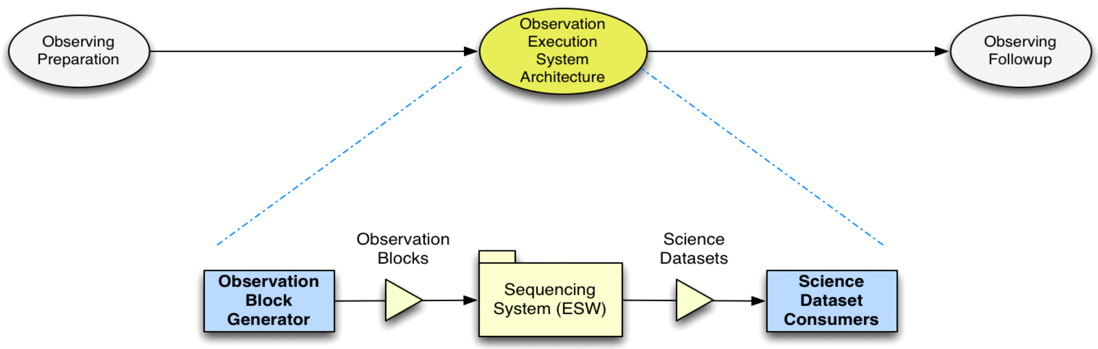


Figure: The ESW sequencing system accepts Observation Blocks (OBs) created by Observation Block Generators. The Sequencing System uses the OB to execute the observation resulting in one or more datasets, which are consumed by Science Dataset Consumers.

[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: Observation execution system architecture sequencer hierarchy.*'*

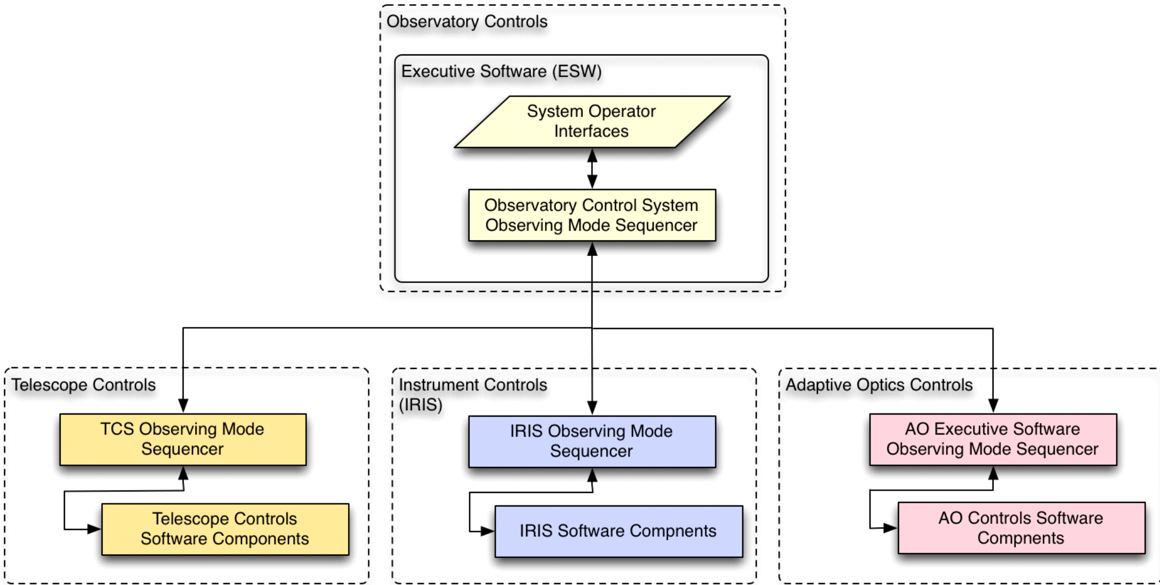


Figure: Observation execution system architecture sequencer hierarchy

[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: 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.

Discussion: The SCMS is a separate subsystem. ESW provides a Hardware Control Daemon (see [REQ-1-OAD-9365]) that allows its information to be used by other OESA systems and for future scheduling applications. ESW provides an observing-oriented user interface to allow its information to be viewed by observers and the Observing Assistant.

[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

Discussion: The ESW will provide user interface standards for use by other subsystems based on the use of Graphical User Interface (UI) technology.

Discussion: 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: 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-OCD-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

[REQ-1-OAD-9362] The Data Management System (DMS) shall provide the necessary software infrastructure to capture, format (as necessary), store and manage the TMT science data streams.

Discussion: This requirement states that DMS is responsible for all infrastructure related to science data creation, storage, security and movement.

[REQ-1-OAD-9820] The DMS shall support the continuous and peak science data throughput estimates of Appendix A.3 of the OpsRD (RD35).

[REQ-1-OAD-9364] The DMS shall provide infrastructure that allows data production from science instruments and other data sources (e.g., wavefront sensors) to integrate with the ESW.

Discussion: This is stating that it is a DMS responsibility to specify how science data is transferred from science instrument detector subsystems to the observatory storage systems.

[REQ-1-OAD-9366] The DMS shall provide infrastructure to capture, store and associate science data metadata during science data acquisition.

Discussion: At TMT, it is a DMS responsibility to capture metadata on behalf of instruments, which is unlike what is done at some observatories.

[REQ-1-OAD-9812] The DMS shall define TMT standards for metadata and data storage. TMT standards shall use and be compatible with astronomy standards such as FITS and Virtual Observatory services and metadata standards.

[REQ-1-OAD-9367] The DMS shall implement the proprietary period policy that allows data products and metadata to be private for a specified amount of time that can vary for each TMT partner.

Discussion: The Operations Plan (RD43) provides a proprietary period policy. It is expected that the policy will change prior to the end of construction so the software must allow for expected changes.

5.4.3.1 Data Movement

[REQ-1-OAD-9368] The DMS shall provide infrastructure to move detector data from the telescope and instruments to the support facility and on to the archive and partner data centers.

Discussion: This requirement states that DMS must provide a software infrastructure for science data.

Discussion: Support for an archive or movement of data to partner data centers is not part of the construction effort.

5.4.3.2 Data Storage

[REQ-1-OAD-9370] The DMS shall provide a persistent store with adequate space for all science data, engineering data and other long-term data. The storage system shall have the ability to increase its capacity as needed over the lifetime of the observatory if no offsite archive is created or the most recent 2 years if there is an offsite archive.

Discussion: Data Management System provides a data storage system that is used by all systems that require secure, reliably storage. During construction systems are developed using a development storage system, but use the shared Data Management System storage system during operations.

[REQ-1-OAD-9818] The DMS persistent data store shall be initially sized and allow growth over the lifetime of the observatory according to the data estimates of Appendix A.3 of the OpsRD (RD35).

Discussion: The data store at the summit and support facility are initially sized at 250 TB with growth of 134.5 TB/year during full up operations according to the assumptions of Appendix A.3.

[REQ-1-OAD-9503] Two copies of all data objects covered by [REQ-1-OAD-9370] shall be kept in physically separate locations. The physical separation must be large enough that local catastrophic events do not destroy both data copies.

Discussion: the minimal separation solution is one copy on summit, one copy in support facility. A more desirable solution is a separation of 10s of kilometers or more.

[REQ-1-OAD-9506] Functionality shall be provided to guarantee or automatically and regularly check that the two data copies are identical.

[REQ-1-OAD-9371] The DMS shall ensure that science data and other science data products covered by the proprietary period policy is secure and not available to unauthorized users or staff from the time it is created until it is public.

Discussion: The primary concern is that on-site observers do not have access to the proprietary data belonging to other programs/users.

[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.

[REQ-1-OAD-9816] The DMS storage functionality shall use the Single Sign-on Service to authenticate and authorize user identity and roles to ensure users can only access data for which they are entitled.

5.4.3.3 Science Data Access

[REQ-1-OAD-9372] The DMS shall provide functionality that provides users with access to and retrieval capabilities for data packages associated with their observations and science programs. A data package includes all related science, calibration, and technical data as well as any associated information such as observing logs.

Discussion: The exact contents of the data package is determined during the DMS design process.

[REQ-1-OAD-9374] The DMS shall provide a minimal access capability that allows the TMT users, technical staff, partners and the public with local and remote access to TMT data products. This minimal access capability is not meant to provide the features of a full astronomical archive.

Discussion: This requirement allows users to retrieve their data packages and perform other needed functions but is geared towards operations needs.

[REQ-1-OAD-9810] The DMS data access functionality shall provide access to TMT data products according to the TMT proprietary period policies.

Discussion: This requirement ensures that users can only access data for which they are authorized.

[REQ-1-OAD-9814] The DMS access functionality shall use the CSW Single Sign-on Service to authenticate and authorize user roles and set data access rights.

5.4.3.4 Engineering Database

Discussion: Data Management System must also collect, store and provide tools for monitoring engineering telemetry. DMS includes an Engineering Database subsystem for this purpose.

[REQ-1-OAD-9378] The DMS shall provide a subsystem that captures and stores engineering events (time-stamped) or event streams and provides tools that allow TMT staff to perform simple time-based queries and extract data for further analysis.

Discussion: The primary source and only source of data for the construction Engineering Database is the telemetry that is transmitted throughout the system via the CSW Event Service. Some engineering data sources may not be covered by this restriction. Some high bandwidth engineering data sources include their own collection systems (e.g., AO and ESEN).

Discussion: 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 shall support extraction of data to formats recognizable by these tools.

[REQ-1-OAD-9822] The Engineering Database must support the steady state events and telemetry data rates of Appendix A.3 in the OpsRD (RD35).

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 Engineering Database shall be able to capture short bursts of high-bandwidth telemetry according to [REQ-1-OCD-2375].

[REQ-1-OAD-9824] The set of telemetry that is persisted in the Engineering Database shall be selected during operations, but is assumed to be a subset of the available telemetry.

Discussion: Storage of telemetry items is more resource intensive than capturing or displaying telemetry items. Therefore, the assumption is that a subset of the most important engineering data will be persisted. The estimate in the OpsRD (RD35) used to calculate required storage is 50%.

[REQ-1-OAD-9826] The storage system and backup strategy defined for science data shall also be used for the Engineering Database storage.

Discussion: See section 1.1.5.2. This requirement is stronger than [REQ-1-OCD-2370].

[REQ-1-OAD-9828] The Engineering Database shall provide an access user interface that allows time-based range queries on a subset of stored telemetry items. The list of query items shall be user selectable at query time. It shall be possible to download results in common formats for analysis in familiar desktop tools.

[REQ-1-OAD-9830] The Engineering Database shall include the ability to generate daily reports of telemetry trends for the purpose of monitoring technical performance.

Discussion: This requirement is vague. It is assumed that the reports are based on results that are similar to activities that can be interactively obtained using the access user interface.

5.4.3.5 Catalog Access Service

[REQ-1-OAD-9253] The Catalog Service shall provide access to a defined set of astronomical catalogs stored at the telescope site and support facility using the Data Management shared storage system. The service includes a catalog of guide stars for the use of all other TMT software subsystems.

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

*Discussion: 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: 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.*

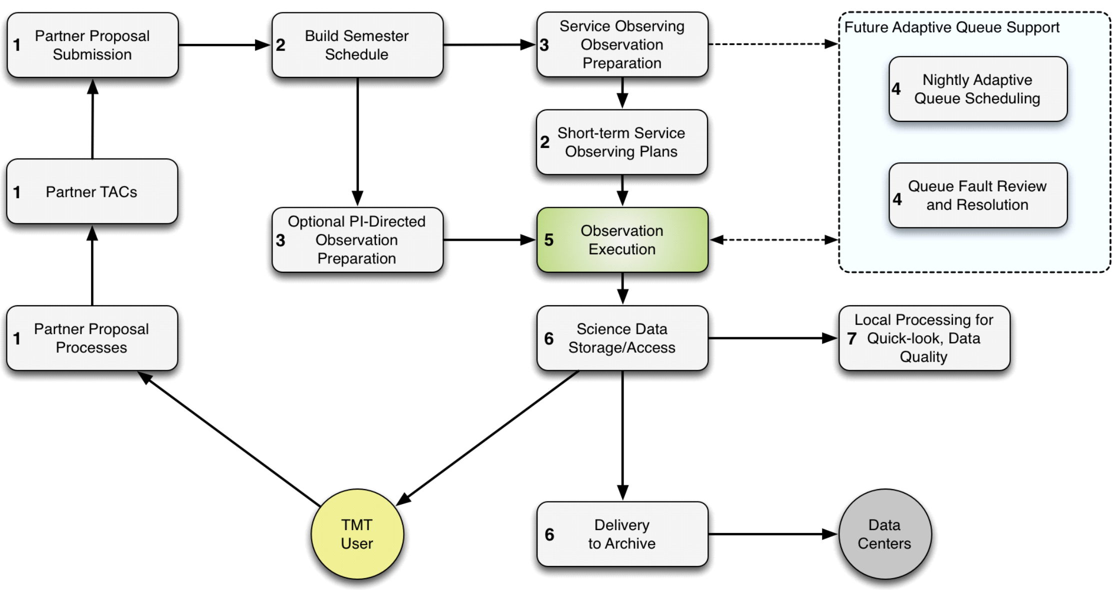


Figure: The TMT Operations Plan observing workflow

[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.

[REQ-1-OAD-9435] Each instrument may have one or more tools for instrument simulation, integration time estimation, and configuration setup support (e.g. multi-object mask definition). As necessary, PESA subsystems must be able to ingest and parse output from those instrument-specific tools.

Discussion: The integration of instrument simulators and time estimators is not part of the construction effort. Its development is deferred until first light.

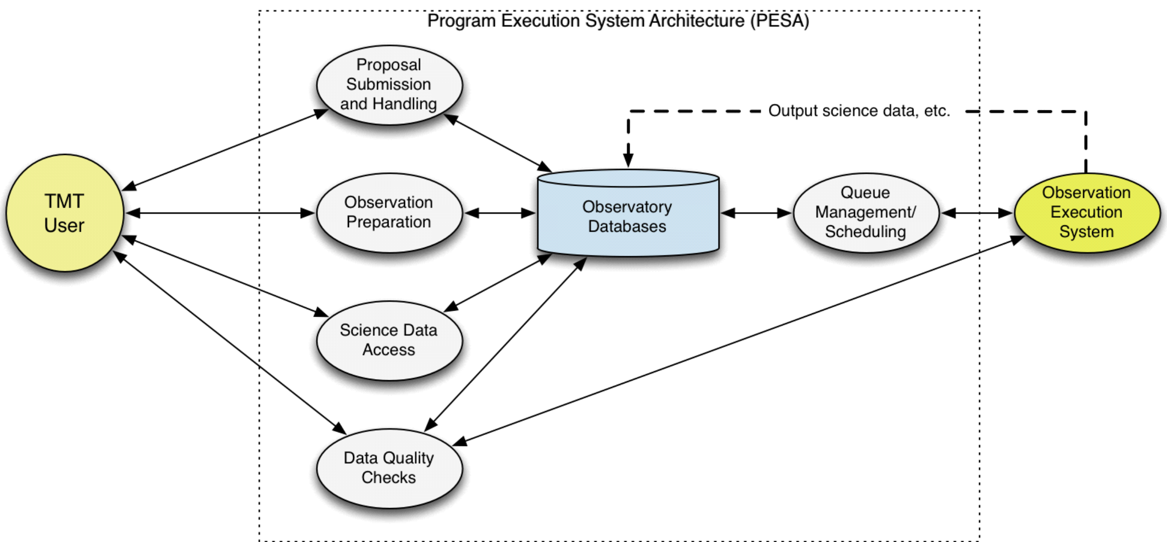


Figure: Program Execution System Architecture decomposition and relationship to Observation Execution System Architecture

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

Discussion: Based on the information gathered during the proposal process, a semester schedule and other scheduling artifacts are created.

Discussion: Adaptive Queue Scheduling is not planned for TMT, but the Operations Plan (RD43) requires that tools be provided to allow Adaptive Scheduling during a PI-Directed observing period or during a longer partner observing period [REQ-1-OCD-4005]. Supporting Adaptive Queue Scheduling is through a class of scheduling tools that differ from the long-term schedule tools. The Semester Scheduling System would be extended to support Adaptive Queue Scheduling.

[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 PI-Directed observing programs, Pre-planned Queue Service observing programs, Engineering Time and scheduled down-time. 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 Pre-planned Queue 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 Pre-planned and PI-Directed observing modes.

Discussion: The use of the P2S is required for the Pre-planned Observing mode, but is optional for the PI-Directed 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: 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 as specified in the OpsRD (RD35).

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

Discussion: 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, configuration and performance data.*

***Event** - In this context an event is a data item, including an accurate 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. 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 and assessing performance. Events that are to be logged in the DMS engineering database are subscribed to by DMS. Event Streams and Telemetry as defined below all are both special cases of published events.*

***Event Stream** – Event Stream – An Event Stream consists of Events that are generated by calculations in one component and serve as input to calculations or other actions in one or more other components. Only Event Streams can be used as input to control actions. Event streams can be published either on a regular time cadence or intermittently. For example, an event stream could be the zenith distance published by the TCS to be used by the STR subsystem as demands to the Alt-Az mount positions.*

***Telemetry** - Telemetry Events are the published internal state or status values of a component that may be of interest to other components in the system. Telemetry is used for informational purposes only, no control actions will be taken based on telemetry events. For example, the temperature of a component could be published as Telemetry. Telemetry Events are published either on a regular cadence or intermittent, for example when a status value changes.*

***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 are written to the Alarm Service Database, and then the Alarm Service responds. 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 calculated from the state of the Alarm Service Database. It provides summary status of alarms evaluated at various levels within the system, including component, subsystem and system. 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 (TBD). 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.

As an example, a typical use case is the measurement of Telescope Wind jitter rejection, which would require data acquisition and retrieval as follows:

This test is performed during AO observations using a bright natural guide star. Data for external wind, MCS encoder error data and NFIRAOS tip/tilt mirror data are acquired for a period of several minutes during an observation. After the observation, the data is retrieved and analyzed to determine the residual wind jitter before and after AO correction.

The following telemetry diagnostic sample rates are required for this test:

- *Wind anemometer data from the top end of the telescope (ESEN, 100 Hz)*
- *Accelerometer data from telescope top end in two axes (ESEN, 100 Hz)*
- *Wind speed data from SCMS (10 Hz)*
- *Encoder error data from STR Alt, Az at (100 Hz)*
- *Tip/tilt error data from NFIRAOS tip/tilt mirror at (100 Hz)*

The following addition technical data are required:

- *Alarm and health data at the start and during the observation are retrieved from the normal operations engineering database.*
- *System logs for the time period of the test are retrieved by querying the logging service for entries that occured during the test time period.*
- *The system configuration, including items such as the MCS control parameters are retreived from the configuration database.*

[REQ-1-OAD-9901] All TMT sub-systems (including instruments) are required to produce status and diagnostic telemetry for the purposes of performance monitoring and failure analysis.

5.5.4 Technical Data Storage Capacity and Persistence

[REQ-1-OAD-9900] The DMS engineering database and CSW configuration service design architecture shall support the maintenance of technical data necessary for operations, for the lifetime of the observatory, provided that periodic updates are made to storage, processing hardware, database and file archive software.

Discussion: Detailed software interfaces are defined using model files, and are published using the Software ICD Database Program. When writing a model file a flag is available in the ICD database that indicates that this event should be archived by the DMS. I.E. the DMS-subsystem interface should include this event being archived by the DMS engineering database.

Discussion: Past experience with Keck has shown that it will be necessary to maintain technical data for the lifetime of the observatory, especially in relation to the APS and M1CS, M1, M2 and M3 systems, and for site conditions monitoring. Specific examples of data that will be referred to many years in the past (15+ years at Keck) include warping harness forces, correlations of focus mode with temperature, trends of sensors with humidity, mirror coating lifetime analysis, and M1CS sensor calibrations.

[REQ-1-OAD-9903] Sub-systems shall provide regular operations and diagnostic modes that provide event stream and telemetry rates, thresholds, set-points and dead-bands that support standard observing use-cases for monitoring performance, and diagnostic test and verification use cases.

Discussion: The purpose of this requirement is to have a predefined set of diagnostic modes that the system must implement, rather than requiring real-time configuration of modes that would be more difficult to implement. 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. It is anticipated that all systems will publish telemetry data at a limited number of predefined rates that are multiples of each other, such as 0.1, 1, 10, 100, 1000 Hz (TBD), so that data can be more easily compared across systems.

Representative use cases will have to be documented to support the flow-down of this requirement.

[REQ-1-OAD-9902] The DMS shall be capable of capturing and storing at least five year's worth of event and other technical data that are needed for establishing current and past technical performance and system configuration information.

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

Discussion: 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: The technical data acquisition would be run from a different script in ESW than the observation. The start of the 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 along side 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 telemetry events.

[REQ-1-OAD-9905] The commands for acquisition and retrieval of technical data shall be savable as a script or data structure, that can be reviewed, saved, and re-run.

Discussion: This enables automation of the process of system verification, trouble-shooting, and evaluation of system performance. Such an automated process will result in a very significant saving of engineering effort and on-sky technical testing time over the lifetime of the observatory.

[REQ-1-OAD-9906] It shall be possible, through submission of a single script or data object to ESW, to trigger the storage of multiple events and multiple technical data products from multiple subsystems.

Discussion: The following use case illustrates the intended use of this requirement:

Based on a set of events matching a pre-defined state, a script is triggered that puts a set of subsystems into diagnostic mode for a period of time. The events that triggered the diagnostic mode and other technical data (regular Events, etc that could be subscribed to) are then collected and stored. The collected data may be ingested or stored as a file in the DMS Engineering Database. An e-mail may be sent to the user that the data was collected and is available.

[REQ-1-OAD-9907] The 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.

[REQ-1-OAD-9908] It shall be possible through submission of a single script or data object to DMS to trigger the retrieval of multiple events and multiple technical data products from multiple subsystems for a specified period 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-9910] It shall be possible through submission of a single script or data object to DMS to trigger the retrieval of a complete subsystem state 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 including alarms and health.

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] It shall be possible through submission of a single script or data object to DMS to trigger the retrieval of system logs for a specified period of time.

5.5.6 Event Data

Discussion: 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] It shall be possible, through submission of a single data object to an ESW sequencer, to modify across multiple subsystems, the publishing behavior of events over a specified period of time.

Discussion: The implementation of this requirement could be a data structure (similar to an observing block) or script language submission to ESW that configures the characteristics of multiple telemetry event publications. The types of modifications that may be made to telemetry events include but are not limited to:

- *Start and stop time*
- *Rate of publishing of telemetry events (by changing to a predefined diagnostic mode from observation mode)*
- *Range or threshold limits that set the criteria for publishing asynchronous telemetry events (per the pre-defined diagnostic mode).*
- *Whether or not telemetry events are subscribed (and therefore saved to the engineering database) by the DMS*

In many cases it would be desirable to have data collection synchronized across systems, such that each data point is taken at the same time instant (within a tolerance). However, it is not certain if this will be possible within the observatory software architecture. If data is not synchronized then a higher diagnostic sample rate may be necessary so that the data can be interpolated.

Data is always timestamped in the DMS engineering database and can be retrieved in that format. When collecting the data from the database an option is to get an interpolated synchronized set based on a query.

[REQ-1-OAD-9916] Specific event publishing characteristics that are modifiable from ESW calls to observatory subsystems shall be as agreed in applicable ICDs.

Discussion: An efficient method of documentation may be a configuration controlled global system event database that can be applicable to ICDs. The event publishing characteristics described in this database would be levied as requirements on observatory subsystems. It would provide a list of events that are required for system operation, trouble-shooting and maintenance, and the key characteristics of these events. Having this single database would relieve significant effort in documenting interfaces between systems.

[REQ-1-OAD-9918] CSW shall record the time of occurrence of published events using the TMT Time Service, as described in [REQ-1-OAD-9250].

Discussion: Note that this is the time of event publishing. It is expected that the latency between time of occurrence and time of publishing the event will be insignificant. This requirement should trace to subsystem requirements constraining the latency of publishing event data. If there is significant latency at the component level between a measurement and publishing an event, the Event could include a data object of the time of occurrence.

Discussion: The time service offers two levels of accuracy, using IEEE 1588 (RD31) with and without a hardware board.

Discussion: As per [REQ-1-OAD-9250], the CSW and CIS systems will support the IEEE 1588 (RD31) GPS based time, with different levels of accuracy with and without a hardware time board.

[REQ-1-OAD-9922] The CIS, CSW, and DMS systems shall have the capacity to handle and store, over and above the peak loading during regular observing operations, up to 20 (TBC) technical data event data streams, synchronized in time at 1 kHz each, of events containing 64 bytes of data each (TBC).

5.5.6.2 Event Data Retrieval

[REQ-1-OAD-9924] It shall be possible, through submission of a single query to DMS, to retrieve data of multiple specified events over a specified period of time.

[REQ-1-OAD-9925] It shall be possible to write the retrieved data to a file and to export it to an external computer.

[REQ-1-OAD-9926] It shall be possible to extract scalar or vector event data from DMS either in as-logged time events, or as a regularly time-spaced series at a specified rate that may be different from the logged rate.

[REQ-1-OAD-9928] Event data extracted in the form of a time series at a regular rate different than the publish rate shall be interpolated 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. This characteristic shall be individually selectable for each event in a requested dataset.

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] Results of requested event data queries shall be able to be delivered in standard machine parse-able ASCII format.

Discussion: For example, as a CSV file. Date/time formats should be standard, such as ISO 8601 (RD30).

[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 (TBC) 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 (TBC) 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 event data, either real time, or 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] The charts described in [REQ-1-OAD-9936] shall have "multi-trace oscilloscope" plotting with a common time axis, of up to 10 Event Streams 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.

[REQ-1-OAD-9940] DMS shall provide a means, including a standard interface, to send real-time event data to third party systems for more complex processing.

Discussion: This requirement is intended to establish an interface to send real time event data to 3rd party systems. For example, event data could be passed over the network to Labview for displaying a processed combination of event signals, or for frequency domain processing. The DMS subsystem requirements should specify an appropriate standard for this data interface.

5.5.7 System Configuration

[REQ-1-OAD-9944] The CSW configuration service shall be able to provide both historical and current system configuration information.

Discussion: Previous configurations can be obtained by setting the default file to be a previous version in the configuration database.

Consider the need to identify "baseline configurations" through the use of tags in the revision control system. Flow to level 2 as appropriate.

It is an operations decision as to how far back configuration data will be stored. Ideally, it will be stored from AIV onwards throughout the lifetime of the observatory.

[REQ-1-OAD-9946] It shall be possible through the use of the CSW configuration service to re-establish a previous component, subsystem or entire system configuration as the current configuration.

5.5.8 Observatory System Status and Alarms

[REQ-1-OAD-9948] Alarms, including alarm flags, and out of range numeric monitors, shall be assessed by each host subsystem and communicated to ESW as alarm events.

Discussion: Conditions for alarms for each subsystem shall be included in the appropriate ICD documents. An alarm summary document that is applicable to ICDs may be an efficient method for documentation.

[REQ-1-OAD-9952] ESW shall provide a GUI screen in the observatory control room with a visualization of the health and alarm status of the observatory subsystems and system.

Discussion: This functionality, and the publishing of observatory system level health and alarm status, is provided by the ESW Subsystem.

Discussion: An acceptable implementation of this requirement would be similar to the Gemini health and status and alarms database system.

[REQ-1-OAD-9954] Simple statistical information (mean, median, standard deviation) for numeric monitor status values from the health and alarm status screen shall be available from ESW.

[REQ-1-OAD-9956] ESW shall provide the means to easily generate simple charts of alarm values for a specified period of time from the health and alarm status GUI.

Discussion: The above guiding requirements on health and alarm status GUI will flow to more detailed reporting requirements in the level 2 DRD.

5.5.9 Other Technical Data Products

Discussion: This set of requirements recognizes that some technical data products may be saved locally at subsystems. Examples include AGWFS image data (processed and unprocessed), tip-tilt mirror control data, DM actuator command data. These requirements ensure that the storage and retrieval of this data is controllable from a single interface in the observatory system. It is understood that his data may not be persistent on the subsystem storage device for periods of more than one day. These requirements *follow the paradigm of storage of AO RTC data, where telemetry is collected for an entire night, and deleted every day.*

[REQ-1-OAD-9958] 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. A reference technical data product document will summarize the data products needed to be stored by subsystems, in support of this flowdown.

[REQ-1-OAD-9960] It shall be possible, through submission of a single command to ESW, to trigger the storage of technical data products on a subsystem at a specified rate for a specified period of time.

Discussion: The location of data storage is TBD, and may be non-permanent and local to the subsystem. This requirement implies that multiple calls would be made to ESW to store technical data (for example from multiple AGWFS) on a single subsystem, and that additional calls would be required to trigger storage across multiple subsystems and devices.

Discussion: Specific data products to be stored and retrieved, and their characteristics, will be identified through an interface control document.

6. DEFINITIONS

6.1 COORDINATE SYSTEMS

[REQ-1-OAD-9990] The following coordinate system are standards for the Thirty Meter Telescope project (see (RD11) for full definition).

Table: 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)	
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 of 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

Coordinate System	Origin	X axis	Y axis	Z axis	Rotation Angle Definition	Notes
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].
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)	The center of the focal surface	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 (SCRSj)	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 aes	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.		
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).		

Coordinate System	Origin	X axis	Y axis	Z axis	Rotation Angle Definition	Notes
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.		
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.

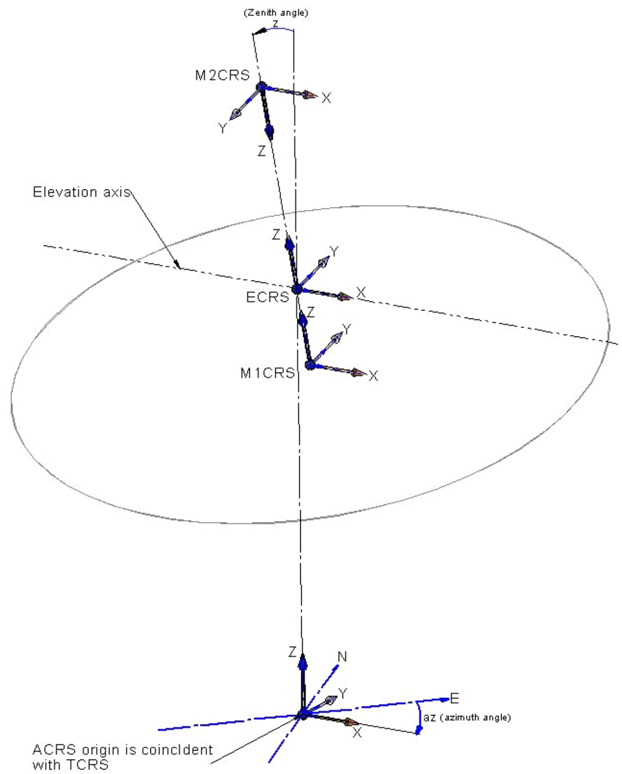


Figure: The basic coordinate systems of the telescope

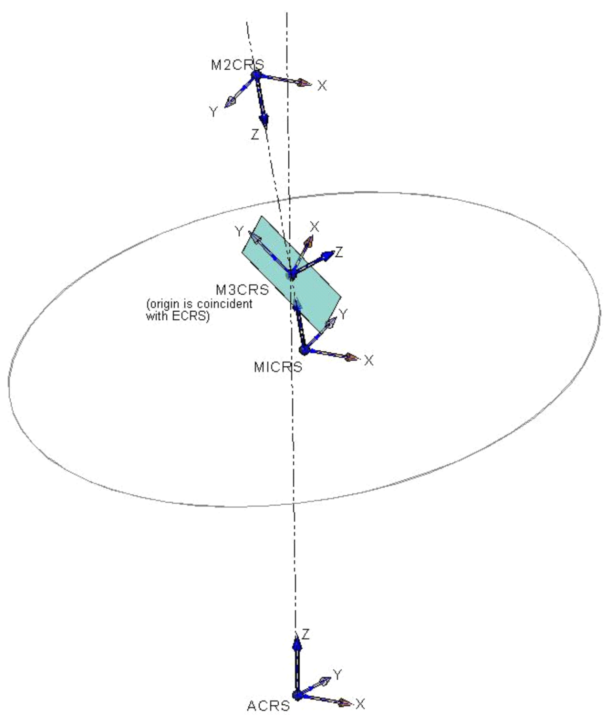


Figure: Tertiary mirror coordinate system (M3CRS) shown in the context of the M1CRS and M2CRS

7. APPENDIX

7.1 WAVELENGTH BANDS

7.1.1 Astronomical Filters

Table: Astronomical Filters

Band	Center wavelength	Bandwidth
U	0.3663 μm	0.0650 μm
B	0.4361 μm	0.0890 μm
V	0.5448 μm	0.0840 μm
R	0.6407 μm	0.1580 μm
I	0.7980 μm	0.1540 μm
J	1.250 μm	0.16 μm
H	1.635 μm	0.29 μm
K'	2.12 μm	0.34 μm
K_s	2.15 μm	0.32μm
K	2.2 μm	0.34 μm
L	3.77 μm	0.7 μm
M	4.68 μm	0.22 μm
N	10.47 μm	5.2 μm
Q	20.13 μm	7.8 μm

Data in the table is from (RD6).

7.1.2 Atmospheric Transmission Windows

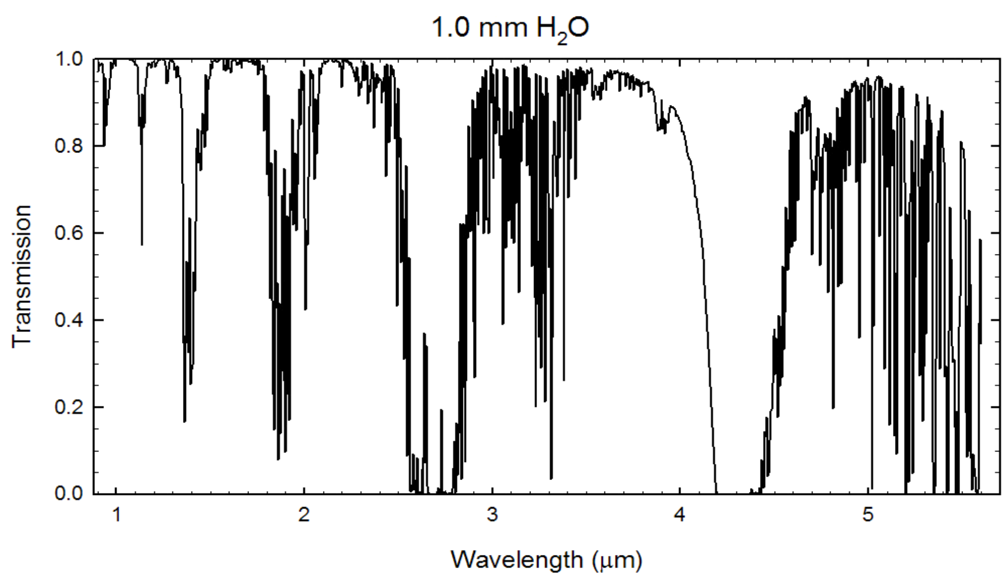


Figure: Near and mid infrared atmospheric transmission windows for 1 mm precipitable water vapor (RD7)

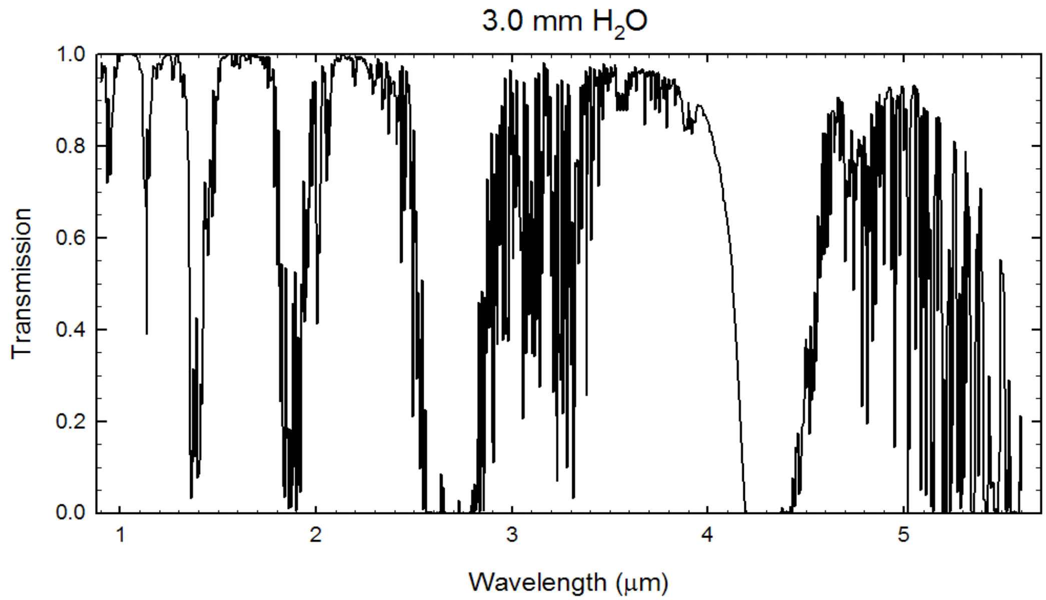


Figure: Near and mid infrared atmospheric transmission windows for 3 mm precipitable water vapor (RD7)

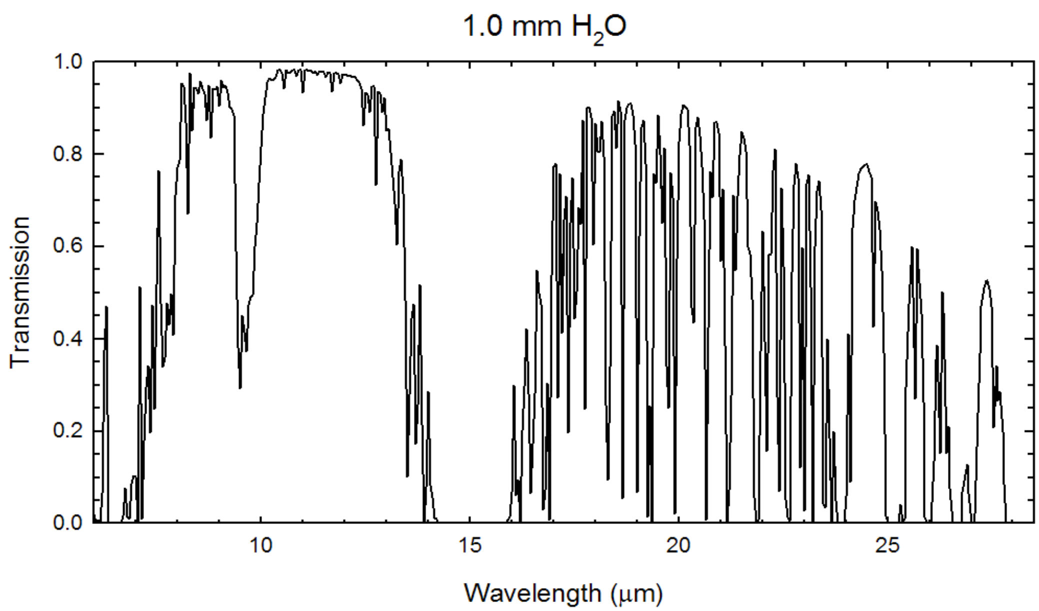


Figure: Infrared atmospheric transmission windows for 1 mm precipitable water vapor (RD7)

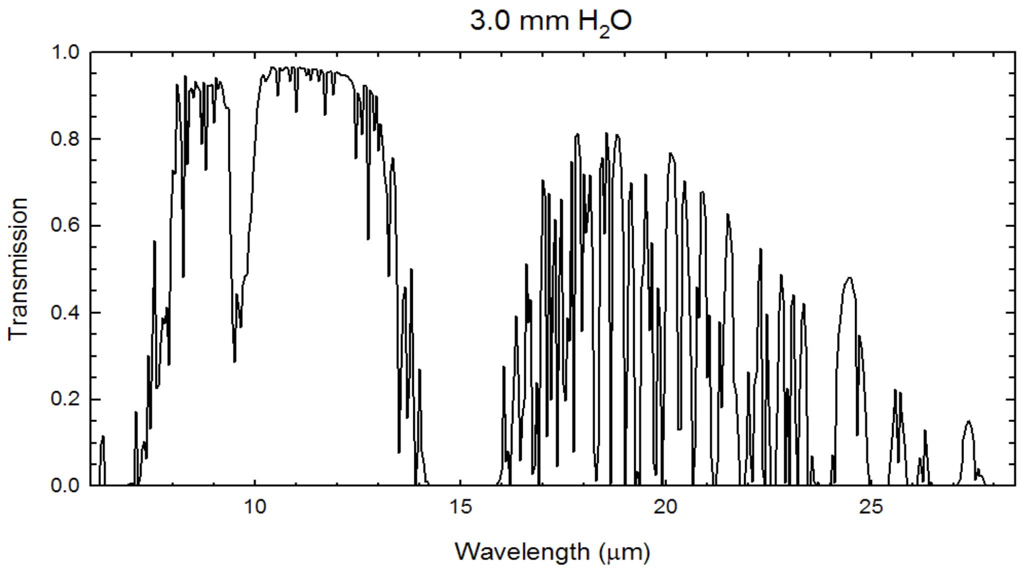


Figure: Infrared atmospheric transmission windows for 3 mm water vapor (RD7)

7.2 ACQUISITION

The figures below show characteristic acquisition sequences for seeing limited, NGS and LGS AO operating modes. These sequences illustrate current best estimates; they do not meet the SRD (RD33) and ORD (RD34) requirement of 5 minutes between observations.

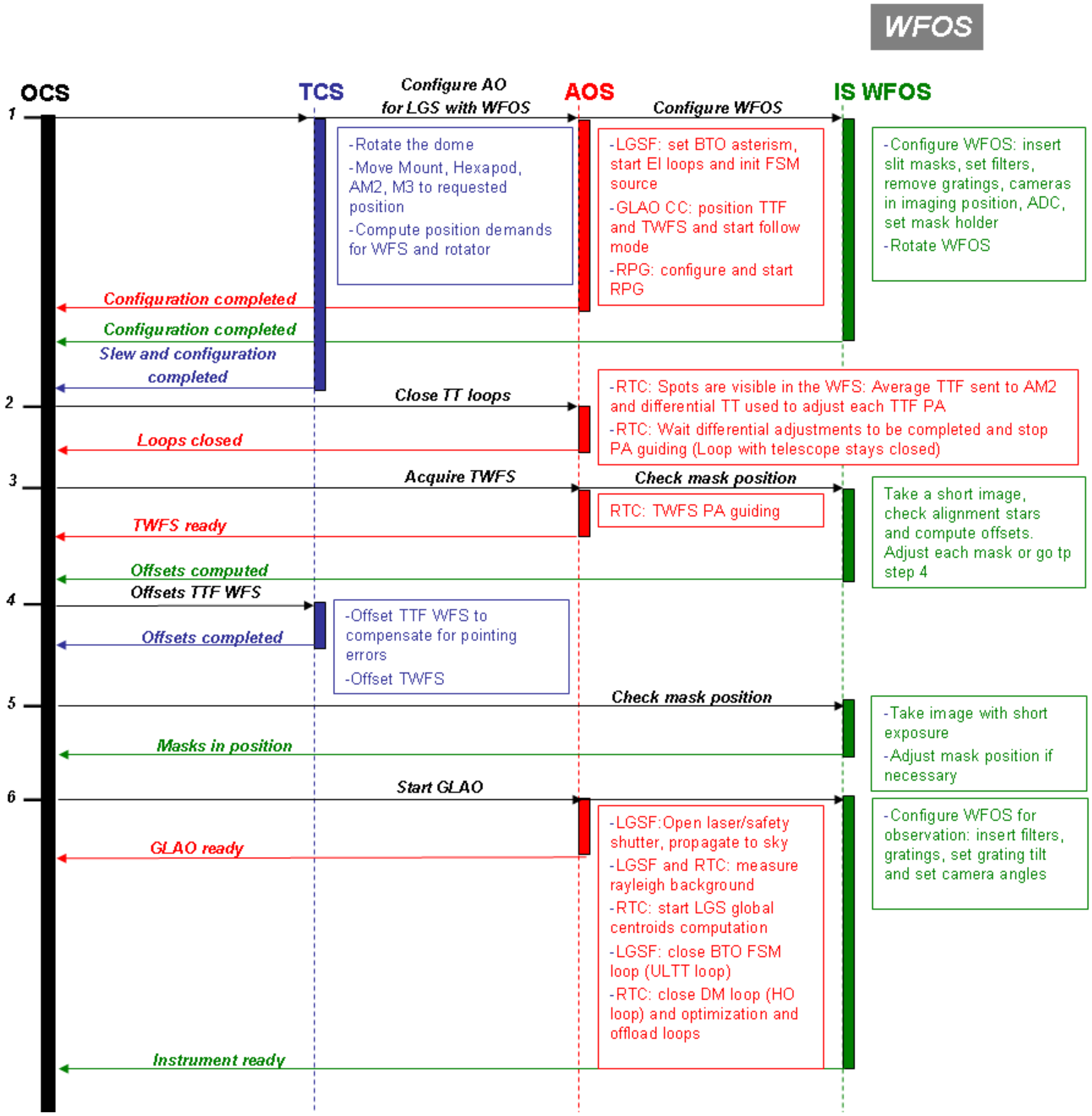


Figure: Example acquisition scheme for a GLAO system configuration (WFOS). FOV of guide (TT) WFS is large enough to acquire guide star in one step.

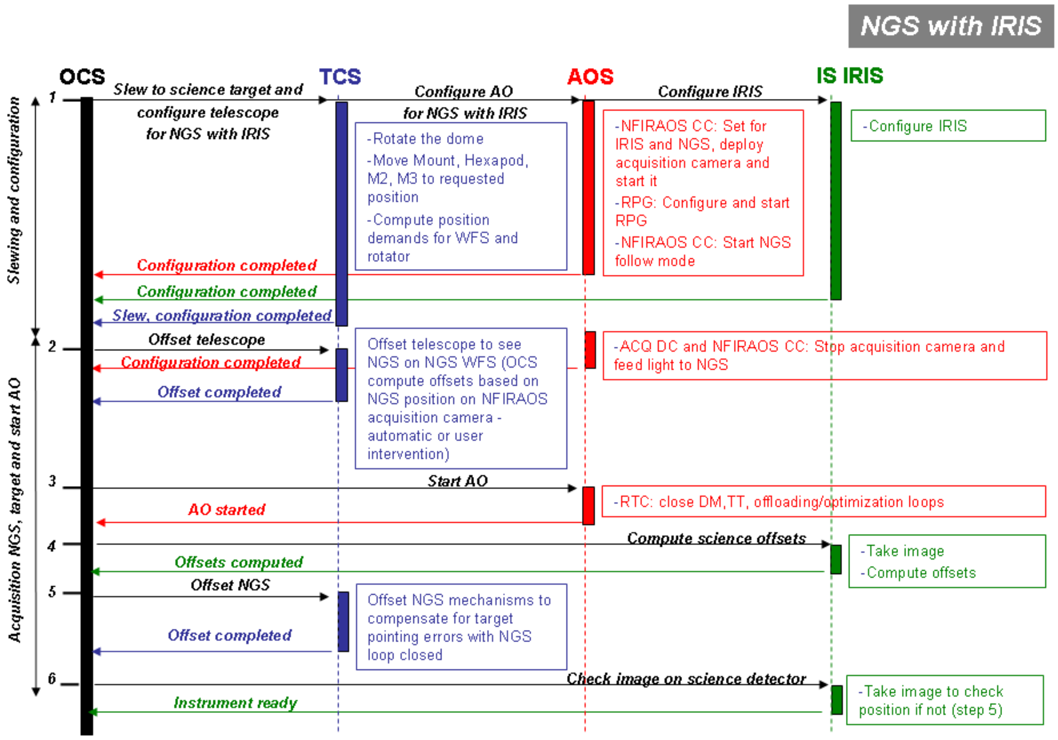


Figure: Example acquisition scheme for a NGS MCAO system configuration (IRIS). FOV of guide (TT) WFS is not enough for blind pointing the telescope on the WFS; Instrument acquisition camera is needed.

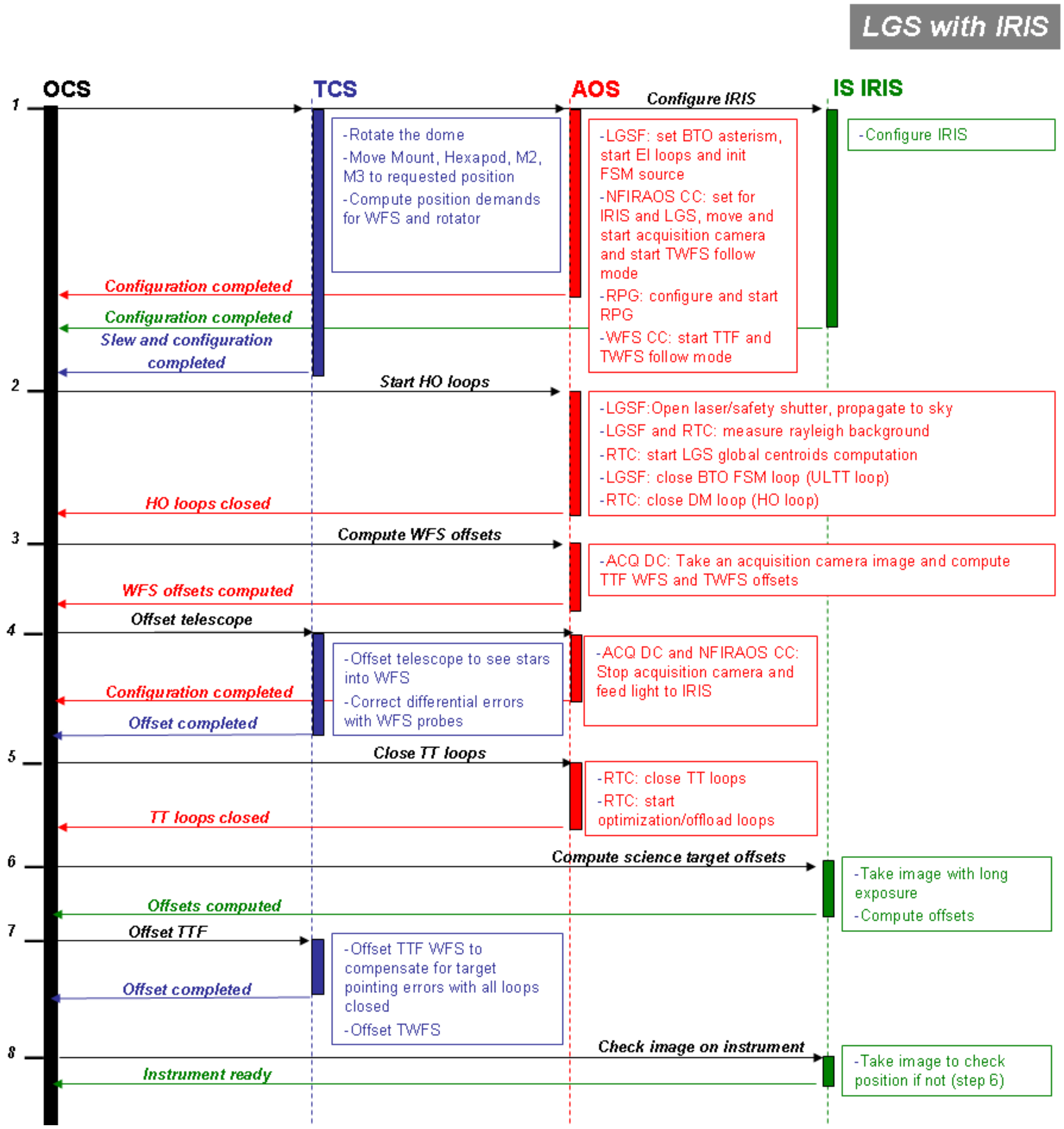


Figure: Example acquisition scheme for a LGS MCAO system configuration (IRIS). Procedure is similar to the previous figure, but for faint guide stars. The faint natural guide stars are enhanced by higher order, LGS based AO correction.

7.3 OBSERVATORY CONTROL ARCHITECTURE

Table: 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		
M1	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
M1	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
M2	Tip/Tilt	2	Hexapod	Local encoder	≥ 10	< 1	0.1	APS/GMS[9]				
M2	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]		
M3	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 more frequently is TBD.
11 Coma will be corrected on M2 via tip/tilt, de-center, or rotation about the neutral point. The optimum approach is TBD; the architecture will easily support any of these three possibilities.
12 Focus will be corrected via M2 piston.
13 The instruments and the APS will have the ability to slowly control pupil position via M3 tilt.

7.4 FIRST DECADE INSTRUMENT LAYOUT

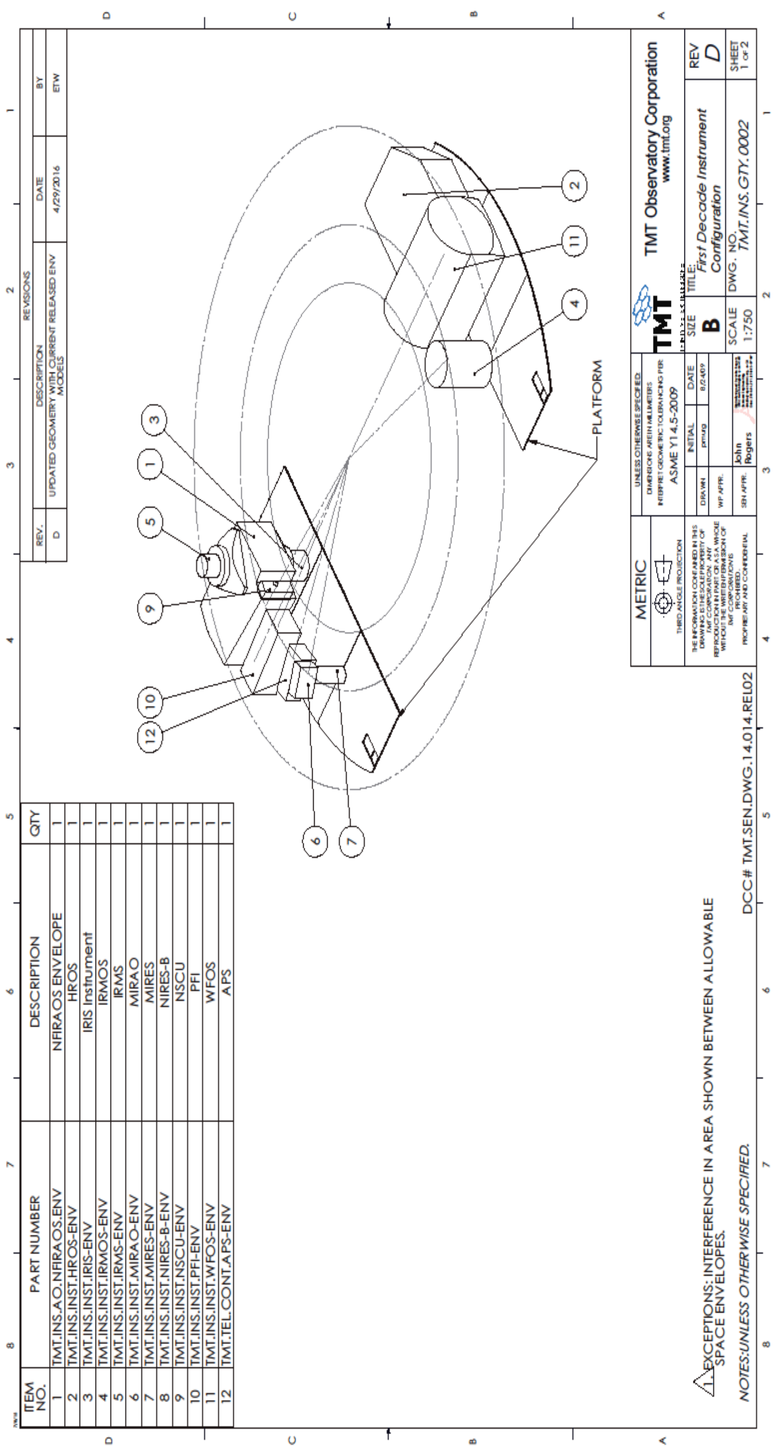


Figure: Full SAC Instrument Layout (RD24)

Discussion: The -X Nasmyth is configured as follows: NFIRAOS and its associated instruments (any three of IRIS, IRMS, NIRES and WIRC) are located at the 174.5 degree position. PFI is located at the +183 degree position, APS at its desired +194 degree position, and MIRES/MIRAO is at +203 degrees.

The +X Nasmyth is configured as follows: WFOS is oriented horizontally on the elevation axis (0 degrees). HROS is located at the back of this platform, within the trimmed envelope, and is fed by the M3 at +5 degrees. The beam to HROS must be deflected in front of WFOS to reach the instrument. IRMOS is located at the -20 degree location on this platform.

7.5 ENCLOSURE GEOMETRY DRAWING

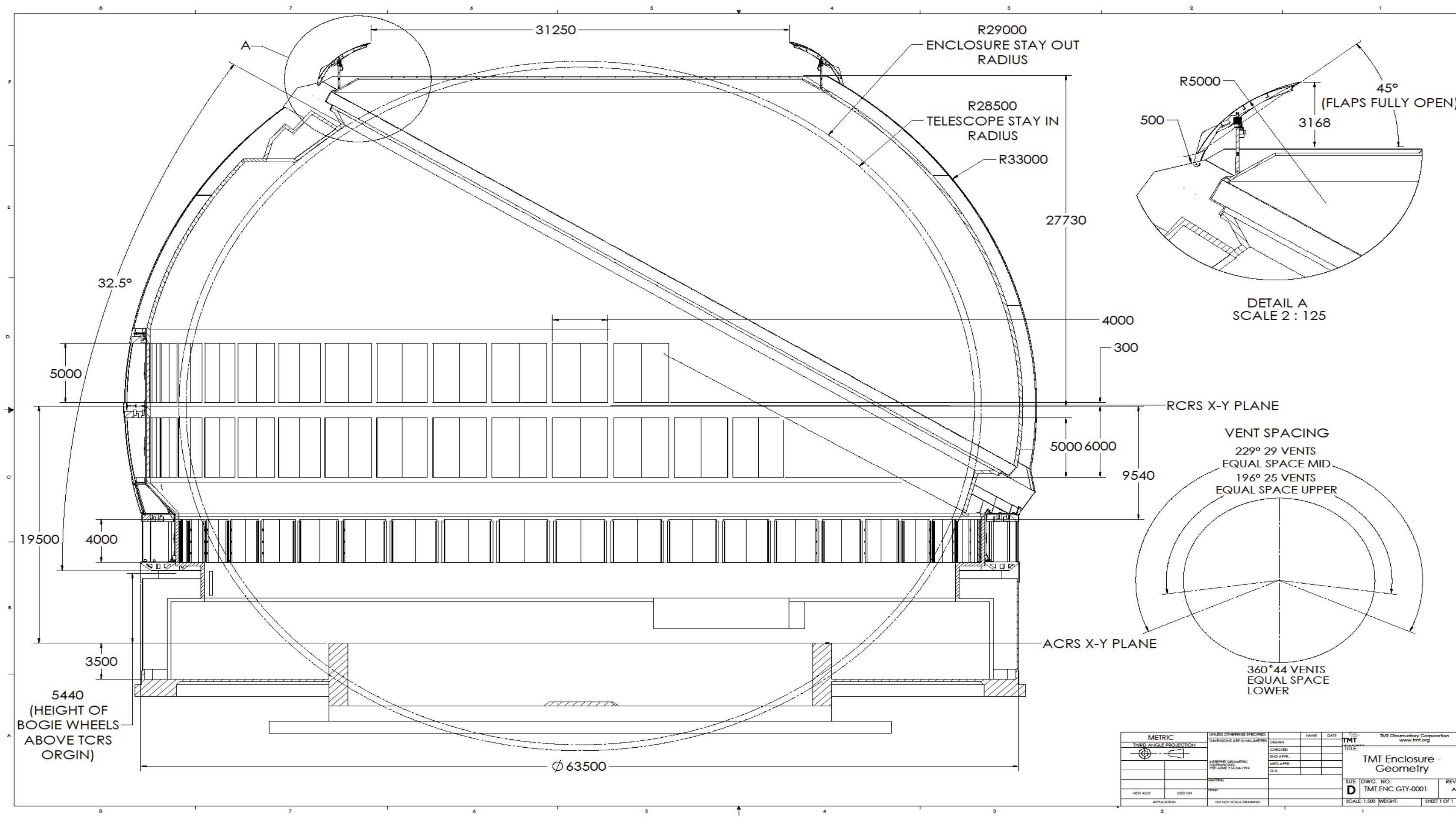


Figure: TMT Enclosure Geometry (AD75)

7.6 EXAMPLE MIRROR COATING REFLECTANCE CURVES

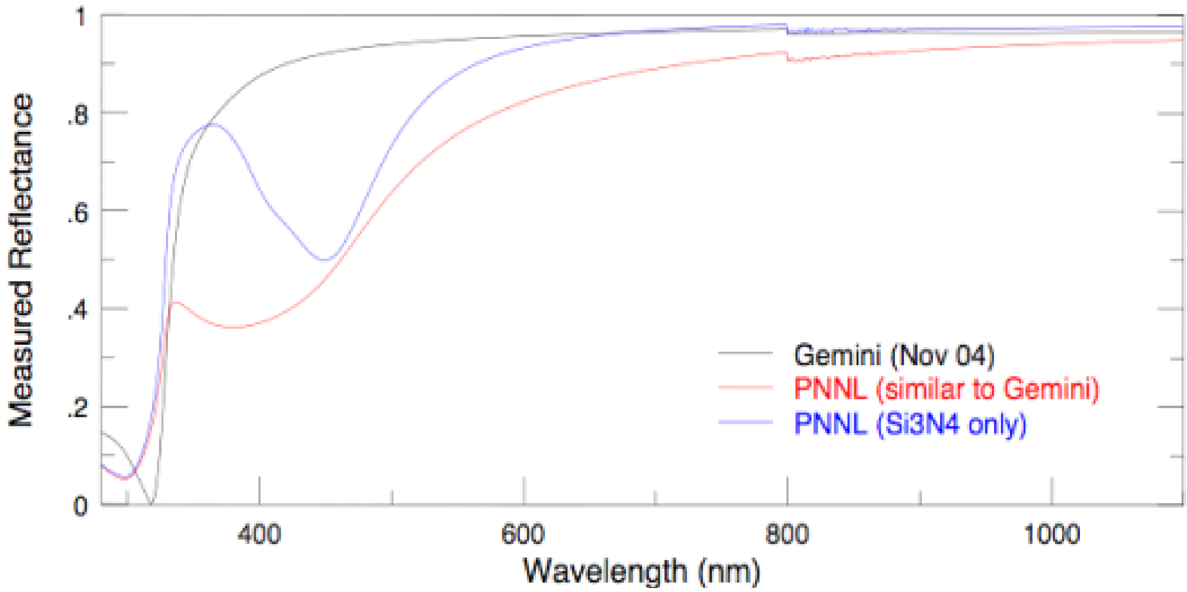


Figure: Gemini coating plus other coatings in development. Dip in reflectivity other coatings is caused by surface Plasmon resonances.

8. OPEN ISSUES

Discussion: Regarding [REQ-1-OAD-3092] K-band Background: What about all other bands? We may need to add additional OAD requirements to cover background in other bands for the IRIS CSRO, Imager, IFS and cryostat. It also seems that the IRIS level 2 requirements should be split into separate requirements for background in K-band and other bands. We will have to talk with the IRIS team to sort out if and what the OAD requirement should be for background. That will not happen until after the IRIS review.