OBSERVATORY ARCHITECTURE DOCUMENT

TIO.SEN.DRD.05.002.CCR41

December 18, 2024

SIGNATURE PAGE

Author Release Note:
See Document Change Record for change requests incorporated at this time

Prepared By:
See CR authors in Document Change Record.

Concurrence:

\signature on file\

Gelys Trancho
TIO Project Systems Engineer

\signature on file\

Robert Anderson
TIO ES&H Group Leader

Approval:

\signature on file\

Fengchuan Liu
TIO Project Manager

Document Change Record

Revision	Change Request Approval	Release Approval	Date Released
CCR41	CR392: Collection-31675 CR406: Collection-34097 CR407: Collection-34098 CR409: Collection-34428 CR411: Collection-34836 CR412: Collection-34837 CR417: Collection-35017 CR422: Collection-35027 CR424: Collection-35029 CR425: Collection-35030 CR429: Collection-35274 CR434: Collection-35421 CR448: Collection-36291 CR449: Collection-38346 CR455: Collection-38511 CR456: Collection-38583 Done: VIB, DATA, CIS, POINT, REL, Actuator/Stroke, PLATE, OPD Wavefront, CR457: Collection-38584 CR459: Collection-38659 CR469: Collection-38843 CR470: Collection-38935 CR479: Collection-40475 CR480: Collection-40628 CR481: Collection-40773 (part 1) CRADMIN Changed TMT to TIO	G. Trancho routing #119796	December 18, 2024
CCR40	CR333: Collection-25970, CR334: Collection-25975, CR345: Collection-33507, CR359: Collection 28825, CR376: Collection 29710, CR390: Collection-30989, CR391: Collection-31030, CR392: Collection-31675,	G. Trancho routing #91843	September 29, 2022

	CR398: Collection-32461, CR402: Collection-33464, CR408: Collection-34848, CRADMIN		
CCR39	CR278: Collection-20093, CR299: Collection-23478, CR313: Collection-24819, CR328: Collection-25943, CR341: Collection-26259, CR357: Collection-28650, CR360: Collection-28841, CR362: Collection-29732, CR363: Collection-28923, CR365: Collection-29387, CR366: Collection-29390, CR367: Collection-29391, CR368: Collection-29406, CR372: Collection-29529, CR373: Collection-29556, CR375: Collection-29755, CR379: Collection-29890, CR380: Collection-29956, ADMIN: ADs	G. Trancho, routing #76953	May 24, 2021
CCR38	Released per: CR279: Collection-20094, CR322: Collection-26053, CR324: Collection-25666, CR302: Collection-23830, CR337: Collection-26045, CR321: Collection-25545, CR338: Collection-26133, CR344: Collection-26683, CR352: Collection-28522, CR355: Collection-28559, CR356: Collection-28620, CR361: Collection-28892, ADMIN: Figures and Table numbers, ADs	G. Trancho, routing #68533	October 27, 2020
CCR37	Released per: CR273: Collection-24689, CR282: Collection-24347, CR296: Collection-22983, CR309: Collection-24408,	G. Trancho, routing #59136	January 8, 2020

	CR318: Collection-25410, CR301: Collection-23669, CR302: Collection-23830, ADMIN		
CCR36	Released per: CR233: Collection-14943, CR243: Collection-19722, CR276: Collection-20085, CR277: Collection-20092, CR287: Collection-23633, CR291: Collection-22522, CR295: Collection-22934, CR298: Collection-23602, CR300: Collection-23480, ADMIN	G. Trancho, routing #48542	March 7, 2019
CCR35	Released per: CR143: Collection-8486, CR232: Collection-14939, CR244: Collection-15785, CR257: Collection-16224, CR259: Collection-16182, CR261: Collection-16318, CR266: Collection-16771, CR268: Collection-19721, CR270: Collection-19843, CR272: Collection-19852, ADMIN: AD/RD updates	S. Roberts, routing #32643	June 18, 2018
CCR34	Released per: CR225: Collection-14719, CR240: Collection-15481 CR242: Collection-15738, ADMIN: Update IRIS, APS, CRYO, M2 envelope ADs	S. Roberts, routing #26275	January 23, 2018
CCR33	Released per: CR218: Collection-13981, CR235: Collection-14957 ADMIN: Update LGSF drawing ADs	S. Roberts, routing # 19749	September 13, 2017
CCR32	Released per: CR161: Collection-9292 (missing from CCR30),	S. Roberts, routing # 16397	June 5, 2017

	CR175: Collection-10859, CR198: Collection-12467, CR203: Collection-12579, CR222: Collection-14558, ADMIN: Update AD/RDs		
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, TIO.SEN.TEC.07.038.REL10	See approval page in CCR25	June 6, 2012
CCR24	Released per: CR050: Collection-4199, CR087: Collection-5447,	See approval page in CCR24	October 12, 2011

	CR090: Collection-5508, CR093: Collection-5627, Updates as per Level 1 DRD Change History Document, TIO.SEN.TEC.07.038.REL09		
CCR23	Released per: CR080: Collection-4913, Updates as per Level 1 DRD Change History Document, TIO.SEN.TEC.07.038.REL08	See approval page in CCR23	December 1, 2010
CCR22	Released per: CR062: Collection-4324, CR070: Collection-4529, CR071: Collection-4564, CR072: Collection-4566 Updates as per Level 1 DRD Change History Document, TIO.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, TIO.SEN.TEC.07.038.REL06	See approval page in CCR21	December 17, 2009
CCR20	Updates as per Level 1 DRD Change History Document, TIO.SEN.TEC.07.038.REL05	See approval page in CCR20	March 27, 2009
CCR19	Updates as per Level 1 DRD Change History Document, TIO.SEN.TEC.07.038.REL04	See approval page in CCR19	January 28, 2009
CCR18	Updates as per Level 1 DRD Change History Document, TIO.SEN.TEC.07.038.REL03	See approval page in CCR18	September 4, 2008
CCR17	Updates as per Level 1 DRD Change History Document, TIO.SEN.TEC.07.038.REL02	See approval page in CCR17	March 19, 2008
CCR16	Updates as per Level 1 DRD Change History Document, TIO.SEN.TEC.07.038.REL01	See approval page in CCR16	November 14, 2007
CCR15	Updates as per systems engineering watch list document, TIO.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 TIO.SEN.TEC.07.025.DRF05	See approval page in CCR13	May 25, 2007

Document Waiver Log

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

TABLE OF CONTENTS

TABLE OF TABLES

TABLE OF FIGURES

1 INTRODUCTION

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

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

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

1.1 PURPOSE

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

It does not contain requirements that define the overall performance of the observatory as viewed in the context of the top-level Science Requirements Document (SRD) (RD33) and Operations Requirement Document (OpsRD) (RD35).

1.2 SCOPE

This document outlines high-level site-specific requirements organized into the following key areas:

- **System Definition**: provides a clear decomposition and description of the overall system, establishing a foundation for the observatory's structure and functionality.
- **System Budgets:** defines key performance metrics and constraints, including reliability, availability, error budgets, and other essential allocations that ensure the observatory meets its operational goals.
- **System Specification:** details the technical and functional specifications of the observatory's components and subsystems, ensuring alignment with performance and scientific objectives.
- **System Software and Control Architecture:** focuses on the software and control systems, providing a framework for seamless integration and coordinated operation of all observatory systems. This architecture ensures the observatory's efficiency, precision, and adaptability.

1.3 APPLICABLE DOCUMENTS

AD1-AD15 Deleted

AD16 TIO M1S Segmentation Database

TIO.OPT.TEC.07.044 CCR17

https://docushare.tmt.org/docushare/dsweb/Get/Version-119022

AD17-AD36 Deleted

AD37 TIO System Level Hazard Analysis

TIO.SEN.TEC.13.001 REL12

https://docushare.tmt.org/docushare/dsweb/Get/Version-104788

AD38 Deleted

AD39 Directive 2011/65/EU of the European Parliament and of the Council of 8 June 2011 on the restriction of the use of certain hazardous substances in electrical and electronic equipment (including CORRIGENDUM)

Directive 2011-65-EU

https://docushare.tmt.org/docushare/dsweb/Get/Version-49518

AD40 Reserved

AD41 Pupil Obscuration Pattern
CAD Drawing No: TIO.TEL.GTY-0001 Rev D
TIO.SEN.DWG.14.003 REL01
https://docushare.tmt.org/docushare/dsweb/Get/Version-47459

AD42 STR Keep-In Space Envelope
CAD Drawing No: TIO.TEL.STR-ENV Rev E
TIO.SEN.DWG.12.012 REL06
https://docushare.tmt.org/docushare/dsweb/Get/Version-109406

AD43-AD51 Deleted

AD52 Nasmyth Platform Instrument Envelope
CAD Drawing No: TIO.INS.GTY-0003 Rev C
TIO.SEN.DWG.14.004 REL03
https://docushare.tmt.org/docushare/dsweb/Get/Version-134823

AD53-AD69 Deleted

AD70 ENC Stay Out Space Envelope
CAD Drawing No: TIO.FAC.ENC-ENV Rev E
TIO.SEN.DWG.12.013 REL05
https://docushare.tmt.org/docushare/dsweb/Get/Version-109410

AD71 STR Top End Space Envelope
CAD Drawing No: TIO.FAC.ENC.TEP-ENV Rev D
TIO.SEN.DWG.14.008 REL04
https://docushare.tmt.org/docushare/dsweb/Get/Version-134784

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

AD73 Light Beams for TIO Instruments
CAD Drawing No: TIO.SEN.OPTBEAM-ENV Rev B
TIO.SEN.DWG.11.003 REL02
https://docushare.tmt.org/docushare/dsweb/Get/Version-128716

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

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

AD76-AD78 Deleted

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

AD80 TIO Environmental Safety and Health Hazard/Risk Assessment Processes and Guidelines
TIO.PMO.MGT.10.004 CCR11

https://docushare.tmt.org/docushare/dsweb/Get/Version-144666

AD81 M1 Field of View Keep Out Volume
CAD Drawing No: TIO.TEL.GTY-0003 Rev B
TIO.SEN.DWG.17.001 REL02
https://docushare.tmt.org/docushare/dsweb/Get/Version-139714

AD82-AD83 Deleted

AD84 Design Requirements Document for the Local Safety Controllers
TIO.CTR.DRD.17.001 CCR02
https://docushare.tmt.org/docushare/dsweb/Get/Version-140762

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

AD86 TIO Software Design Document Software Architecture and Design-Conceptual Design Phase (Vol 1 of 2)
TIO.SFT.TEC.12.014 REL06
https://docushare.tmt.org/docushare/dsweb/Get/Version-70041

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

AD88-AD90 Deleted

AD91 Observatory Safety Access Summary
TIO.SEN.TEC.17.065 REL06
https://docushare.tmt.org/docushare/dsweb/Get/Version-113631

AD92 Deleted

AD93 Telescope Work Areas
TIO.STR.DRD.15.003 REL04
https://docushare.tmt.org/docushare/dsweb/Get/Version-98583

AD94-AD95 Deleted

AD96 Telescope Azimuth and Elevation Wrap Allocations
TIO.SEN.TEC.18.023 REL16
https://docushare.tmt.org/docushare/dsweb/Get/Version-143201

AD97 Space Envelope, Maximum Component Size
CAD Drawing No: TIO.SEN.GTY-0003 Rev A
TIO.SEN.DWG.20.003 REL01
https://docushare.tmt.org/docushare/dsweb/Get/Version-111447

AD98 First Light Instrument Configuration
CAD Drawing No: TIO.INS.GTY-0001 Rev J
TMT.SEN.DWG.14.006 REL07
https://docushare.TIO.org/docushare/dsweb/Get/Version-139650

AD99 First Decade Instrument Configuration
CAD Drawing No: TIO.INS.GTY-0002 Rev H
TIO.SEN.DWG.14.014 REL06
https://docushare.TIO.org/docushare/dsweb/Get/Version-136978

AD100 TIO Sub-Systems Electronics Space Envelopes
CAD Drawing No: TIO.SEN.GTY-0001 Rev E
TIO.SEN.DWG.18.003 REL05
https://docushare.tmt.org/docushare/dsweb/Get/Version-132681

AD101 Telescope-Mounted Subsystems Space Envelopes
CAD Drawing No: TIO.SEN.GTY-0006 Rev A
TIO.SEN.DWG.20.026 REL01
https://docushare.tmt.org/docushare/dsweb/Get/Version-118339

AD102 Safety of machinery -- Emergency stop function -- Principles for design
ISO 13850 Edition 3
https://www.iso.org/standard/59970.html

AD103 3F and 4F Floor Cart Path
CAD Drawing No: TIO.SEN.GTY-0013 Rev B
TIO.SEN.DWG.20.009 REL02
https://docushare.tmt.org/docushare/dsweb/Get/Version-134782

1.4 Reference Documents

RD1 TIO Interface N2 Diagram
TIO.SEN.TEC.05.035
https://docushare.tmt.org/docushare/dsweb/Get/Document-4780

RD2 TIO M1CS Actuator Range and M1S Warping Harness Stroke Performance Budgets
TIO.SEN.TEC.20.085
https://docushare.tmt.org/docushare/dsweb/Get/Document-85052

RD3 TIO Image Size and Wavefront Error Budgets, Report No. 10 (V.11.0), Volume 1 of 3
TIO.OPT.TEC.07.021
https://docushare.tmt.org/docushare/dsweb/Get/Document-8822
TIO Image Size and Wavefront Error Budgets, Report No. 10 (V.11.0), Volume 2 of 3
TIO.OPT.TEC.07.022
https://docushare.tmt.org/docushare/dsweb/Get/Document-8823
TIO Image Size and Wavefront Error Budgets, Report No. 10 (V.11.0), Volume 3 of 3
TIO.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
TIO.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 TIO Product Breakdown Structure

TIO.SEN.TEC.19.010

https://docushare.tmt.org/docushare/dsweb/Get/Document-76646

RD9 TIO Product Data Package Definition

TIO.SEN.SPE.12.001

https://docushare.tmt.org/docushare/dsweb/Get/Document-21506

RD10 Impact of Observatory Wavefront Errors upon DM Stroke Requirements for NFIRAOS

TIO.AOS.TEC.08.028

https://docushare.tmt.org/docushare/dsweb/Get/Document-10919

RD11 TIO Coordinate Systems and Transforms

TIO.SEN.TEC.07.031

https://docushare.tmt.org/docushare/dsweb/Get/Document-8763

RD12 Seeing-Limited Plate Scale Distortion Variation (PSDV) Budget

TIO.TEL.TEC.09.001

https://docushare.tmt.org/docushare/dsweb/Get/Document-13037

RD13-RD14 Deleted

RD15 Normalized point source sensitivity for off-axis optical performance evaluation of the Thirty Meter Telescope by B-J Seo et al., SPIE Proceedings 7738(Vol. 77380G, 2010)

TIO.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

TIO.STR.TEC.10.001

URS Report 33761857

https://docushare.tmt.org/docushare/dsweb/Get/Document-16229

RD17 Specification and Analysis of TIO Seismic Requirements for STR and STR Mounted Subsystems

TIO.SEN.TEC.12.009

https://docushare.tmt.org/docushare/dsweb/Get/Document-22542

RD18 Overview of the TIO Safety Architecture

TIO.SEN.TEC.14.028

https://docushare.tmt.org/docushare/dsweb/Get/Document-32282

RD19 Image Quality (PSS) Error Budget

TIO.SEN.DRD.07.026

https://docushare.tmt.org/docushare/dsweb/Get/Document-9105

RD20 TIO NFIRAOS LGS MCAO, NGSAO and IRIS Imager Wavefront Error Budget and Current Best Estimate

TIO.AOS.COR.16.062

https://docushare.tmt.org/docushare/dsweb/Get/Document-52202

RD21 Mass Budget for Telescope Mounted Subsystems
TIO.SEN.TEC.07.028
https://docushare.tmt.org/docushare/dsweb/Get/Document-8607

RD22 Vibration Budget
TIO.SEN.TEC.14.009
https://docushare.tmt.org/docushare/dsweb/Get/Document-27582

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

RD24 -RD28 Deleted

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

RD30 - RD31 Deleted

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

RD33 Science-Based Requirements Document
TIO.PSC.DRD.05.001
https://docushare.tmt.org/docushare/dsweb/Get/Document-319

RD34 Deleted

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

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

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

RD38 -RD39 Deleted

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

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

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

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

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

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

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

RD47 TIO Reliability Budget Spreadsheet
TIO.SEN.TEC.07.006
https://docushare.tmt.org/docushare/dsweb/Get/Document-8088

RD48 Acquisition Time Budget
TIO.SEN.TEC.16.029
https://docushare.tmt.org/docushare/dsweb/Get/Document-66286

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

RD50 -RD51 Deleted

RD52 TIO AO Astrometry Error Budget Rationale
TIO.AOS.TEC.12.039
https://docushare.tmt.org/docushare/dsweb/Get/Document-31383

RD53 TIO AO Astrometry Error Budget
TIO.AOS.TEC.14.066
https://docushare.tmt.org/docushare/dsweb/Get/Document-31384

RD54 Point Source Sensitivity Error Budget for NFIRAOS and IRIS Imager
TIO.SEN.TEC.16.088
https://docushare.tmt.org/docushare/dsweb/Get/Document-58304

RD55 Point Source Sensitivity and Pupil Alignment Budget Description for NFIRAOS and IRIS Imager
TIO.AOS.TEC.17.165
https://docushare.tmt.org/docushare/dsweb/Get/Document-63843

RD56 End to end M1 Pupil Undersizing Budget for IRIS Lyot Mask
TIO.AOS.TEC.17.167
https://docushare.tmt.org/docushare/dsweb/Get/Document-63844

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

RD58 -RD59 Deleted

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

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

RD62 TIO Photometry Error Budget
TIO.OPT.TEC.20.004
https://docushare.tmt.org/docushare/dsweb/Get/Document-85501

RD63 TIO Photometry Error Budget Description Report
TIO.OPT.TEC.20.005
https://docushare.tmt.org/docushare/dsweb/Get/Document-85502

RD64 TIO Maintenance Budget
TIO.SEN.TEC.19.009
https://docushare.tmt.org/docushare/dsweb/Get/Document-76642

RD65 TIO Seeing-Limited Off-Axis Image Budget Rationale
TIO.SEN.TEC.16.032
https://docushare.tmt.org/docushare/dsweb/Get/Document-67263

RD66 TINS Use Cases
TIO.SEN.TEC.20.059
https://docushare.tmt.org/docushare/dsweb/Get/Document-83579

RD67 TIO Pointing Error Budget
TIO.SEN.TEC.21.013
https://docushare.tmt.org/docushare/dsweb/Get/Document-87471

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

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

RD70 TIO Throughput Budget
TIO.SEN.TEC.16.087
https://docushare.tmt.org/docushare/dsweb/Get/Document-58294

RD71 TIO Cranes, Lifts, and Deployable Maintenance Platforms
TIO.SEN.TEC.22.007
https://docushare.tmt.org/docushare/dsweb/Services/Document-94567

RD72 ESW User Interface Integration Detailed Design
TIO.SFT.TEC.18.014
https://docushare.tmt.org/docushare/dsweb/Get/Document-73509

RD73 TIO Measuring Equipment Vibration Contributions to TIO Image Jitter
TIO.SEN.TEC.21.022
https://docushare.tmt.org/docushare/dsweb/Get/Document-88291

RD74 Ritchey-Chrétien Baseline Design
TIO.SEN.SPE.06.001
https://docushare.tmt.org/docushare/dsweb/Get/Document-7364

1.5 ABBREVIATIONS

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

2 SYSTEM DEFINITION

2.1 GENERAL

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

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

2.2 TIO STANDARDS

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

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

Compliance with these standards is generally governed either by SOW or local government permitting and inspection processes. The Systems Engineering (SE) verification process does not apply to standards, unless specific standards are enumerated as requirements in a DRD. The verification of standards, codes and regulation is cover by the TIO Product Data Package Definition (PDPD, RD9).

2.3 TIO DECOMPOSITION

TIO System decomposition (Table 2-1) identifies WBS (RD36) elements that are not just tasks, but also deliverable subsystems of the observatory. The list of subsystems below is comprehensive, i.e. the aggregate of these subsystems will form the complete observatory.

TIO Product Breakdown Structure (PBS, RD8) is decomposed into the subsystems as shown in 'Table 2-1: TIO Decomposition' below.

Table 2-1: TIO Decomposition (PBS vs WBS)

System (PBS)	Related WBS Element(s)
Facilities	
Enclosure (ENC)	TMT.FAC.ENC
Sea Level Facilities (SLF)	TMT.FAC.INF.SLF.HQ , TMT.FAC.INF.SLF.WH
Summit Facilities (SUM)	TMT.FAC.INF.SUM, TMT.FAC.INF.ROAD
Telescope	
Alignment and Phasing System (APS)	TMT.TEL.CONT.APS
Engineering Sensors (ESEN)	TMT.TEL.CONT.ESEN
M1 Coating System (M1 COAT)	TMT.TEL.OPT.COAT.M1
M1 Control System (M1CS)	TMT.TEL.CONT.M1CS
M1 Optics System (M1S)	TMT.TEL.OPT.M1
M2 System (M2S)	TMT.TEL.OPT.M2
M2/M3 Coating System (M2/M3 COAT)	TMT.TEL.OPT.COAT.M2M3
M3 System (M3S)	TMT.TEL.OPT.M3
Observatory Safety System (OSS)	TMT.TEL.CONT.OSS
Optical Cleaning Systems (CLN)	TMT.TEL.OPT.CLN
Optics Handling Equipment (HNDL)	TMT.TEL.OPT.HNDL
Telescope Control System (TCS)	TMT.TEL.CONT.TCS
Telescope Structure (STR)	TMT.TEL.STR
Test Instruments (TINS)	TMT.TEL.OPT.TINS, TMT.TEL.CONT.TINC
Instrumentation	
First Light	
Adaptive Optics Executive Software (AOESW)	TMT.INS.AO.AOESW
Cryogenic Cooling System (CRYO)	TMT.INS.COOL.CRYO
InfraRed Imaging Spectrometer (IRIS)	TMT.INS.INST.IRIS, TMT.INS.AO.COMP.IRCAM.IRIS
Laser Guide Star Facility (LGSF)	TMT.INS.AO.LGSF, TMT.INS.AO.COMP.SLASR
Multi-Objective Diffraction-limited High-Resolution Infrared Spectrograph (MODHIS)	TMT.INS.INST.MODHIS, TMT.INS.AO.COMP.IRCAM.MODHIS
Narrow Field Near Infrared On-Axis AO System (NFIRAOS)	TMT.INS.AO.NFIRAOS
	TMT.INS.AO.COMP.VCAM.NFIRAOS
	TMT.INS.AO.COMP.RTC.NFIRAOS
	TMT.INS.AO.COMP.WC.NFIRAOS
	TMT.INS.AO.NFIRAOS.NSCU
Refrigerant Cooling System (REFR)	TMT.INS.COOL.REFR
Wide Field Optical Spectrometer (WFOS)	TMT.INS.INST.WFOS
First Decade	
Adaptive secondary Mirror System (AM2)	
High Resolution Optical Spectrometer (HROS)	
Near-Infrared Multi-Object Sectrometer (IRMOS)	
Mid-Infrared AO System (MIRAO)	
Mid-Infrared Echelle Spectrometer (MIRES)	
Near Infrared Echelle Spectrometer (NIRES-R)	
NFIRAOS Side Instrument (NSI)	
Planet Formation Instrument (PFI)	
Operations	
Communications and Information Systems (CIS)	TMT.DEOPS.CIS
Common Software (CSW)	TMT.DEOPS.OSW.CSW
Data Management System (DMS)	TMT.DEOPS.OSW.DMS
Executive Software (ESW)	TMT.DEOPS.OSW.ESW
Site Conditions Monitoring System (SCMS)	TMT.DEOPS.SCMS
US-ELTP (SOSS, DPS)	TMT.DEOPS.OSW.UPP

2.4 INTERFACES

The interfaces between the subsystems are as defined in the TIO Interface N2 Diagram (RD1).

Utilities such as electrical power, coolants, compressed air, and data and control signals are supplied by some subsystems, physically distributed across other subsystems, and supplied to yet another set of subsystems. To simplify the TIO 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 SYSTEM BUDGETS

3.1 RELIABILITY AND AVAILABILITY BUDGETS

A detailed discussion of the TMT International Observatory (TIO) Reliability and Availability Budget is given in (RD57).

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

Table 3-1: TIO Downtime Allocation (RD47)

		Normal Observing		Degraded Mode
Requirement ID	Description	Downtime (no backup available)	Downtime (backup available)	Operating in Degraded Mode
[REQ-1-OAD-0311]	TIO Downtime (First Light and First Decade)	3%		7%
[REQ-1-OAD-0312]	**Facilities**	0.41%		1.32%
	Enclosure (ENC)	0.39%		1.05%
	Sea Level Facilities (SLF)	N/A		N/A
	Summit Facilities (SUM)	0.02%		0.26%
[REQ-1-OAD-0314]	**Telescope**	1.21%		4.59%
	Alignment and Phasing System (APS)	0.02%		0.01%
	Engineering Sensors (ESEN)	0.01%		0.00%
	M1 Coating System (M1 COAT)	N/A		N/A
	M1 Control System (M1CS)	0.24%		4.09%
	M1 Optics System (M1S)	0.03%		0.16%
	M2 Optics System (M2S)	0.16%		0.01%
	M2/M3 Coating System (M2/M3 COAT)	N/A		N/A
	M3 Optics System (M3S)	0.16%		0.03%
	Observatory Safety System (OSS)	0.04%		0.00%
	Optical Cleaning System (CLN)	0.01%		0.01%
	Optics Handling Equipment (HNDL)	N/A		N/A
	Telescope Control System (TCS)	0.02%		0.00%
	Telescope Structure (STR)	0.51%		0.27%
	Test Instruments (TINS)	N/A		N/A
	Instrumentation			
[REQ-1-OAD-0348]	**First Light**	0.82%		1.10%
	AO Executive Software (AOESW)	0.08%		0.00%
	Cryogenic Cooling System (CRYO)	0.10%		0.00%
	InfraRed Imaging Spectrometer (IRIS)		0.12%	0.14%
	Laser Guide Star Facility (LGSF)		0.19%	0.14%
	Multi-Objective Diffraction Limited High Resolution Spectrograph (MODHIS)		0.12%	0.02%
	Narrow Field Near Infrared AO System (NFIRAOS)	0.43%		0.71%
	Refrigerant Cooling System (REFR)	0.10%		0.00%
	Wide Field Optical Spectrometer (WFOS)		0.14%	0.09%
N/A	**First Decade**	0.72%		0.60%
	Adaptive secondary Mirror System (AM2)	0.16%		0.01%
	High Resolution Optical Spectrometer (HROS)		0.14%	0.02%
	Near-Infrared Multi-Object Sectrometer (IRMOS)		0.12%	0.14%
	Mid-Infrared AO System (MIRAO)	0.42%		0.60%
	Mid-Infrared Echelle Spectrometer (MIRES)		0.12%	0.14%
	Near Infrared Echelle Spectrometer (NIRES-R)		0.12%	0.02%
	NFIRAOS Side Instrument (NSI)		0.12%	0.02%
	Planet Formation Instrument (PFI)		0.30%	0.14%
[REQ-1-OAD-0370]	**Operations**	0.26%		0.00%
	Common Software (CSW)	0.02%		0.00%
	Communication and Information Systems (CIS)	0.01%		0.00%
	Data Management System (DMS)	0.03%		0.00%
	Executive Software (ESW)	0.14%		0.00%
	Site Conditions Monitoring System (SCMS)	0.02%		0.00%
	US-ELTP (SOSS, DPS)	0.04%		0.00%
	Reserve	0.20%		0.00%

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

3.2 HEAT DISSIPATION BUDGETS

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

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

Requirement ID	Description	Location	Power Dissipated to Air (kW), average – Inside Summit Facilities – Daytime REQ	Inside Summit Facilities – Nighttime REQ	Inside Enclosure – Daytime REQ	Inside Enclosure – Nighttime REQ	Notes
[REQ-1-OAD-0499]	TIO Power Dissipated to Air (First Light and First Decade)	Total	173.6	141.1	54.0	23.0	(5)
		SF 0	1.3	1.3			
		SF 1 [CR]	47.4	59.2			(1)
		SF 1 [UR]	124.5	79.6			(2)
		FB 1	15.4	9.1	10.6	0.3	(5)
		AZ 0			4.7	2.5	
		NAS -X 3			0.3		
		NAS +X 3			0.3		
		-X			11.8	2.9	(7)
		+X			11.8	2.9	(7)
		M1C 5			8.9	9.3	
		NAS -X 4			2.6	2.6	
		NAS +X 4			0.9	0.9	
		EL -X 5			1.5	1.8	
		EL +X 5			0.5		
		TOP 7			0.2	0.3	(3)
		Reserve	0.3	1.2	0.9	0.4	
[REQ-1-OAD-0501]	Facilities		70.3	23.2	11.9	1.6	
	Enclosure (ENC)	SF 1 [CR]					(6), (1)
		FB 1			10.60	0.30	
	Summit Facilities (SUM)	SF 1 [UR]	69.00	22.90			(2)
		-X			0.65	0.65	(7)
		+X			0.65	0.65	(7)
		SF 1 [CR]	1.30	0.30			
[REQ-1-OAD-0515]	Telescope		54.6	50.0	36.4	16.1	
	Alignment and Phasing System (APS)	NAS -X 4			0.09	0.09	
		NAS -X 4			0.21	0.21	
		SF 1 [CR]	0.51	0.24			
	Engineering Sensors (ESEN)	-X			0.30	0.30	
		+X			0.30	0.30	
		SF 1 [CR]	0.40	0.40			(1)
	M1 Coating System (M1 COAT)	SF 1 [UR]	15.44	9.05			(2), (4)
	M2/M3 Coating System (M2/M3 COAT)	FB 1	15.44	9.05			(4), (5)
	M1 Optics System (M1S)	N/A					
	M1 Control System (M1CS)	M1C 5			6.50	6.50	
		M1C 5			2.00	2.00	
		SF 1 [CR]	1.21	2.41			
	M2 Optics System (M2S)	TOP 7			0.09	0.09	
		SF 1 [CR]					(6),(1)
		EL -X 5			0.21	0.51	
	M3 Optics System (M3S)	M1C 5			0.15	0.30	
		SF 1 [CR]					(6),(1)
		M1C 5			0.21	0.51	
	Optical Cleaning System (CLN)	NAS -X 3			0.17		
		NAS +X 3			0.16		
		NAS -X 3			0.15		
		NAS +X 3			0.15		
		SF 1 [CR]	0.16				
	Optics Handling Equipment (HNDL)	N/A					
	Observatory Safety System (OSS)	SF 1 [CR]	0.60	0.60			(1)
		-X			0.05	0.05	(1),(7)
		+X			0.05	0.05	(1),(7)
	Telescope Structure (STR)	SF 1 [UR]	13.40	20.90			
		SF 1 [UR]	5.50	5.50			
		SF 1 [CR]					(6),(1)
		AZ 0			4.70	2.50	
		SF 0	1.30	1.30			
	Telescope Utilities (STR.TUS)	-X			10.20	1.35	(7)
		+X			10.20	1.35	(7)
	Telescope Control System (TCS)	SF 1[CR]	0.53	0.53			(1)
	Test Instruments (TINS)	EL +X 5			0.50		
		SF 1 [CR]	0.12				

	Instrumentation		**38.3**	**45.4**	**4.6**	**5.0**	
[REQ-1-OAD-0520]	***First Light***		**33.8**	**35.9**	**2.9**	**3.3**	
	AO Executive Software (AOESW)	SF 1 [CR]	5.32	5.32			(1)
	Cryogenic Cooling System (CRYO)	SF 1 [UR]	16.30	16.30			
		-X			0.10	0.05	(7)
		+X			0.10	0.05	(7)
	InfraRed Imaging Spectrometer (IRIS)	NAS -X 4			0.28	0.28	
		NAS -X 4			0.02	0.02	
		SF 1 [CR]	1.84	1.84			(1)
	Laser Guide Star Facility (LGSF)	TOP 7			0.17	0.17	
		EL -X 5			1.04	1.04	
		SF 1 [CR]	1.55	2.32			
	Multi-Objective Diffraction Limited High Resolution Spectrograph (MODHIS)	NAS -X 4			0.09	0.09	
		NAS -X 4			0.21	0.21	
		SF 1 [CR]	0.60	0.60			(1)
	Narrow Field Near Infrared AO System (NFIRAOS)	NAS -X 4			0.18	0.18	
		NAS -X 4			0.42	0.42	
		SF 1 [CR]	2.67	4.00			(1)
	Refrigerant Cooling System (REFR)	SF 1 [UR]	4.90	4.90			
		-X			0.25	0.25	(7)
		+X			0.25	0.25	(7)
	Wide Field Optical Spectrometer (WFOS)	NAS +X 4			0.09	0.09	
		NAS +X 4			0.21	0.21	
		SF 1 [CR]	0.60	0.60			
N/A	***First Decade***		**4.5**	**9.5**	**1.7**	**1.7**	
	Adaptive Secondary Mirror (AM2)	TOP 7			0.05	0.10	
		EL -X 5			0.21	0.21	
		SF 1 [CR]	2.50	5.00			(1)
	High Resolution Optical Spectrometer (HROS)	NAS +X 4			0.09	0.09	
		NAS +X 4			0.21	0.21	
		SF 1 [CR]	0.24	0.36			(1)
	Near-Infrared Multi-Object Sectrometer (IRMOS)	NAS +X 4			0.09	0.09	
		NAS +X 4			0.21	0.21	
		SF 1 [CR]	0.48	0.72			(1)
	Mid-Infrared AO System (MIRAO)	NAS -X 4			0.03	0.03	
		NAS -X 4			0.07	0.07	
		SF 1 [CR]	0.48	0.60			(1)
	Mid-Infrared Echelle Spectrometer (MIRES)	NAS -X 4			0.03	0.03	
		NAS -X 4			0.07	0.07	
		SF 1 [CR]	0.20	1.84			(1)
	Near Infrared Echelle Spectrometer (NIRES-R)	NAS -X 4			0.09	0.09	
		NAS -X 4			0.21	0.21	
		SF 1 [CR]	0.24	0.36			(1)
	NFIRAOS Side Instrument (NSI)	NAS -X 4			0.09	0.09	
		NAS -X 4			0.21	0.21	
		SF 1 [CR]	0.40	0.60			(1)
	Planet Formation Instrument (PFI)	NAS -X 4			0.09	0.09	
		NAS -X 4			0.21	0.21	
		SF 1 [CR]	0.48	0.72			(1)
[REQ-1-OAD-0540]	**Operations**		**25.5**	**30.4**	**0.5**	**0.5**	
	Communication and Information Systems (CIS)	SF 1 [CR]	6.08	6.08			(1)
		-X			0.25	0.25	(1), (7)
		+X			0.25	0.25	(1), (7)
	Common Software (CSW)	SF 1 [CR]	4.93	6.16			(1)
	Data Management System (DMS)	SF 1 [CR]	7.32	7.32			(1)
	Executive Software (ESW)	SF 1 [CR]	3.68	7.36			(1)
	Site Conditions Monitoring System (SCMS)	SF 1 [CR]	2.02	2.02			(1)
	US-ELTP (SOSS & DPS)	SF 1 [CR]	1.44	1.44			(1)

Notes:

(1) Heat dissipation requirements are not imposed on subsystems for equipment in the Computer & Control Rooms (i.e. no flowdown to Level 2, and no verification is required). The Systems Engineering (SE) team has performed a conservative analysis of the Computer & Control Room heat dissipation estimates to inform the SUM cooling design. SUM is responsible for air cooling the various rooms in the Summit Facilities according to the budgets presented here. The subsystems are bound to their power allocations in the Computer & Control Rooms, which SE uses to estimate the heat dissipation. Thus, while SE is not imposing heat dissipation requirements in these areas, there is still control of the estimates via the power budgets. SE will work with the subsystems to refine the Computer & Control Room heat dissipation estimates according to various use cases of the observatory.
(2) As mentioned in note (1), SUM is responsible for air cooling the various rooms in the Summit Facilities. For subsystems with equipment in other areas of the Summit Facilities (e.g. Utility Room, Coating areas), heat dissipation requirements are imposed on those subsystems as noted by (2) in the table.
(3) AM2 & M2S are non-concurrent.
(4) M1 COAT & M2/M3 COAT are non-current.
(5) M2/M3 COAT is only used during shutdown (while no observations are scheduled). As such, no requirement flowdown is imposed.
(6) TCS provided the Computer in CR, no flow down to subsystem (ENC, STR, M2S and M3S)
(7) Distributed on the Telescope

3.3 THROUGHPUT

Discussion: The Throughput budget (RD70) is a critical component for evaluating and optimizing the efficiency of light transmission across the optical pathway of TIO. This budget accounts for *every element involved in the system, from the primary mirror through subsequent optics, filters, instruments, and detectors.*

3.3.1 FRESH COATING

Discussion: Fresh Coating refers to a newly applied layer of reflective or protective material on an optical surface, such as the mirrors of a telescope. This coating is designed to maximize reflectivity, minimize absorption, and protect against environmental degradation such as oxidation or contamination. Fresh coatings are typically optimized to maintain high optical performance, ensuring efficient light collection and minimal signal loss for astronomical observations. Regular re-coating of telescope mirrors helps to sustain optimal throughput and performance over the instrument's operational life.

Table 3-3: Subsystems Throughput after Fresh Optical Coatings

		Wavelengths															
		0.31		0.34		0.35		0.36		0.40		0.50		0.60		0.70	
REQ#	Item	REQ	GOAL	REQ	GOAL	REQ	GOAL	REQ	GOAL	REQ	GOAL	REQ	GOAL	REQ	GOAL	REQ	GOAL
	Total throughput Telescope	0%	51%	18%	73%	26%	73%	37%	73%	59%	86%	80%	94%	86%	94%	91%	94%
	Total throughput IRIS IFU+Telescope+NFIRAOS																
	Total throughput IRIS Imager+Telescope+NFIRAOS																
	Total throughput MODHIS+Telescope+NFIRAOS																
	Total throughput Telescope +WFOS	0%	28%	4%	40%	12%	40%	17%	40%	27%	47%	36%	52%	39%	52%	41%	52%
[REQ-1-OAD-1600]	M1S	0%	80%	56%	90%	64%	90%	72%	90%	84%	95%	93%	98%	95%	98%	97%	98%
[REQ-1-OAD-1600]	M2S	0%	80%	56%	90%	64%	90%	72%	90%	84%	95%	93%	98%	95%	98%	97%	98%
[REQ-1-OAD-1600]	M3S	0%	80%	56%	90%	64%	90%	72%	90%	84%	95%	93%	98%	95%	98%	97%	98%
[REQ-1-OAD-2811]	NFIRAOS													0%	70%	0%	70%
[REQ-1-OAD-3089]	IRIS+imager																
[REQ-1-OAD-3088]	IRIS+IFU																
[REQ-1-OAD-3280]	MODHIS																
[REQ-1-OAD-3338]	WFOS	25%	55%	25%	55%	45%	55%	45%	55%	45%	55%	45%	55%	45%	55%	45%	55%

		Wavelengths																	
		0.80		0.84		0.93		0.98		1.00		1.10		2.40		2.46		28	
REQ#	Item	REQ	GOAL	REQ	GOAL	REQ	GOAL	REQ	GOAL	REQ	GOAL	REQ	GOAL	REQ	GOAL	REQ	GOAL	REQ	GOAL
	Total throughput Telescope	91%	94%	91%	94%	91%	94%	91%	94%	91%	94%	91%	94%	91%	94%	91%	94%	91%	94%
	Total throughput IRIS IFU+Telescope+NFIRAOS			16%	24%	16%	24%	16%	24%	16%	24%	22%	24%	22%	24%				
	Total throughput IRIS Imager+Telescope+NFIRAOS			25%	36%	25%	36%	25%	36%	25%	36%	33%	36%	33%	36%				
	Total throughput MODHIS+Telescope+NFIRAOS							5%	8%	5%	8%	7%	8%	7%	8%	0%	7%		
	Total throughput Telescope +WFOS	41%	52%	41%	52%	41%	42%	23%	24%	23%	24%								
[REQ-1-OAD-1600]	M1S	97%	98%	97%	98%	97%	98%	97%	98%	97%	98%	97%	98%	97%	98%	97%	98%	97%	98%
[REQ-1-OAD-1600]	M2S	97%	98%	97%	98%	97%	98%	97%	98%	97%	98%	97%	98%	97%	98%	97%	98%	97%	98%
[REQ-1-OAD-1600]	M3S	97%	98%	97%	98%	97%	98%	97%	98%	97%	98%	97%	98%	97%	98%	97%	98%	97%	98%
[REQ-1-OAD-2811]	NFIRAOS	60%	85%	60%	85%	60%	85%	60%	85%	60%	85%	80%	85%	80%	85%	0%	70%		
[REQ-1-OAD-3089]	IRIS+imager			45%	45%	45%	45%	45%	45%	45%	45%	45%	45%	45%	45%				
[REQ-1-OAD-3088]	IRIS+IFU			30%	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%				
[REQ-1-OAD-3280]	MODHIS							10%	10%	10%	10%	10%	10%	10%	10%	10%	10%		
[REQ-1-OAD-3338]	WFOS	45%	55%	45%	55%	45%	45%	25%	25%	25%	25%								

[REQ-1-OAD-1600] The M1, M2, and M3 Optical Coatings shall have a Minimum Reflectivity per Surface of:

- N/A [Goal >0.8] over a wavelength range of [0.14 - 0.34] µm
- 0.56 → 0.72 [Goal >0.9] over a wavelength range of]0.34 - 0.36] µm
- 0.72 → 0.84 [Goal 0.9-0.95] over a wavelength range of]0.36 - 0.40] µm
- 0.84 → 0.93 [Goal 0.95-0.98] over a wavelength range of]0.4 - 0.5] µm
- 0.93 → 0.97 [Goal >0.98] over a wavelength range of]0.5 - 0.7] µm
- 0.97 [Goal >0.98] over a wavelength range of]0.7 - 28] µm

[REQ-1-OAD-2811] The NFIRAOS average throughput to science instruments shall exceed 60% over 0.8 – 1.1 microns, and 80% over the 1.1 - 2.4 micron wavelength range [Goal: exceed 70% from 0.6 to 2.5 microns, and exceed 85% from 0.8 to 2.4 microns].

[REQ-1-OAD-3088] Throughput of the entire IRIS spectrograph from entrance window to detector shall be greater than 30% over the wavelengths defined in [REQ-1-OAD-3070], 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% over the wavelengths defined in [REQ-1-OAD-3070], 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-3280] The MODHIS science channel end-to-end throughput of the peaks in each high-resolution order shall be ≥ 10% over the wavelengths given in [REQ-1-OAD-3260].

Discussion: The requirement excludes the performance of both the telescope and NFIRAOS. In particular, it does not include fiber coupling which is related to the delivered NFIRAOS Strehl ratio. The "peak" in the requirement refers to the peak throughputs for each order in the high resolution *spectrograph. Verification will be performed by comparing each peak value with the required minimum value.*

[REQ-1-OAD-3338] WFOS, in spectroscopy mode at any spectral resolution, shall have an on-axis throughput of > 25% from 0.31 µm – 1.00 µm, and > 45% from 0.35 µm – 0.93 µm, not including the telescope.

Discussion: WFOS in spectroscopy mode carries a goal throughput of 55% over a wavelength range of 0.310 - 0.895 µm.

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

Discussion: Verification is performed in low-resolution spectroscopy mode, and allows for a dropout at the dichroic beamsplitter

3.3.2 After In-Situ Cleaning

Discussion: In-situ cleaning of mirrors is a specialized cleaning process designed to remove dust, contaminants, and other particulates from telescope mirrors without the need to remove the mirrors from their mounts. This technique is essential for maintaining the reflectivity and optical performance of telescope mirrors, as dirt and contaminants can degrade image quality and reduce the amount of light collected by the telescope.

In-situ cleaning methods used for TIO mirrors is done by using CO_2 Snow Cleaning.

Table 3-4: Subsystems Throughput after in-Situ Cleaning

		Wavelengths																																	
		0.31		0.34		0.35		0.36		0.40		0.50		0.60		0.70		0.80		0.84		0.93		0.98		1.00		1.10		2.40		2.46		28	
REQ#	Item	REQ	GOAL	REQ	GOAL	REQ	GOAL	REQ	GOAL	REQ	GOAL	REQ	GOAL	REQ	GOAL	REQ	GOAL	REQ	GOAL	REQ	GOAL	REQ	GOAL	REQ	GOAL	REQ	GOAL	REQ	GOAL	REQ	GOAL	REQ	GOAL	REQ	GOAL
	Total throughput Telescope	0%	13%	15%	15%	23%	25%	33%	39%	53%	64%	73%	83%	77%	83%	80%	83%	80%	83%	80%	83%	80%	83%	80%	83%	80%	83%	80%	83%	80%	83%	80%	83%	80%	83%
	Total throughput IRIS IFU+Telescope+NFIRAOS																			14%	21%	14%	21%	14%	21%	14%	21%	19%	21%	19%	21%				
	Total throughput IRIS Imager+Telescope+NFIRAOS																			22%	32%	22%	32%	22%	32%	22%	32%	29%	32%	29%	32%				
	Total throughput MODHIS+Telescope+NFIRAOS																							5%	7%	5%	7%	6%	7%	6%	7%	0%	6%		
	Total throughput Telescope +WFOS	0%	7%	4%	8%	10%	14%	15%	21%	24%	35%	33%	46%	34%	46%	36%	46%	36%	46%	36%	46%	36%	37%	20%	21%	20%	21%								
[REQ-1-OAD-1608]	M1S	0%	50%	53%	53%	61%	63%	69%	73%	81%	86%	90%	94%	92%	94%	93%	94%	93%	94%	93%	94%	93%	94%	93%	94%	93%	94%	93%	94%	93%	94%	93%	94%	93%	94%
[REQ-1-OAD-1608]	M2S	0%	50%	53%	53%	61%	63%	69%	73%	81%	86%	90%	94%	92%	94%	93%	94%	93%	94%	93%	94%	93%	94%	93%	94%	93%	94%	93%	94%	93%	94%	93%	94%	93%	94%
[REQ-1-OAD-1608]	M3S	0%	50%	53%	53%	61%	63%	69%	73%	81%	86%	90%	94%	92%	94%	93%	94%	93%	94%	93%	94%	93%	94%	93%	94%	93%	94%	93%	94%	93%	94%	93%	94%	93%	94%

[REQ-1-OAD-1608] After in-situ cleaning, the optical reflectivity of each mirror (M1,M2 and M3) shall have a minimum reflectivity per surface of:

- N/A [Goal >0.5] over a wavelength range of [0.31 - 0.34] µm
- 0.53 → 0.69 [Goal >0.73] over a wavelength range of]0.34 - 0.36] µm
- 0.69 → 0.81 [Goal 0.73-0.86] over a wavelength range of]0.36 - 0.40] µm
- 0.81 → 0.9 [Goal 0.86-0.94] over a wavelength range of]0.4 - 0.5] µm
- 0.9 → 0.93 [Goal >0.94] over a wavelength range of]0.5 - 0.7] µm
- 0.93 [Goal >0.94] over a wavelength range of]0.7 - 28] µm

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

3.4 Image Quality Budget for Seeing-Limited Operations

3.4.1 PSSN On-Axis and Off-Axis Budget

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

- On-axis images delivered to any instrument location
- Telescope pointing to a 30 degree zenith angle.
- Median site wind speed

- r0 = 0.2 m
- The median observing temperature (REQ-1-OAD-0010), or at a temperature difference of 2.5K from the APS alignment temperature.

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

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

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

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

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

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

A more detailed discussion of PSS_N is in (RD4). The error categories of the budget in Table 3-5: Telescope Image Quality Error Budget (RD19) are explained in the Appendix, Section 6.2. Observatory performance is a function of the actual environmental and operational conditions and parameters. The PSS image quality error budget (RD19) is defined under the following conditions:

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

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

The image blur of an R-C optical design increases with field angle due to field dependent astigmatism inherent to the design.

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

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

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

Where $PSF_{t+a+e,\varphi}$ is combined point spread function of atmosphere, ideal telescope and aberration at field angle φ and $PSF_{t+a,\varphi}$ is the PSF of the atmosphere and ideal telescope at field angle φ, and θ represents the 2 dimensional coordinates of the PSF.

Table 3-5: Telescope Image Quality Error (PSSN and PSSNF) Budget (RD19)

		ON AXIS				OFF AXIS			
Requirement ID	Description	PSSN (ON-axis)		AO WFE (ON-axis) [nm RMS]		PSSNF\ (OFF-axis, 10 arcminutes radius)	AO WFE \ (OFF-axis, 17 arcs radius) [nm RMS]	AO WFE (OFF-axis, 1 arcm radius) [nm RMS]	Notes
[REQ-1-OAD-0400]	TIO Seeing-Limited IQ (up to the Nasmyth Focus)	0.8300	[Goal:0.85]	62.0	[Goal:60]	0.80 [Goal:0.81]	67 [Goal:65]	112 [Goal:111]	30 degrees zenith, median seeing, median wind. AO=LGS MCAO
	Thermal Seeing	0.9650		30		0.9650	30	30	
[REQ-1-OAD-0402]	Mirror and Dome seeing		0.9650		30	0.9650	30	30	Thermal Seeing -Mirror (TS)
	Optical surface shapes	0.8890		32		0.8502	41	79	
[REQ-1-OAD-0406]	M1 shape		0.9333		24	0.9333	24	24	
	M1 Segment residual figure error		0.9583		17.4				Segment residual figure error (SRFE)
	M1 Segment thermal distortion		0.9999		2.3				Segment thermal distortion (STD)
	M1 Segment support print through		0.9922		6.2				Segment support print through (SSPT)
	M1 Segment in-plane displacement		0.9998		1.7				Segment in-plane displacement (SIPD)
	M1 Segment out-of-plane residual		0.9918		6.1				Segment out-of-plane displacement (SOPD)
	M1 Segment dynamic displacement residual		0.9901		14.1				Segment dynamic residuals (SDDR)
	M1 Segment drift errors		0.9999		0.5				Segment drift errors (SDE)
[REQ-1-OAD-0422]	M2 shape		0.9823		12	0.9478	21	32	
	M2 residual figure error		0.9851		11.2	0.9750	17.2	20.0	M2 residual figure error (M2RFE)
	M2 thermal distortion		0.9984		0.9	0.9984	0.9	0.9	M2 thermal distortion (M2TD)
	M2 support print through		0.9992		2.1	0.9741	5.1	25.0	M2 support print through (M2SPT)
	M2 dynamic shape residual		0.9997		0.8	0.9997	0.8	0.8	M2 dynamic shape residual (M2DSR)
	M2 shape drift errors		0.9999		0.5	0.9999	1.0	1.0	M2 shape drift errors (M2SDE)
[REQ-1-OAD-0434]	M3 shape		0.9932		8	0.9932	19	51	
	M3 residual figure error		0.9950		5.7	0.9950	14.7	32.0	M3 residual figure error (M3RFE)
	M3 thermal distortion		0.9997		0.9	0.9997	0.9	0.9	M3 thermal distortion (M3TD)
	M3 support print through		0.9986		0.8	0.9986	11.8	39.0	M3 support print through (M3SPT)
	M3 dynamic shape residual		1.0000		0.8	1.0000	0.8	0.8	M3 dynamic shape residual (M3DSR)
	M3 shape drift errors		0.9999		0.5	0.9999	0.5	0.5	M3 shape drift errors (M3SDE)
[REQ-1-OAD-0460]	M1 shape calibration/wfs		0.9764		16	0.9678	16	46	
	M1 WH WF measurement error		0.9896		11.7	0.9896	11.7	11.7	M1 warping harness wavefront measurement error (WFSWH)
	M1 segment phasing WF measurement error		0.9970		5.8	0.9970	5.8	5.8	M1 segment phasing wavefront measurement error (WFSSP)
	LOWF measurement error		0.9988		0.9	0.9900	3.9	43.0	Low order wavefront measurement error (APS and Instrument) (WFSLO)
	M1 segment T/T WF measurement error		0.9908		9.0	0.9908	9.0	9.0	M1 segment tip/tilt wavefront measurement error (WFSTT)
	Optical alignment	0.9926		37		0.9922	40	73	
[REQ-1-OAD-0448]	Telescope collimation		0.9997		0	0.9993	17	63	
	Optics Collimation/Alignments errors		0.9997		0.0	0.9995	14.0	52.0	Telescope collimation errors (COLL)
	Prescription Tolerances		1.0000		0.0	0.9998	10.0	35.0	
[REQ-1-OAD-0454]	Image jitter		0.9947		17	0.9947	17	17	
	M1 jitter (relative to the sky) Guider noise		0.9990		0.0				Instrument Guider Noise (CN-INS)
	M1 jitter (relative to the sky) Mount control noise		0.9980		9.0				Mount Control Noise (CN-INS)
	M2 jitter		0.9978		5.4				M2 jitter(CN-M2)
	M3 jitter		0.9999		13.4				M3 jitter (CN-M3)
[REQ-1-OAD-0480]	Wind jitter		0.9986		12	0.9986	12	12	
	STR wind residual		0.99864		12.0				STR wind residual (WJ-STR)
	M2 wind residual		0.99998		1.4				M2 wind residual (WJ-M2)
	M3 wind residual		0.99999		1.0				M3 wind residual (WJ-M3)
[REQ-1-OAD-0486]	Vibration jitter		0.9995		30	0.9995	30	30	
N/A	Dynamic blur		1.0000		0	1.0000	0	0	
	Reserve	0.9747		23.8		0.9747	24	24	

3.4.2 Elevation Angle Dependence of the Budget

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

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

3.5 Image Quality for Adaptive Optics Operations

3.5.1 Adaptive Optics Wavefront Error Budget

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

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

TIO AO Error Budget and CBE Description (RD41) defines all the error terms and their rationales used in (RD20), summarized in Table 3-8: NFIRAOS NGSAO and IRIS RMS wavefront error budget and Table 3-8: NFIRAOS LGS MCAO 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 -3 dB error rejection bandwidth of 30 Hz and order 60 x 60 wavefront compensation.

Table 3-7: NFIRAOS NGSAO and IRIS RMS wavefront error budget and Table 3-9: NFIRAOS LGS MCAO and IRIS RMS wavefront error budget below therefore impose requirements upon both the Facility AO system and the other observatory subsystems introducing these disturbances.

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

Table 3-6: NFIRAOS NGSAO MCAO and IRIS RMS wavefront error budget (RD20)

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

Table 3-7: NFIRAOS LGS MCAO and IRIS/MODHIS RMS wavefront error budget (60 x 60 actuators, on axis and 34" x 34") in nm (RD20)

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

Discussion: The Residual T/T tracking jitter is 0.4 mas on the sky after correction by the NFIRAOS tip/tilt rejection transfer function modeled as an integrator with 400 Hz sampling frequency (F_s), 0.4 ms delay (τ) from last photon on OIWFS to last DM actuator commanded by DME, and a gain (g) of 0.63 (See Figure 3-1: AO Rejection Transfer Function). This rejection transfer function is described by:

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

$$s = 2\pi i f$$

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

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

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

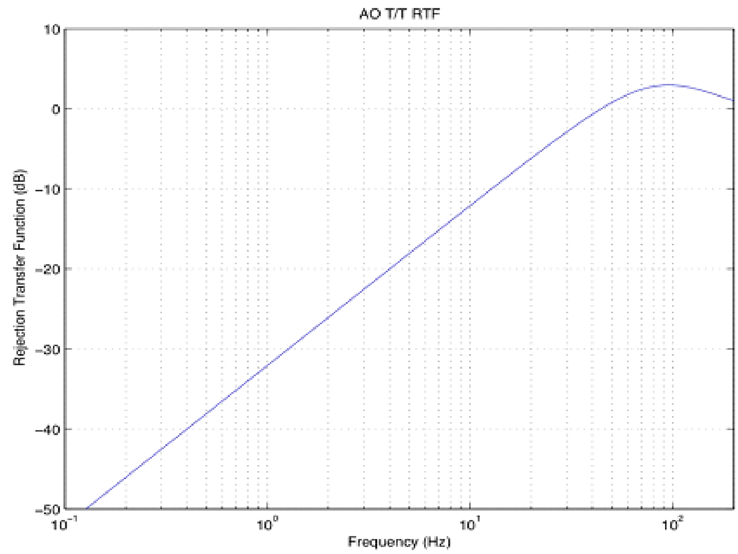

Figure 3-1: AO Rejection Transfer Function

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

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

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

3.5.2 Elevation Angle Dependence of the Budget

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

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

3.5.3 OPD Wavefront Corrector Stroke Allocation

Discussion: The higher-order wavefront errors induced by atmosphere, telescope aberrations, instrument aberrations, and dome/mirror seeing must be correctable to the error budget allocations using a total wavefront correction. The budgeted optical path difference allocation between these sources is shown in (RD10) and in Table 3-8 for DM0 and Table 3-9 for DM11.

Table 3-8: Stroke Budget for the ground layer DM0 OPD Correction of Observatory Wavefront Error.

Requirement ID	Description	OPD budget RMS (µm)
[REQ-1-OAD-0612]	OPD for Ground Layer DM0 Stroke	4.000
N/A	Atmospheric correction required for all seeing	3.200
[REQ-1-OAD-0614]	Facilities	2.150
	Local seeing (Mirror and dome seeing)	2.150
[REQ-1-OAD-0620]	Telescope	0.530
	Telescope (Static and Dynamic)	0.500
	Telescope plate scale	0.030
	Instrumentation	0.320
[REQ-1-OAD-0626]	First Light	
	NFIRAOS quasi-static aberrations in the science path	0.250
	Instrument Optical Path corrected by DM	0.200
	Reserve	0.070

Table 3-9: Stroke Budget for the High Altitude DM11 OPD Correction of Observatory Wavefront Error.

Requirements ID	Item	OPD budget RMS (µm)
[REQ-1-OAD-0613]	OPD for High Altitude DM11 Stroke	4.000
N/A	Atmospheric correction required for all seeing	2.400
[REQ-1-OAD-0636]	Telescope	1.600
	Telescope plate scale corrected by high altitude DM	1.600
	Reserve	0.000

3.5.4 NFIRAOS PSSN

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

Table 3-10: PSSN NFIRAOS LGS MCAO and NGSAO and IRIS Imager

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

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

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

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

3.6 POINTING ERROR BUDGET

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

The TIO Pointing Budget [RD67] allocates allowable residual errors to the alignment tolerances to the key elements of the Observatory. Although the pointing accuracy of the Telescope is an absolute measure, it is achieved by intermittent calibration of the pointing system, i.e. building a pointing model. Consequently, the pointing accuracy depends only on the repeatability of the calibration settings and measurements.

Table 3-12: Pointing Error Budget

Requirement ID	Description	arcsec RMS	
	Telescope Pointing	**1.64**	
[REQ-1-OAD-0661]	**Telescope Pointing after Pointing Test**	**1.00**	
	Residual Astrometry & Atmospheric	0.11	
	Atmospheric Refraction		0.03
	Atmosphere Model Error		0.10
	Pointing Demand Error		0.01
	On Sky Measurement Error		0.01
	Structure & M1S	0.60	
	Azimuth Track Measurement Error		0.20
	Elevation Journal Fitting Error		0.50
	Hysteresis		0.27
	M1CS	0.14	
	Global Tip Tilt Error		0.14
	M2S	0.53	
	Calibration Measurement Error		0.29
	Calibration Fitting Error		0.19
	Control System Accuracy		0.40
	M3S	0.47	
	Calibration Measurement Error		0.25
	Calibration Fitting Error		0.05
	Control System Accuracy		0.40
	Reserve	0.33	
[REQ-1-OAD-0662]	**Telescope Pointing over a Year, Prior to Recalibration**	**1.30**	
	Thermal	0.40	
	Thermal Residual after Correction		0.40
	Temperature Measurement Error		0.01
	Temporal	1.20	
	Settling (1 month)		0.70
	Settling (12 months)		1.20
	Reserve	0.30	

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

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

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

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

3.7 Pupil Shift Budget

3.7.1 Pupil Shift Budget - No AO Feedback

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

Table 3-13: Pupil Shift Budget in RMS, assuming a Gaussian distribution with RMS = 1 sigma (RD5)

Requirement ID	Description	Required Pupil Shift RMS Error (% of pupil diameter)				
[REQ-1-OAD-0702]	**Pupil Shift**	**0.100%**				
[REQ-1-OAD-0703]	**Telescope**		**0.074%**			
	Telescope Structure (STR)			0.035%		
	Mount EL				0.000%	
	Mount EL Control Noise					0.000027%
	Mount EL Wind Jitter					0.000004%
	Mount Decenter				0.016%	
	M1 Decenter Flexure Hysteresis					0.001%
	M2 Decenter Flexure Hysteresis					0.015%
	Instrument Decenter Flexure Hysteresis					0.003%
	Mount Tilt				0.031%	
	M3 Tilt Flexure Hysteresis					0.030%
	Instrument Tilt Flexure Hysteresis					0.007%
	Mount Piston				0.001%	
	M3 Piston Flexure Hysteresis					0.001%
	M2 System (M2S)			0.026%		
	M2S Tilt				0.014%	
	M2 Tilt Actuator Noise					0.014%
	M2S Decenter				0.022%	
	M2 Decenter Actuator Noise					0.0004%
	M2 Decenter Thermal Effects					0.015%
	M2 Decenter LUT Error					0.016%
	M2 Decenter Wind Jitter					0.000001%
	M3 System (M3S)			0.060%		
	M3 Tilt				0.056%	
	M3 Tilt Actuator Noise					0.020%
	M3 Tilt Thermal Effects					0.016%
	M3 Tilt LUT Error					0.051%
	M3 Tilt Wind Jitter Error					0.00001%
	M3 Piston				0.020%	
	M3 Piston Actuator Noise					0.020%
	M3 Piston Thermal Effects					0.005%
	M3 Piston LUT Error					0.002%
	M3 Piston Wind Jitter					0.000001%
[REQ-1-OAD-0715]	**Instrumentation**		**0.045%**			
	Instrument WFS Control Noise				0.001%	
	Mount EL Control Noise					0.00002%
	M2 Tilt Control Noise					0.001%
	Instrument Tilt				0.023%	
	Instrument Tilt Thermal Effects					0.006%
	Instrument Tilt LUT Error					0.022%
	Instrument Tilt Wind Jitter					0.000%
	Instrument Decenter				0.039%	
	Instrument Decenter LUT Error					0.039%
	Instrument Decenter Wind Jitter					0.000%
	Reserve		**0.050%**			

Discussion: The pupil shift value above is specified in RMS; it is assumed that the conversion to P-V for what is effectively the not-to-exceed pupil misalignment is three (3) times the RMS value.

3.7.2 PUPIL SHIFT BUDGET - WITH AO FEEDBACK

Table 3-14 End to End Undersizing Budget for IRIS Lyot Mask contains the bottoms up budget (RD56) for the residual misalignment of the pupil on to IRIS' Lyot stop. Blurring of the Pupil on IRIS Lyot stop due to IRIS optical design is a systematic error that has been analyzed in Zemax at 0.2% and is the largest single item in the budget. Mechanical design guidelines for IRIS random errors are to use 2-sigma tolerances for a total of two times the RMS pupil misalignment, so the top line of the budget is the systematic errors plus double the second line which is the quadrature sum of the random errors in the lines below and to the right. A more detailed description of these terms is in RD5

Table 3-14: End to End Undersizing Budget for IRIS Lyot Mask

Requirement ID	Description	Undersizing IRIS Lyot Mask Requirement (% of Pupil Size)		
[REQ-1-OAD-0716]	**Mask Undersize (Systematic + 2 × Random)**	**0.40%**		
	Systematic Errors		**0.20%**	
	Optical Blurring of Pupil on IRIS Lyot Stop			0.200%
	Random Errors		**0.10%**	
	M3 Tilt			0.002%
	NFIRAOS			0.050%
	PWFS Pupil Mirror Accuracy			
	PWFS Pointing Model Errors			
	Pupil Image Centering			
	M1 Segment Non-uniformity			
	NFIRAOS Exit Pupil Magnification			
	Exit Pupil Axial Tolerance			
	IRIS			0.050%
	Rotating Offset Cryostat Center of Mass			
	Lyot Stop XY Stage Accuracy			
	Lyot Stop Fabrication Accuracy			
	Lyot Stop Z-direction Position Error			
	NFIRAOS Simulator Z-direction Pupil Position Error			
	DM11 Poke Pattern Measurement Error			
	PV Centroiding Mask vs. Poke Pattern			
	Tilt Ring Adjustment Error			
	Rotator Bearing High Frequency Angular Runout			
	Reserve			0.071%

3.8 PLATE SCALE DISTORTION VARIATION BUDGET

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

Table 3-15: Seeing-Limited budget for stability of plate scale, specified in terms of maximum image motion of any point in the full 20 arcmin diameter field relative to the center of the field.

Requirement ID	Description	Maximum Image Motion (mas)	
[REQ-1-OAD-0721]	**Observatory Plate Scale Distortion Budget**	**60.0**	
[REQ-1-OAD-0720]	**Primary Mirror System**	**10.6**	
	Primary Mirror Figure		**8.0**
	Curvature Change of M1 (Focus error)		*8.0*
	Astigmatism mode on M1		*N/A*
	Axial motion of the M1		**7.0**
	X-axis		4.9
	Y-axis		4.9
[REQ-1-OAD-0722]	**Secondary Mirror System (M2S)**	**18.6**	
	Secondary Mirror Figure		**18.4**
	Polishing and Metrology		*14.0*
	M2 Residual Figuring Error (M2RFE)		14.0
	Curvature Change		*11.9*
	M2 Thermal Distortion (M2TD)		8.4
	M2 Support Print Through (M2SPT) - Gravity		8.4
	M2 Support Print Through (M2SPT) - Thermal		
	Focal Surface Tilt		**2.8**
	X decenter of the M2		2.0
	Y decenter of the M2		2.0
[REQ-1-OAD-0724]	**Tertiary Mirror System (M3S)**	**34.4**	
	Tertiary Mirror Figure		**34.2**
	Polishing and Metrology		*19.6*
	M3 Residual Figuring Error (M3RFE)		19.6
	Curvature Change		*28.0*
	M3 Thermal Distortion (M3TD)		N/A
	M3 Support Print Through (M3SPT) - Gravity		28.0
	M3 Support Print Through (M3SPT) - Thermal		
	Back Focal Distance		**3.5**
	Axial motion of M3		*3.5*
	X-axis		2.5
	Y-axis		2.5
[REQ-1-OAD-0732]	**Telescope Structure (STR)**	**42.1**	
	Focal Surface Tilt		**21.5**
	X_Tilt of the focal surface		15.0
	Y_Tilt of the focal surface		15.0
	X_Tilt of the M1		2.4
	Y_Tilt of the M1		2.4
	Decenteration of Telescope Distortion Pattern		**25.0**
	Shift of the telescope optical axis in the FoV		25.0
	Back Focal Distance		**26.1**
	Axial movement of focal surface		25.8
	Uncompensated axial motion of M1		4.0
	Reserve	**13.9**	

3.9 MASS BUDGET

Table 3-16: Mass Budget for Telescope Mounted Sub-systems (RD21).

Requirement ID	Description	REQ (tonnes) Elevation	Azimuth
[REQ-1-OAD-0739]	**Telescope+Payload**	1300	1350
	Only Nasmyth -X		120
	Only Nasmyth +X		120
[REQ-1-OAD-0740]	**Telescope**	1281	1116
	Alignment and Phasing System (APS)		6.0
	Engineering Sensors (ESEN)	0.3	0.1
	M1 Control System (M1CS)	29.1	
	M1 System (M1S)	130	
	M2 System (M2S)	7.1	
	M3 System (M3S)	12.5	
	ObservatorySafety System (OSS)	0.05	0.05
	Optical Cleaning System (CLN)	1.0	10.2
	Telescope Structure (STR)	1100	1100
	Elev. Structure	1078	
	Az. Structure		956
	Inst. Support Structures		46
	Utility Services Lines and Junctions (STR, TUS-2, TUS-3)	23	98
	Test Instruments (TINS)	0.2	0.1
	Instrumentation	23	221
[REQ-1-OAD-0764]	**First Light**	15	128
	Cryogenic Cooling System (CRYO)		11.5
	InfraRed Imaging Spectrometer (IRIS)		10.4
	Laser guide star facility (LGSF)	14.4	
	Multi-Objective Diffraction Limited High Resolution Spectrograph (MODHIS)		10.8
	Narrow Field Near Infrared AO System (NFIRAOS)		52.1
	Refrigerant Cooling System (REFR)	0.1	1.2
	Wide Field Optical Spectrometer (WFOS)		42.0
N/A	**First Decade**	9	93
	Adaptive Secondary Mirror System (AM2)	8.8	
	High Resolution Optical Spectrometer (HROS)		43.6
	Near-Infrared Multi-Object Sectrometer (IRMOS)		18.6
	Mid-Infrared AO System (MIRAO)		5.4
	Mid-Infrared Echelle Spectrometer (MIRES)		5.5
	Near Infrared Echelle Spectrometer (NIRES-R)		7.9
	NFIRAOS Side Instrument (NSI)		6.9
	Planet Formation Instrument (PFI)		5.3
[REQ-1-OAD-0787]	**Operations**	1.2	1.3
	Communication and Information Systems (CIS)	1.2	1.3
N/A	**Miscelaneous**		20.0
	Misc. Nasmyth		20.0
	Reserve	2.4	11.0

3.10 VIBRATION BUDGET

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

This results in the following allocations of vibration contributions to system AO WFE among subsystems in 'Table 3-17: Vibration Budget (RD22)' below. The allocations are separated into contributions in three locations, on the telescope, within the enclosure and in the summit facilities. Each line of the table with a requirement number should be interpreted as follows: vibration sources within the designated subsystem shall contribute less than the number of nm specified in the table to NFIRAOS-corrected RMS WFE.

Table 3-17: Vibration Budget (RD22)

		Inside Summit Facilities		Inside Enclosure			
		Support Buiding		Within Enclosure		On Telescope	
Requirement ID	Description	AO WFE impact (nm)	Estimated allowable force (N rms)	AO WFE impact (nm)	Estimated allowable force (N rms)	AO WFE impact (nm)	Estimated allowable force (N rms)
[REQ-1-OAD-1118]	**TIO Vibrations** (First Light and First Decade)	30.0					
		6.0		22.2		14.3	
	Reserve	7		7		8.3	
[REQ-1-OAD-1091]	**Facilities**	4.2		22.2		0.0	
	Enclosure (ENC)			21.8	260.00		
	Sea Level Facilities (SLF)						
	Summit Facilities (SUM)	4.2	100.00	4.2	10.00		
[REQ-1-OAD-1093]	**Telescope**	3.8		1.5		12.9	
	Alignment and Phasing System (APS)	0.2	5.00			2.4	1.00
	Engineering Sensors (ESEN)	0.0	0.00	0.0	0.0	0.0	0.00
	M1 Coating System (M1 COAT)	0.8	20.00				
	M1 Control System (M1CS)	0.2	5.00			1.5	0.50
	M1 Optics System (M1S)	0.0	0.00			0.0	0.00
	M2 Optics System (M2S)	0.2	5.00			3.9	
	M2/M3 Coating System (M2/M3 COAT)			0.0	20.00		
	M3 Optics System (M3S)	0.2	5.00			0.7	0.60
	Observatory Safety System (OSS)	0.2	5.00	0.1	1.00	0.0	0.00
	Optical Cleaning Systems (CLN)	0.0	0.00	0.0	0.00		
	Optics Handling Equipment (HNDL)	0.0	0.00	0.0	0.00		
	Telescope Control System (TCS)	0.2	5.00				
	Telescope Structure (STR)	3.7	50.00	1.5	10.00	12.0	
	Test Instruments (TINS)	0.2	5.00	0.0	0.00		
	Instrumentation	2.0				6.0	
[REQ-1-OAD-1095]	**First Light**	1.9				5.6	
	Adaptive Optics Executive Software (AOESW)	0.4	10.00				
	Cryogenic Cooling System (CRYO)	1.3	30.00			1.9	1.00
	InfraRed Imaging Spectrometer (IRIS)	0.2	5.00			1.0	0.50
	Laser Guide Star Facility (LGSF)	0.4	10.00			4.1	
	Multi-Object Diffraction Limited High Res. Spectrograph (MODHIS)	0.2	5.00			1.0	0.50
	Narrow Field Near Infrared AO System (NFIRAOS)	0.2	5.10			1.9	1.12
	Refrigerant Cooling System (REFR)	1.3	30.00			1.9	1.00
	Wide Field Optical Spectrometer (WFOS)	0.2	5.00			1.2	0.80
N/A	**First Decade**	0.5				2.3	
	Adaptive Secondary Mirror System (AM2)	0.2	5.00			3.9	
	High Resolution Optical Spectrometer (HROS)	0.2	5.00			1.0	0.50
	Near-Infrared Multi-Object Sectrometer (IRMOS)	0.2	5.00			1.0	0.50
	Mid-Infrared AO System (MIRAO)	0.2	5.00			1.0	0.50
	Mid-Infrared Echelle Spectrometer (MIRES)	0.2	5.00			1.0	0.50
	Near Infrared Echelle Spectrometer (NIRES-R)	0.2	5.00			1.0	0.50
	NFIRAOS Side Instrument (NSI)	0.2	5.00			1.0	0.50
	Planet Formation Instrument (PFI)	0.2	5.00			1.0	0.50
[REQ-1-OAD-1098]	**Operations**	0.5		0.1		1.0	
	Data Management System (DMS)	0.2	5.00				
	Executive Software (ESW)	0.2	5.00				
	Communication and Information Systems (CIS)	0.2	5.00	0.1	1.00	1.0	0.50
	Common Software (CSW)	0.2	5.00				
	Site Conditions Monitoring System (SCMS)	0.2	5.00				
	US-ELTP (SOSS, DPS)	0.2	5.00				

Discussion: It is understood that the AO WFE due to vibration for either image jitter or M1 segment dynamics cannot be readily calculated for most subsystems. The purpose of the "Estimated allowable force" and "sensitivity" columns are to provide an interpretation of these requirements that is considered acceptable to TIO 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 each location 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 on either side of those frequencies (allowing more force if the source is at lower or higher frequency). For f < 5 Hz, the rate of decrease is calculated as $(f/5)^2$, and for f > 20 Hz, the rate is $(f/20)^{-2}$.

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.

Verification of these requirements should be done following the methodology defined in RD73.

3.11 ACTUATOR/STROKE BUDGETS

3.11.1 M1CS ACTUATOR RANGE OF TRAVEL BUDGET

The range of travel of the M1CS position actuators is budgeted to accommodate the factors listed in 'Table 3-18: M1CS Actuator Range of Travel Budget'. The full budget is available in RD2.

Table 3-18: M1CS Actuator Range of Travel Budget.

Requirement ID	Description	Actuator Travel Allowance (mm)
[REQ-1-OAD-0808]	M1CS Actuator Travel	5.0
[REQ-1-OAD-0800]	STR	2.6
	Gravity Deflection of Telescope Elevation Structure and M1S	1.8
	Thermal Deflection of Telescope Elevation Structure and M1S	0.4
	M1 Subcell installation errors	0.4
N/A	M1CS	0.5
	Diagnostics	0.3
	End of Travel Margin	0.2
[REQ-1-OAD-0809]	M1S	1.0
	Mounted Segment Assembly Tolerances	0.7
	M1 Radius of Curvature Uncertainty	0.3
	Reserve	0.9

3.11.2 M1S WARPING HARNESS STROKE BUDGET

The following table sets limits for what percentage of warping harness stroke can be used to correct errors present on the M1 segments, M2 & M3 mirrors, and the M1 Cell. 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. The full budget is available in RD2.

Table 3-19: M1S Warping Harness Stroke Budget.

Requirement ID	Description	% Warping Harness Stroke Allocated
[REQ-1-OAD-1979]	% Warping Harness Stroke on any one of the 21 warping harness actuators on any individual segment	76
[REQ-1-OAD-1980]	M1S	46
	M1 Segment Polishing errors	20
	M1 Segment installation errors	6
	M1 Surface Change due to Coating Stress errors	5
	M1 Segment Thermal Distortion errors	5
	M1 Segment Assembly and Manufacturing tolerances errors	10
[REQ-1-OAD-1981]	STR	5
	Mirror Cell Thermal Effects errors	5
[REQ-1-OAD-1986]	M2S	20
	M2 Shape Tolerances errors	10
	M2 Polishing errors	5
	M2 Support Print Through errors	5
[REQ-1-OAD-1988]	M3S	5
	M3 Polishing errors	5
	Reserve	24

3.12 MAINTENANCE BUDGETS

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

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

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

3.12.1 SHUTDOWN MAINTENANCE

[REQ-1-OAD-0815] TIO Observatory Scheduled Maintenance activities shall not exceed 6 elapsed hours on any given day, with exception of the shutdown activities defined in Table-3-20 and Table 3-21, and certain system level maintenance activities as defined in Table 3-22.

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

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

The TIO Maintenance Budget (RD64) allocates time to subsystems for Observatory Shutdown Maintenance activities as shown in Table 3-20 and Instrumentation Shutdown Maintenance as shown in Table 3-21.

Table 3-20: Observatory Shutdown Maintenance Budget (for activities that prevent nighttime observations)

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

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

Table 3-21: Instrumentation Shutdown Budget (for activities that limit nighttime observations)

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

* Can overlap with annual Observatory Shutdown

**Only one instrument shutdown activity occurs each year

3.12.2 System Level Maintenance

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

Table 3-22: System Level Maintenance Budget

Requirement Number	Maintenance Activity	Subsystems Involved	Time (hours)	Frequency	Activity Hours / Year	Personnel	Personnel Hours / Year
[REQ-1-OAD-0838]	**System Level Maintenance Activities**						**12,398**
[REQ-1-OAD-0840]	M1 Segment Exchange	STR, M1S, HNDL	10	Every 2 weeks	260	8	2,080
[REQ-1-OAD-0841]	M1 Coating	M1S, HNDL, M1 COAT	8	5 days/week	2040	4	8160
[REQ-1-OAD-0842]	M1 CO2 Cleaning	M1S, STR, CLN	8	Every 2 weeks	208	4	832
[REQ-1-OAD-0843]	M2 CO2 Cleaning	M2S, STR, CLN	4	Every 2 weeks	104	3	312
[REQ-1-OAD-0844]	M3 CO2 Cleaning	M3S, STR, CLN	4	Every 2 weeks	104	3	312

3.12.3 Subsystem Maintenance

TIO Maintenance Budget (RD64) allocates time to perform an Environmental Event Inspection and Scheduled Maintenance activities to each subsystem, as shown in Table 3-24.

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

Table 3-24: Subsystem Maintenance Budget

Requirement ID	Description	Maintenance Time Allocation		Additional Shutdown Maintenance?	Additional System Level Maintenance?	Notes
		REQ Survival / 10yr Inspection (person hrs / event) in 1 day	REQ Scheduled Maintenance (person hrs/year)			
[REQ-1-OAD-0849]	**Available Subsystem Inspection/Scheduled Maintenance Time**	144	9,234			
[REQ-1-OAD-0850]	**Facilities**	15	2,850			
	Enclosure (ENC)	12	2,200	Y	N	
	Headquarters (HQ)	0		N	N	
	Summit Facilities (SUM)	3	650	N	N	
[REQ-1-OAD-0852]	**Telescope**	68.85	3,963			
	Alignment & Phasing (APS)	2	80	Y	N	(2)
	Engineering Sensors (ESEN)	4	100	N	N	
	M1 Control (M1CS)	6	800	N	N	(3)
	M1 Optical Coating (M1CP)	3	50	N	Y	
	M1 System (M1S)	25	800	N	Y	(4)
	M2 System (M2S)	2	200	Y	Y	(2)
	M2/M3 Optical Coating (M2M3CP)	3	50	N	N	(5)
	M3 System (M3S)	2	200	Y	Y	(2)
	Observatory Safety System (OSS)	1	100	N	N	
	Optical Cleaning (CLN)	2	100	N	Y	
	Optics Handling (HNDL)	2	75	N	Y	
	Telescope Control (TCS)	0.25	12	N	N	
	Telescope Structure (STR)	12	1,096	N	Y	
	Telescope Utility Services (STR.TUS)	4	250	N	N	
	Test Instruments (TINS)	1	50	N	N	
	Instrumentation	54	1582			
[REQ-1-OAD-0866]	**First Light**	36	942			
	AO Executive Software (AOESW)	0.25	12	N	N	
	Cryogenic Cooling (CRYO)	4	100	Y	N	(2)
	InfraRed Imaging Spectrometer (IRIS)	2	80	Y	N	(1)
	Instrument Refrigeration (REFR)	4	100	Y	N	(2)
	Laser Guide Star Facility (LGSF)	12	330	N	N	
	Multi-Objective Diffraction-limited High-Resolution Infrared Spectrograph (MODHIS)	2	80	Y	N	(1)
	Narrow Field InfraRed AO System (NFIRAOS)	6	80	Y	N	(1)
	Wide Field Optical Spectrometer (WFOS)	6	160	Y	N	(1)
N/A	**First Decade**	18	640	Y	N	
	Adaptive secondary Mirror System (AM2)	3	50	Y	N	(2)
	High Resolution Optical Spectrometer (HROS)	6	160	Y	N	(1)
	Near-Infrared Multi-Object Sectrometer (IRMOS)	2	80	Y	N	(1)
	Mid-Infrared AO System (MIRAO)	2	80	Y	N	(1)
	Mid-Infrared Echelle Spectrometer (MIRES)	2	80	Y	N	(1)
	Near Infrared Echelle Spectrometer (NIRES-R)	2	80	Y	N	(1)
	NFIRAOS Side Instrument (NSI)	2	80	Y	N	(1)
	Planet Formation Instrument (PFI)	2	80	Y	N	(1)
[REQ-1-OAD-0875]	**Operations**	6	188			
	Common Software (CSW)	0.25	12	N	N	
	Communications and Information System (CIS)	1	100	N	N	
	Data Management System (DMS)	0.25	12	N	N	
	Executive Software (ESW)	0.25	12	N	N	
	Site Conditions Monitoring System (SCMS)	4	40	Y	N	(2)
	US-ELTP (UPP.SOSS and DPS)	0.25	12	N	N	
	Reserve	13	651			

Notes: (1) Excludes time for planned instrument shutdown. (2) Excludes shutdown activities. (3) Includes activities not done on the telescope.
(4) Allocation excludes system level activities. (5) Inspection time only if in shutdown.

3.13 Astrometry and Photometry Budgets

3.13.1 AO Astrometry Error Budget

TIO AO Astrometry Error Budget (RD53) allocates differential astrometry error contributions to the subsystems. Errors are one-dimensional RMS position uncertainties, and there are separate requirements for single-observation errors and systematic errors. Errors are residuals after fitting distortions measured with field stars over a 34 arcsecond field of view in H band, with a "single observation" defined as having an integration time of 100 s. These errors should fall as t-1/2, with the limit of t -> ∞ being the systematic error.

TIO AO Astrometry Error Budget Rationale (RD52) describes and defines all error terms, their rationales and how they are combined into an error budget in (RD53).

Tables 3-25 and 3-26 show the requirement allocations for single-observation and systematic errors, respectively.

Table 3-25: Astrometric Accuracy - Single-Observation

		Errors (σ[μas])					
Requirement ID	Description	Single Observation	Focal-Plane Measurement	Opto Mechanical	Atmospheric Refraction	Residual Turbulence	Non Common *
[REQ-1-OAD-0848]	Astrometry Accuracy	50.0	7.3	14.4	7.7	12.3	28.8
	Catalogs	11.8	0.0	0.0	0.0	0.0	11.8
	Fundamental	28.0	2.4	5.0	7.6	0.0	26.3
[REQ-1-OAD-0895]	Telescope	5.0	0.0	5.0	0.0	0.0	
	M1 System (M1S)	0.0	0.0	0.0	0.0	0.0	0.0
	M2 System (M2S)	0.0	0.0	0.0	0.0	0.0	0.0
	M3 System (M3S)	5.0	0.0	5.0	0.0	0.0	0.0
	Instrumentation	20.4	6.9	14.3	1.0	12.3	0.0
[REQ-1-OAD-0896]	First Light	20.4	6.9	14.3	1.0	12.3	0.0
	Narrow Field Near Infrared AO System (NFIRAOS)	15.5	0.0	9.4	0.0	12.3	0.0
	InfraRed Imaging Spectrometer (IRIS)	13.3	6.9	10.8	1.0	0.0	0.0
	Reserve	33.7					

* Non common errors include: noise, coordinate system errors, plate scale errors

Table 3-26: Astrometric Accuracy - Systematic

		Errors (σ[μas])					
Requirement ID	Description	Systematic	Focal-Plane Measurement	Opto Mechanical	Atmospheric Refraction	Residual Turbulence	Non Common *
[REQ-1-OAD-0845]	Astrometry Accuracy	15.0	4.9	10.8	5.0	0.0	4.1
	Catalogs	0.0	0.0	0.0	0.0	0.0	0.0
	Fundamental	7.6	2.0	3.5	5.0	0.0	4.1
[REQ-1-OAD-0846]	Telescope	3.5	0.0	3.5	0.0	0.0	
	M1 System (M1S)	0.0	0.0	0.0	0.0	0.0	0.0
	M2 System (M2S)	0.0	0.0	0.0	0.0	0.0	0.0
	M3 System (M3S)	3.5	0.0	3.5	0.0	0.0	0.0
	Instrumentation	10.7	4.5	9.5	0.0	0.0	0.0
[REQ-1-OAD-0847]	First Light	10.7	4.5	9.5	0.0	0.0	0.0
	Narrow Field Near Infrared AO System (NFIRAOS)	6.0	0.0	6.0	0.0	0.0	0.0
	InfraRed Imaging Spectrometer (IRIS)	8.9	4.5	7.4	0.0	0.0	0.0
	Reserve	6.2					

* Non common errors include: noise, coordinate system errors, plate scale errors

3.13.2 AO PHOTOMETRY ERROR BUDGET

TIO AO Photometry Error Budget Spreadsheet (RD62) allocates the AO differential photometry components for point sources with SNR=100 and not fainter than magnitude 24 (Vega) in J band over a 34x34 arcsec field of view. It is assumed that at least one reference star is in each image and that the image is moderately crowded as defined in the TIO AO Photometry Error Budget Description Report (RD63).

The error budget applies to imaging of point sources and assumes photometric conditions. RD63 defines all the error terms, assumptions and their rationales. Errors are reported as percentages.

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

Table 3-27: Differential and Absolute AO Photometry Error Budget Allocations

Requirement ID	Description	Errors (%) Absolute Photometry	Differential Photometry	Astronomical source	Detector	Residual atmospheric turbulence	Atmospheric refraction errors	Opto mechanical	Data reduction
[REQ-1-OAD-0891]	**AO Photometry**	2.00	5.00	0.65	0.36	0.25	0.14	0.47	2.45
	Fundamental	1.10	1.10	0.46	0.00	0.00	0.00	0.00	1.00
	Calibration errors	0.00	1.88	0.46	0.33	0.25	0.10	0.36	1.73
[REQ-1-OAD-0893]	**Telescope**	0.17	0.00	0.00	0.00	0.00	0.00	0.17	0.00
	M3 System (M3S)	0.17	0.00	0.00	0.00	0.00	0.00	0.17	0.00
	Instrumentation	1.51	1.51	0.00	0.14	0.00	0.10	0.24	1.41
[REQ-1-OAD-0989]	**First Light**	1.51	1.51	0.00	0.14	0.00	0.10	0.24	1.41
	Adaptive Optics Executive Software (AOESW.PSF-R)	1.41	1.41	0.00	0.00	0.00	0.00	0.00	1.41
	InfraRed Imaging Spectrometer (IRIS)	0.30	0.30	0.00	0.14	0.00	0.10	0.24	0.00
	Narrow Field Near Infrared AO System (NFIRAOS)	0.44	0.44	0.00	0.30	0.25	0.00	0.20	0.00
	Reserve	0.69	4.24						

3.14 DATA STORAGE BUDGET

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

Table 3-28: TIO DMS Data Storage Requirements

Requirement ID	Subsystem	REQ TIO Science DMS (GB/night) (c) (d)	REQ US-ELTP Science Archive (GB/night) (c) (d) (e)	REQ TIO Engineering DMS (MB/night) (a) (b) (d)	Notes
REQ-1-OAD-9600	**Total TMT DMS Data Storage (First Light)** (calculation made with the more demanding First Light case scenario as defined in Science Data Yearly Rates sheet)	1,158	4,659	481,328	(a) Included under TCS (b) Included under SUM.FMCS (c) Includes raw and processed data (d) Includes ancillary files (e) Includes raw readouts data
REQ-1-OAD-9601	**Total TMT DMS Data Storage (First Decade)** (calculation made with First Decade operations instrument usage as defined in Science Data Yearly Rates sheet)	628	4,159	514,579	
REQ-1-OAD-9640	**Facilities**			7	
	Enclosure (ENC)			(a)	
	Summit Facilities (SUM, FMCS)(b)			7	
	Sea Level Facilities (SLF)			N/A	
REQ-1-OAD-9642	**Telescope**			233,705	
	Telescope Structure (STR)			(a)	
	M1 Optics System (M1S)			(a)	
	M2 Optics System (M2S)			(a)	
	M3 Optics System (M3S)			(a)	
	Optical Cleaning Systems (CLN)			1	
	M1 Coating System (M1 COAT)			(b)	
	M2/M3 Coating System (M2/M3 COAT)			(b)	
	Test Instruments (TINS)			2	
	Optics Handling Equipment (HNDL)			N/A	
	Telescope Control System (TCS)(a)			3,545	
	M1 Control System (M1CS)			14,782	
	Alignment and Phasing System (APS)			136,420	
	Observatory Safety System (OSS)			330	
	Engineering Sensors (ESEN)			78,626	
	Instrumentation				
REQ-1-OAD-9644	**First Light Instruments and AO system**	1,397	6,721	94,156	
	Narrow Field Near Infrared AO System (NFIRAOS)			76,100	
	Laser Guide Star Facility (LGSF)			1,406	
	AO Executive Software (AOESW)	142	142	60	
	InfraRed Imaging Spectrometer (IRIS)	918	4,565	5,530	
	Multi-Object Diffraction Limited High Res. Spectrograph (MODHIS)	118	1,937	5,530	
	Wide Field Optical Spectrometer (WFOS)	77	77	5,530	
	Refrigerant Cooling System (REFR)			1	
	Cryogenic Cooling System (CRYO)			1	
N/A	**First Decade Instruments and AO system**	265	39,330	27,648	
	PSI	62	2,235	5,530	
	NIRES-R	62	2,235	5,530	
	IRMOS	124	4,469	5,530	
	HROS	16	16	5,530	
	MICHI	1	30,376	5,530	
REQ-1-OAD-9648	**Operations**	118	118	77,631	
	Data Management System (DMS)	1	1	0	
	Executive Software (ESW)	1	1	0	
	Communication and Information Systems (CIS)			0	
	Common Software (CSW)			0	
	UPP (Science Operations Support Systems, Data Processing System)	1	1	0	*TBC, pending Noirlab updates
	Site Conditions Monitoring System (SCMS)	115	115	77,629	
	Reserves (First Light)	19%	20%	19%	
	Reserves (First Decade)	18%	20%	19%	

3.15 END-TO-END SCIENCE EXPOSURE TRANSFER LATENCY BUDGET

TIO end-to-End Science Exposure Transfer Latency Budget (RD69) in Table 3-29 establishes latency requirements to ensure files are available for PIs in the US-ELTP Science Archive in a timely manner.

Table 3-29: TIO End-to-End Science Exposure Transfer Latency Budget

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

3.16 Telescope Short Move Time & Accuracy Budget for Seeing Limited (SL) & Diffraction-Limited (AO)

3.16.1 Accuracy Allocation

During telescope moves including Diffraction-Limited (AO) and Seeing-Limited guider offsets, nods and dithers, the telescope accuracy will 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 3-30: Sub-allocation of accuracy requirements for Seeing-Limited and Diffraction-Limited Acquisition and Guider Offsets

			Minimum Accuracy (arcsec RMS)							
			Offset (Guider)						Offset (No Guider)	
Requirement ID	Description	Steady State	<2 arcsecs	<5 arcsecs	<10 arcsecs	<30 arcsecs	<300 arcsecs	<3600 arcsecs	<0.1 deg	<1.0 deg
[REQ-1-OAD-6000]	Seeing Limited	0.05	0.07	0.07	0.07	0.07	0.07	0.07	0.56	0.56
[REQ-1-OAD-6002]	Telescope	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.55	0.55
	M1 Control System (M1CS)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	M2 System (M2S)	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0450	0.0450
	M3 System (M3S)	N/A	N/A	N/A	N/A	0.04	0.04	0.04	0.35	0.35
	Telescope Control System (TCS)	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005
	Telescope Structure (STR) AZ	0.041	0.041	0.041	0.041	0.027	0.027	0.027	0.300	0.300
	Telescope Structure (STR) EL	0.029	0.029	0.029	0.029	0.022	0.022	0.022	0.300	0.300
[REQ-1-OAD-6003]	Instrumentation	N/A	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050
	Wide Field Optical Spectrometer (WFOS)	N/A	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
[REQ-1-OAD-6004]	Diffraction Limited	N/A	0.002	0.002	0.002	0.002	N/A	N/A	N/A	N/A
	InfraRed Imaging Spectrometer (IRIS)	N/A	0.002	0.002	0.002	0.002	N/A	N/A	N/A	N/A
	Multi-Objective Diffraction-limited High-Resolution Infrared Spectrograph (MODHIS)	N/A	0.002	0.002	0.002	0.002	N/A	N/A	N/A	N/A
	Narrow Field Near Infrared AO System (NFIRAOS)	N/A	0.002	0.002	0.002	0.002	N/A	N/A	N/A	N/A
	Telescope Control System (TCS)	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005

Discussion: The Diffraction-limited 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.

3.16.2 TIME TO MOVE

The following requirements define time and accuracy for telescope Seeing-Limited (SL) and Diffraction-Limited (AO) guider offsets, nods and dithers, and acquisition offsets.

Table 3-31: Time to move requirements for nodding, dithering; Seeing-Limited (SL) and Diffraction-Limited (AO).

			Maximum Time (seconds)							
			Offset (Guider)						Offset (No Guider)	
REQ ID	Subsystem	Steady State	<2 arcsecs	<5 arcsecs	<10 arcsecs	<30 arcsecs	<300 arcsecs	<3600 arcsecs	<0.1 deg	<1.0 deg
[REQ-1-OAD-6010]	Seeing Limited	N/A	2.0	2.5	4.0	5.0	5.0	5.0	7.0	11.3
[REQ-1-OAD-6012]	Telescope	N/A	2.0	2.5	4.0	5.0	5.0	5.0	7.0	11.3
	M1 Control System (M1CS)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	M2 System (M2S)	N/A	0.10	0.10	0.10	4.00	4.00	4.00	4.00	4.00
	M3 System (M3S)	N/A	N/A	N/A	N/A	5.00	5.00	5.00	7.00	11.30
	Telescope Control System (TCS)	N/A	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025
	Telescope Structure (STR)	N/A	2.0	2.5	4.0	5.0	5.0	5.0	7.0	11.3
[REQ-1-OAD-6013]	Instrumentation	N/A	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	Wide Field Optical Spectrometer (WFOS)	N/A	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
[REQ-1-OAD-6014]	Diffraction Limited	N/A	2.0	2.5	4.0	5.0	N/A	N/A	N/A	N/A
	InfraRed Imaging Spectrometer (IRIS)	N/A	2.0	2.5	4.0	5.0	N/A	N/A	N/A	N/A
	Multi-Objective Diffraction-limited High-Resolution Infrared Spectrograph (MODHIS)	N/A	2.0	2.5	4.0	5.0	N/A	N/A	N/A	N/A
	Narrow Field Near Infrared AO System (NFIRAOS)	N/A	2.0	2.5	4.0	5.0	N/A	N/A	N/A	N/A
	Telescope Control System (TCS)	N/A	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025

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

[REQ-1-OAD-1199] The observatory shall support a pattern of non-redundant dithers extending over a period of 4 hours with a time interval between two consecutive dithers (T_A in Figure 3-2) as short as 20 seconds with an RMS accuracy given in Table 3-32.

Discussion: Accuracy is defined with respect to the mean of all the dither positions in the pattern. This assumes all dither end points are contained in a box of up to 30 arcsec square for AO guiding, and 1 arcmin for seeing limited dithers. Non-redundant in this requirement means that each point in the dither pattern sequence is used only once. An example of a non-redundant dither is shown in Figure 3-2.

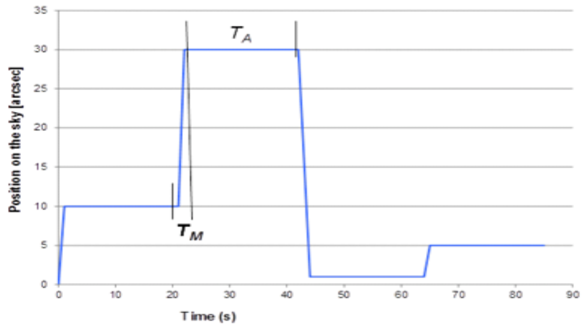

Figure 3-2: Example of non-redundant dither. T_A is the time between dither moves as per REQ-1-OAD-1199, i.e., the open shutter/dwell time ($T_A \geq 20$ s), T_M is move time or dither loss.

3.17 Open Loop Tracking Accuracy Budget

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

Table 3-32: Open Loop Tracking Accuracy

	Open Loop Tracking over 5 minutes	
REQ ID	Subsystem	Accuracy (arcsec RMS)
[REQ-1-OAD-6020]	Seeing Limited	0.22
[REQ-1-OAD-6022]	Telescope	0.21
	M1 Control System (M1CS)	0.01
	M2 System (M2S)	0.045
	M3 System (M3S)	0.045
	Telescope Control System (TCS)	0.0005
	Telescope Structure (STR)	0.2

3.18 Services Budgets

3.18.1 Power Budget

The electrical power types delivered to various locations of the observatory are described in 'Table 3-33: TIO Power Types'.

Table 3-33: TIO Power Types

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

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

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

Discussion: Electrical power is provided to the observatory at the locations described in 'Table 3-34: Power Loads Inside Dome' and 'Table 3-35: Power Loads Inside Summit Facilities'.

Table 3-34: Power Loads Inside Dome

Power Loads Inside Dome					
REQ ID	**Subsystem**	**Location**	**Power Type**	**Allocated: Total Connected (kW)**	**Notes**
[REQ-1-OAD-0801]	First Light	Distributed	EMUPS	6.87	(1)
			H3D	258.27	
			H3DG	1831.65	
			L3C	38.98	
			L3CUG	86.19	
			L3D	154.83	
			L3DG	68.30	
	First Decade	Distributed	EMUPS	7.37	
			H3D	258.27	
			H3DG	1831.65	
			L3C	50.98	
			L3CUG	117.14	
			L3D	164.83	
			L3DG	72.81	
[REQ-1-OAD-0986]	AM2	EL +X 5	L3CUG	12.02	(2)
[REQ-1-OAD-0911]	APS	NAS -X 4	L3C	0.61	
			L3CUG	1.02	
			L3D	4.19	
[REQ-1-OAD-0934]	CIS	EL -X 5	L3CUG	0.70	
		EL +X 5	L3CUG	0.70	
		FB 1	L3CUG	0.70	
		NAS -X 4	L3CUG	0.70	
		NAS +X 4	L3CUG	0.70	
[REQ-1-OAD-0907]	CLN	EL -X 5	L3CUG	0.32	
		EL +X 5	L3CUG	0.32	
		NAS -X 3	L3CUG	0.86	
		NAS +X 3	L3CUG	0.86	
		NAS -X 3	H3D	1.96	
		NAS +X 3	H3D	1.96	
[REQ-1-OAD-0908]	M2/M3 COAT	FB 1	H3D	160.00	
			L3CUG	0.02	
			L3D	40.20	
[REQ-1-OAD-0982]	CRYO	NAS -X 3	L3CUG	0.10	
			L3D	0.50	
		NAS +X 3	L3CUG	0.10	
			L3D	0.50	
[REQ-1-OAD-0900]	ENC	FB 1	H3DG	1682.80	
			L3CUG	2.70	
[REQ-1-OAD-0916]	ESEN	EL -X 5	L3CUG	0.60	
		EL +X 5	L3CUG	0.40	
		NAS -X 4	L3CUG	0.10	
		NAS +X 4	L3CUG	0.10	
[REQ-1-OAD-0926]	HROS	NAS +X 4	EMUPS	0.49	
			L3C	3.00	
			L3CUG	2.02	
			L3D	10.00	
			L3DG	4.51	
[REQ-1-OAD-0923]	IRIS	NAS -X 4	L3C	2.25	
			L3CUG	8.95	
[REQ-1-OAD-0927]	IRMOS	NAS +X 4	L3C	5.00	
			L3CUG	2.02	
[REQ-1-OAD-0920]	LGSF	EL -X 5	L3C	10.40	
			L3CUG	3.01	
			L3D	26.09	
		TOP 7	L3CUG	1.73	
[REQ-1-OAD-0914]	M1CS	M1C 5	L3CUG	17.50	
[REQ-1-OAD-0905]	M2S	EL +X 5	L3CUG	2.58	(2)
[REQ-1-OAD-0906]	M3S	M1C 5	L3CUG	6.10	
[REQ-1-OAD-0929]	MIRAO	NAS -X 4	L3CUG	5.02	
[REQ-1-OAD-0930]	MIRES	NAS -X 4	L3CUG	2.02	
[REQ-1-OAD-0925]	MODHIS	NAS -X 4	L3CUG	1.95	
[REQ-1-OAD-0918]	NFIRAOS	NAS -X 4	EMUPS	0.43	
			L3C	5.38	
			L3CUG	8.54	
			L3D	41.53	
[REQ-1-OAD-0932]	NIRES-R	NAS -X 4	L3CUG	6.03	
[REQ-1-OAD-0902]	OSS	AZ 2	L3CUG	0.03	
		NAS +X 4	L3CUG	0.03	
		NAS -X 4	L3CUG	0.03	
		EL -X 5	L3CUG	0.03	
		M1C 5	L3CUG	0.03	
		SHS 6	L3CUG	0.03	
[REQ-1-OAD-0928]	PFI	NAS -X 4	L3C	4.00	
			L3CUG	4.02	
[REQ-1-OAD-0983]	REFR	M1C 5	L3CUG	0.50	
		NAS -X 4	H3D	4.75	
			L3CUG	0.50	
		NAS +X 4	H3D	4.75	
			L3CUG	0.50	
		TOP 7	L3CUG	0.50	
[REQ-1-OAD-0917]	STR.TUS	AZ 0	EMUPS	0.08	(3)
			L3D	0.36	
			L3DG	0.16	
		AZ 1	EMUPS	0.88	
			L3D	3.60	
			L3DG	1.23	
		AZ 2	EMUPS	0.19	
			L3D	1.08	
			L3DG	0.65	
		AZ 3	EMUPS	0.11	
			L3D	0.36	
			L3DG	0.11	
		EL -X	EMUPS	0.33	
		EL -X 5	EMUPS	0.09	
			L3D	0.72	
			L3DG	0.30	
		EL -Y	EMUPS	0.53	
			L3D	1.08	
			L3DG	0.33	
		EL +-X,-Y	L3D	0.36	
		EL +-X,+-Y	EMUPS	0.30	
			L3D	0.72	
		EL +-X,+-Y	L3DG	2.20	
		EL +X	EMUPS	0.33	
		EL +X 5	L3DG	0.10	
		EL +Y	EMUPS	0.34	
			L3D	0.36	
			L3DG	0.16	
		M1C 5	EMUPS	0.66	
			L3D	7.56	
			L3DG	3.79	
		NAS -X 2	EMUPS	0.33	
			L3D	0.90	
			L3DG	0.62	
		NAS -X 3	EMUPS	0.19	
			L3D	2.34	
			L3DG	0.60	
		NAS -X 4	EMUPS	0.64	
			L3D	2.52	
			L3DG	1.43	
		NAS -X 5	EMUPS	0.06	
			L3DG	0.10	
		NAS +X 2	EMUPS	0.19	
			L3D	0.36	
			L3DG	0.46	
		NAS +X 3	EMUPS	0.22	
			L3D	2.34	
			L3DG	0.60	
		NAS +X 4	EMUPS	0.57	
			L3CUG	0.10	
			L3D	2.52	
			L3DG	1.29	
		NAS +X 5	L3D	0.72	
		NAS +X 6	L3D	0.72	
		SHS 6	EMUPS	0.06	
			L3D	1.08	
			L3DG	0.10	
[REQ-1-OAD-0901]	SUM	FB 1	H3D	76.34	
			H3DG	79.02	
			L3C	9.54	
			L3D	1.28	
			L3DG	6.12	
		FB E2	L3C	10.80	
[REQ-1-OAD-0909]	TINS	EL +X 5	L3CUG	0.75	
[REQ-1-OAD-0924]	WFOS	NAS +X 4	EMUPS	0.38	
			H3D	8.50	
			L3CUG	13.39	
			L3D	10.85	
[REQ-1-OAD-0903]	STR	AZ 0	H3DG	30.00	
		AZ 1	H3DG	27.83	
			L3CUG	0.24	
		AZ 2	L3CUG	0.92	
			L3DG	0.75	
		EL -X 5	L3CUG	1.12	
			L3DG	17.80	
		EL +X 5	L3CUG	0.90	
			L3DG	9.10	
		NAS -X 2	H3DG	12.00	
			L3CUG	1.70	
		NAS -X 3	L3CUG	0.30	
		NAS +X 2	L3CUG	1.70	
		NAS +X 3	L3CUG	0.70	
			L3DG	10.00	
		SHS 6	L3CUG	1.27	
			L3DG	10.30	

Notes:

(1) These values show total connected load and are not representative of power usage (which will be less).

(2) Power system is sized for larger of AM2/M2S

(3) TUS lighting is split as normal + emergency (L3DG) and emergency only (EMUPS)

Table 3-35: Power Loads Inside Summit Facilities

Power Loads Inside SUM					
REQ ID	Subsystem	Location	Power Type	Allocated: Total Connected (kW)	Notes
[REQ-1-OAD-0803]	First Light	Support Building/ Tunnel	H3D	1341.64	(1)
			H3DG	255.81	
			L3C	25.02	
			L3CUG	109.15	
			L3D	125.51	
			L3DG	9.70	
	First Decade	Support Building/ Tunnel	H3D	1341.64	
			H3DG	255.81	
			L3C	25.02	
			L3CUG	121.15	
			L3D	125.51	
			L3DG	9.70	
[REQ-1-OAD-0987]	AM2	SF 1	L3CUG	2.00	(2)
[REQ-1-OAD-0962]	AOESW	SF 1	L3CUG	13.30	
[REQ-1-OAD-0952]	APS	SF 1	L3CUG	3.00	
[REQ-1-OAD-0975]	CIS	SF 1	L3CUG	7.60	
[REQ-1-OAD-0988]	CLN	SF 1	L3CUG	0.20	
[REQ-1-OAD-0949]	M1 COAT	SF 1	H3D	172.75	
			L3C	3.70	
			L3CUG	0.02	
			L3D	40.20	
[REQ-1-OAD-0984]	CRYO	SF 1	H3D	189.00	
			L3CUG	1.00	
			L3D	1.00	
[REQ-1-OAD-0976]	CSW	SF 1	L3CUG	7.70	
[REQ-1-OAD-0977]	DMS	SF 1	L3CUG	9.15	
[REQ-1-OAD-0980]	DPS	SF 1	L3CUG	1.50	
[REQ-1-OAD-0957]	ESEN	SF 1	L3CUG	0.50	
[REQ-1-OAD-0978]	ESW	SF 1	L3CUG	9.21	
[REQ-1-OAD-0967]	HROS	SF 1	L3CUG	1.50	
[REQ-1-OAD-0964]	IRIS	SF 1	L3CUG	4.60	
[REQ-1-OAD-0968]	IRMOS	SF 1	L3CUG	3.00	
[REQ-1-OAD-0961]	LGSF	SF 1	L3CUG	5.80	
[REQ-1-OAD-0955]	M1CS	SF 1	L3CUG	3.02	
[REQ-1-OAD-0946]	M2S	SF 1	L3CUG	1.50	(2)
[REQ-1-OAD-0947]	M3S	SF 1	L3CUG	1.50	
[REQ-1-OAD-0970]	MIRAO	SF 1	L3CUG	1.50	
[REQ-1-OAD-0971]	MIRES	SF 1	L3CUG	1.50	
[REQ-1-OAD-0966]	MODHIS	SF 1	L3CUG	1.50	
[REQ-1-OAD-0959]	NFIRAOS	SF 1	L3CUG	10.00	
[REQ-1-OAD-0973]	NIRES-R	SF 1	L3CUG	3.00	
[REQ-1-OAD-0943]	OSS	SF 1	L3CUG	0.75	
[REQ-1-OAD-0969]	PFI	SF 1	L3CUG	3.00	
[REQ-1-OAD-0985]	REFR	SF 1	H3D	82.00	
			L3CUG	0.50	
[REQ-1-OAD-0981]	SCMS	SF 1	L3CUG	2.53	
[REQ-1-OAD-0979]	SOSS	SF 1	L3CUG	2.10	
[REQ-1-OAD-0944]	STR	SF 1	H3D	394.29	
			H3DG	20.10	
			L3CUG	3.12	
[REQ-1-OAD-0942]	SUM	AZ 0	L3D	2.00	
		SF 1	H3D	503.61	
			H3DG	235.71	
			L3C	21.32	
			L3CUG	15.40	
			L3D	82.31	
			L3DG	9.70	
[REQ-1-OAD-0953]	TCS	SF 1	L3CUG	0.66	
[REQ-1-OAD-0950]	TINS	SF 1	L3CUG	1.50	
[REQ-1-OAD-0965]	WFOS	SF 1	L3CUG	1.50	

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

3.18.2 FIXED TEMPERATURE CHILLED WATER

Fixed Temperature Chilled Water is a chilled water/glycol mixture provided within the Summit Facilities for cooling the Enclosure air handlers, HBS oil supply, REFR compressors, CRYO compressors, STR drive amplifiers, and various pumps and chillers, as described in 'Table 3-36: FTCW Loads'.

Two types of FTCW are provided for different cooling schemes. FTCW supplies chilled water at a nominal temperature of +7 ºC, and FTCW-L supplies chilled water at a nominal low temperature of -15 ºC.

Table 3-36: FTCW Loads

FTCW Loads				
REQ ID	Subsystem Equipment (Location)	FTCW Type	Allocation: Rejected Heat Load [kW]	Notes
[REQ-1-OAD-0811]	First Light	FTCW	352.1	
		FTCW-L	317.8	
	First Decade	FTCW	489.6	
		FTCW-L	364.4	
[REQ-1-OAD-0993]	SUM			
	Computer Room (AHU-01) (SF 1)	FTCW	82.4	
	Engineering & Optics Lab (AHU-02) (SF 1)	FTCW	12.3	
	Control Room (AHU-03) (SF 1)	FTCW	4.9	
	M1 Coating (FC-05) (SF 1)	FTCW	4.8	
	Facility Air Compressors (SF 1)	FTCW	45.0	
	Water/Electrical (FC-07) (SF 1)	FTCW-L	15.5	
	VTCW (HX-01) (SF 1)	FTCW-L	55.0	
	Enclosure Cooling (AHU-05,06,07) (FB 1)	FTCW-L	160.0	
[REQ-1-OAD-1998]	M1COAT			
	M1 Mirror Coating (SF 1)	FTCW	57.7	(1)
[REQ-1-OAD-1997]	M2M3COAT			
	M2/M3 Mirror Coating (FB 1)	FTCW	57.7	(1)
[REQ-1-OAD-0995]	CRYO			
	LN2 Compressors (SF 1)	FTCW	150.0	
	Sub-LN2 Compressors (SF 1)	FTCW	37.5	
[REQ-1-OAD-0996]	REFR			
	REF-SZ/A Cooling (SF 1)	FTCW-L	133.9	
	REF-H Cooling (SF 1)	FTCW	95.0	
Notes:				
(1) FTCW system is sized for M1COAT (not concurrently operated with M2M3COAT)				

3.18.3 VARIABLE TEMPERATURE CHILLED WATER

The Variable Temperature Chilled Water system circulates water/glycol that has been cooled to +5 ºC below ambient conditions and is expecting the water to leave the instrument at ambient air temperature. It is capable of generating VTCW down to -10 ºC. VTCW is provided to the telescope Laser Platform on the Elevation structure for removal of heat from the lasers and laser electronics, and to STR equipment at the locations described in 'Table 3-37: VTCW (Glycol) Loads'.

Table 3-37: VTCW (Glycol) Loads

VTCW (Glycol) Loads			
REQ ID	**Subsystem** Location	**Allocation : CON [L/min]**	**Notes**
[REQ-1-OAD-0812]	**First Light**	**279.7**	
	First Decade	**398.8**	
[REQ-1-OAD-2001]	**M2S, AM2**		
	EL +X 5	7.6	
[REQ-1-OAD-2002]	**M3S**		
	M1C 5	9.5	
[REQ-1-OAD-2003]	**APS**		
	NAS -X 4	22.2	
[REQ-1-OAD-0990]	**LGSF**		
	EL -X 5	68.0	(1)
[REQ-1-OAD-2004]	**IRIS**		
	NAS -X 4	22.2	
[REQ-1-OAD-2005]	**MODHIS**		
	NAS -X 4	6.3	
[REQ-1-OAD-2006]	**WFOS**		
	NAS +X 4	15.8	
[REQ-1-OAD-2007]	**HROS**		
	NAS +X 4	31.7	
[REQ-1-OAD-2008]	**IRMOS**		
	NAS +X 4	31.7	
[REQ-1-OAD-2009]	**MIRAO**		
	NAS -X 4	12.4	
[REQ-1-OAD-2010]	**MIRES**		
	NAS -X 4	12.4	
[REQ-1-OAD-2011]	**NIRES-R**		
	NAS -X 4	12.4	
[REQ-1-OAD-2012]	**PFI**		
	NAS -X 4	12.4	
[REQ-1-OAD-2013]	**NSI**		
	NAS -X 4	6.3	
[REQ-1-OAD-0991]	**STR**		
	NAS -X 2	28.0	
	NAS +X 2	28.0	
	NAS -X 3	16.0	
	NAS +X 3	16.0	
	AZ 0	40.0	
[REQ-1-OAD-1996]	**SUM**		
	Engineering & Optics Lab	10.0	(2)
	Instrument Station Observing Floor #1	10.0	
	Instrument Station Observing Floor #2	10.0	
	Instrument Station Wedge Room	10.0	

Notes:

(1) VTCW system is sized with sufficient margin for LGSF + future upgrade.

(2) VTCW system is not sized for service ports/instrument stations; consumption at these locations is non-concurrent with consumption of payloads in final configuration (installed).

3.18.4 Refrigerant (CO2)

Liquid CO2 refrigerant is provided to the telescope for removal of electronics heat via phase-change cooling at the locations described in 'Table 3-38: REFR Loads'.

Three types of CO_2 refrigerant are provided for different cooling schemes. Ambient refrigerant (REF-A) is used to cool electronics and equipment enclosures on the telescope to ambient temperature. Sub-zero refrigerant (REF-SZ) is provided to instruments that require cooling to a temperature of approximately -35°C to reduce infrared thermal emission from optical surfaces. HBS oil refrigerant (REF-H) is used to cool the hydrostatic bearing subsystem (HBS) oil for the telescope.

Table 3-38: REFR Loads

REFR Loads				
REQ ID	Subsystem Location	REFR Type	Allocation: Cool-Down Power [kW]	Allocation: Steady-State Power [kW]
[REQ-1-OAD-0813]	First Light	REF-A	-	15.5
		REF-SZ	28.5	8.2
	First Decade	REF-A	-	25.0
		REF-SZ	38.2	16.8
[REQ-1-OAD-1031]	M2S*			
	TOP 7	REF-A	-	0.5
[REQ-1-OAD-1032]	AM2*			
	TOP 7	REF-A	-	10.0
[REQ-1-OAD-1035]	NFIRAOS			
	NAS -X 4	REF-A	-	13.0
	NAS -X 4	REF-SZ	25.1	7.0
[REQ-1-OAD-1036]	LGSF			
	TOP 7	REF-A	-	2.0
[REQ-1-OAD-1037]	IRIS			
	NAS -X 4	REF-SZ	1.7	0.6
[REQ-1-OAD-1038]	MODHIS			
	NAS -X 4	REF-SZ	1.7	0.6
[REQ-1-OAD-1042]	IRMOS			
	NAS +X 4	REF-SZ	10.0	8.0
[REQ-1-OAD-1045]	NSI			
	NAS +X 4	REF-SZ	1.7	0.6
[REQ-1-OAD-1048]	STR			
	SUM	REF-H	-	74.2

*REFR system is sized for larger of AM2/M2S. First Light installation includes M2S onl

3.18.5 CRYOGEN

Cryogen is provided to cool instrument detectors to temperatures with sufficiently low dark current and to cool optical components of IR instruments in large dewars to cryogenic temperatures sufficient to keep their contribution to background thermal emission as low as possible, as described in 'Table 3-39: Instrument Steady State Cryogenic Cooling Requirements'.

Two types of cryogen are provided: Liquid Nitrogen (LN_2) is provided for instrument components whose target temperature is above the LN_2 boiling point, and sub-LN_2 is provided for instrument components whose target temperature is below the LN_2 boiling point.

Requirements for cooling future instruments below the boiling point of LN_2 at the ambient pressure in the observatory are under development.

Table 3-39: Instrument Steady State Cryogenic Cooling Requirements

CRYO Loads							
Requirement ID	**Instrument**	**Location**	**Generation**	**Cooling Type**	**Subsystem**	**Steady-State Target Temperature (K)**	**Allocated Steady-State Cooling Power (W)**
[REQ-1-OAD-0814]	**Various**	**Nasmyth**	**First Light**	**LN2**	**-**	**-**	**315**
	Various	**Nasmyth**	**First Decade**	**LN2**	**-**	**-**	**1601**
				sub-LN2	**-**	**-**	**141**
[REQ-1-OAD-4760]	IRIS	NAS -X	First Light	LN_2	Detector+Dewar	77	150
				LN_2	OIWFS	80	10
[REQ-1-OAD-4761]	MODHIS	NAS -X	First Light	LN_2	Detector	77	57
				LN_2	Dewar	120	
				LN_2	OIWFS	82	8
[REQ-1-OAD-4762]	APS	NAS -X	First Light	LN_2	Detector	160	30
[REQ-1-OAD-4763]	WFOS	NAS +X	First Light	LN_2	Detector	173	60
				N/A	AGWFS	N/A	N/A
[REQ-1-OAD-4764]	MIRES	NAS -X	First Decade	sub-LN_2	Detector	6	1
				sub-LN_2	Structure	20	30
				LN_2	Structure + Shield	80	170
				LN_2	OIWFS	82	8
[REQ-1-OAD-4766]	NIRES-R	NAS -X	First Decade	sub-LN_2	Detector	30	10
				sub-LN_2	Structure	60	30
				LN_2	Structure	80	320
				LN_2	OIWFS	82	33
[REQ-1-OAD-4767]	PFI	NAS -X	First Decade	sub-LN_2	Detector+Dewar	40	70
				LN_2	OIWFS	82	25
[REQ-1-OAD-4768]	IRMOS	NAS +X	First Decade	LN_2	Detector	77	620
				LN_2	Dewar	80	
				LN_2	OIWFS	82	50
[REQ-1-OAD-4769]	HROS	NAS +X	First Decade	LN_2	Detector	173	60
				LN_2	AGWFS	N/A	N/A

Discussion: Target temperatures are specified at sea level.

3.18.6 FACILITY COMPRESSED AIR

The Summit Facility Compressed Air (FCA) system provides compressed clean dry air to various locations of the observatory. The FCA system delivers air at 6 bar or higher to each selected telescope subsystem or instrument. The air is filtered and dried at the air compressor. Pipe sizing is adjusted so that the system has less than a 1 bar friction pressure loss.

Continuous (CON) and Intermittent (INT) Facility Compressed Air is provided to the telescope at the locations described in 'Table 3-40 FCA Loads'.

Table 3-40: FCA Loads

FCA Loads					
REQ ID	Subsystem	Location	Allocation: CON [L/S]	Allocation: INT [L/S]	Notes
[REQ-1-OAD-0805]	First Light	Distributed	63.2	2.0	
	First Decade	Distributed	99.7	2.0	
[REQ-1-OAD-0999]	M1CS	M1C 5	17.9	0.0	
[REQ-1-OAD-1002]	M2S	TOP 7	1.0	1.0	(1)
[REQ-1-OAD-1003]	AM2	TOP 7	1.0	1.0	(1)
[REQ-1-OAD-1028]	CLN	NAS -X 3	0.0	1.0	
		NAS +X 3	0.0	1.0	
[REQ-1-OAD-1006]	M1 COAT	SF 1	2.0	0.0	
[REQ-1-OAD-1999]	M2/M3 COAT	FB 1	0.0	2.0	
[REQ-1-OAD-1007]	APS	NAS -X 4	0.0	1.0	
[REQ-1-OAD-1008]	NFIRAOS	NAS -X 4 (NFIRAOS only, no instruments attached)	3.9	1.0	(2) and (3)
		NAS -X 4 (NFIRAOS portion while air sharing with 3 instruments)	4.7	1.0	
		NAS -X 4 (NFIRAOS +3 instruments total while integrated)	6.4	1.0	
[REQ-1-OAD-1009]	LGSF	EL -X 5	10.1	0.0	
		TOP 7	3.4	0.0	
[REQ-1-OAD-1011]	IRIS	NAS -X 4	0.8	0.0	
[REQ-1-OAD-1012]	MODHIS	NAS -X 4	0.8	0.0	
[REQ-1-OAD-1013]	WFOS	NAS +X 4	1.0	0.0	
[REQ-1-OAD-1014]	CRYO	NAS -X 3	0.5	2.0	
		NAS +X 3	0.5	2.0	
		AZ 2	0.0	1.0	
		SF 1	42.8	0.0	
[REQ-1-OAD-1017]	HROS	NAS +X 4	1.0	0.0	
[REQ-1-OAD-1018]	IRMOS	NAS +X 4	1.0	0.0	
[REQ-1-OAD-1019]	MIRAO	NAS -X 4	1.0	0.0	
[REQ-1-OAD-1021]	MIRES	NAS -X 4	1.0	0.0	
[REQ-1-OAD-1023]	NIRES-R	NAS -X 4	1.8	0.0	
[REQ-1-OAD-1024]	PFI	NAS -X 4	1.0	0.0	
[REQ-1-OAD-1029]	STR.TUS	NAS -X 4 (air dryer)	13.6	0.0	(4)
[REQ-1-OAD-1994]	SUM	Engineering & Optics Lab	1.0	1.0	(5)
		Instrument Station Observing Floor #1	0.8	0.0	
		Instrument Station Observing Floor #2	0.8	0.0	
		Instrument Station Wedge Room	0.8	0.0	
Notes					
General: specified in liters of free air per second at 0.6 bar and 0˚C					
(1) FCA system is sized for larger of AM2/M2S					
(2) When instruments are connected to NFIRAOS an "air sharing" approach will be followed where NFIRAOS will consume a portion of the instruments' air allowance. In this case 1m^3/hr per instrument (without margin) and 1.8 m^3/hr per instrument (including margin) will be transferred from the instrument air allowance to NFIRAOS. Thus, the pipe sizing to NFIRAOS should account for the increased airflow during air sharing. When instruments are not connected to NFIRAOS they will have access to their full air allowance and their piping should be sized appropriately.					
(3) FCA system is sized for the integrated FCA demand including NSCU. The NFIRAOS client instruments' standalone allocations should not be double counted in the total continuous FCA demands.					
(4) This allocation is for an air dryer used to deliver the NFIRAOS requirement of [P:W:O] grades [1:1:1].					
(5) FCA system should not be sized for these payloads but SUM/STR.TUS are responsible for routing stubs					

3.18.7 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 CIS based on the location of subsystem components as summarized in Table 3-41.

Table 3-41: CIS CNET Bandwidth

Requirement ID	Description	Location	Bandwidth (Gbps)	Notes
[REQ-1-OAD-4865]	TIO CIS CNET Minimum Bandwith (First light and first decade)	Total	10.0	
		SCT	0.010	
		FB 1	0.020	
		SF 1 [UR]	0.098	
		SF 1 [CR]	5.815	
		SF 1 [OR]	0.080	
		AZ 0	0.020	
		NAS +X 2	0.010	
		NAS -X 2	0.010	
		LTP +X 3	0.020	
		LTP -X 3	0.000	
		NAS +X 3	0.010	
		NAS -X 3	0.010	
		M1C 5	0.030	
		NAS +X 4	0.637	
		NAS -X 4	1.748	
		EL +X 5	0.040	
		EL -X 5	0.070	
		TOP 7	0.050	
		Reserve	1.402	
[REQ-1-OAD-4872]	Facilities		0.312	
	Enclosure (ENC)	FB 1	0.010	
		SF 1 [CR]	0.010	(1)
	Sea Level Facilities (SLF)	N/A	N/A	
	Summit Facilities (SUM)	SF 1 [CR]	0.172	
		SF 1 [OR]	0.080	
		SF 1 [UR]	0.040	
[REQ-1-OAD-4873]	Telescope		0.318	
	Alignment and Phasing System (APS)	SF 1 [CR]	0.142	
		NAS -X 4	1.461	
	Engineering Sensors (ESEN)	SF 1 [CR]	0.010	
		NAS -X 4	0.010	
		NAS +X 4	0.010	
		EL +X 5	0.010	
		EL -X 5	0.010	
		M1C 5	0.010	
		TOP 7	0.010	
	M1 Coating System (M1 COAT)	SF 1 [UR]	0.018	
	M1 Control System (M1CS)	SF 1 [CR]	0.018	
		M1C 5	0.010	
	M1 System (M1S)	N/A	N/A	
	M2 System (M2S)	SF 1 [CR]	0.010	(1)
		EL -X 5	0.010	
	M2/M3 Coating System (M2/M3 COAT)	FB 1	0.010	
	M3 System (M3S)	SF 1 [CR]	0.010	(1)
		M1C 5	0.010	
	Observatory Safety System (OSS)	SF 1 [CR]	0.010	
	Optical Cleaning Systems (CLN)	NAS -X 3	0.010	
		NAS +X 3	0.010	
		EL +X 5	0.020	
		EL -X 5	0.020	
		SF 1 [CR]	0.010	
	Optics Handling Equipment (HNDL)	N/A	N/A	
	Telescope Control System (TCS)	SF 1 [CR]	0.020	
	Telescope Structure (STR)	NAS -X 2	0.010	
		NAS +X 2	0.010	(2)
		LTP +X 3	0.010	(2)
		LTP +X 3	0.010	(2)
		AZ 0	0.020	(2)
		SF 1 [UR]	0.020	
		SF 1 [CR]	0.020	(1)
	Test Instruments (TINS)	NAS -X 4	0.010	
		EL -X 5	0.010	
		EL +X 5	0.010	
		TOP 7	0.010	

[REQ-1-OAD-4874]	**Instrumentation**		6.357	
	First Light		0.192	
	AO Executive Software (AOESW)	SF 1 [CR]	0.031	
	Cryogenic Cooling System (CRYO)	SF 1 [UR]	0.010	
		NAS -X 4	0.010	
		NAS -X 4	0.010	
	InfraRed Imaging Spectrometer (IRIS)	SF 1 [CR]	1.690	
		NAS -X 4	0.031	
	Laser Guide Star Facility (LGSF)	SF 1 [CR]	0.020	
		EL -X 5	0.020	
		TOP 7	0.020	
	Multi-Object Diffraction Limited High Resolution Spectrograph (MODHIS)	SF 1 [CR]	0.115	
		NAS -X 4	0.010	
	Narrow Field Near Infrared AO System (NFIRAOS)	SF 1 [CR]	0.546	
		NAS -X 4	0.010	
	Refrigerant Cooling System (REFR)	SF 1 [UR]	0.010	
		NAS -X 4	0.010	
		NAS -X 4	0.010	
		TOP 7	0.010	
	Wide Field Optical Spectrometer (WFOS)	SF 1 [CR]	0.142	
		NAS -X 4	0.010	
	First Decade		1.479	
	Adaptive secondary Mirror System (AM2)	SF 1 [CR]	0.000	(3)
	High Resolution Optical Spectrometer (HROS)	SF 1 [CR]	0.090	
		NAS +X 4	0.019	
	Near-Infrared Multi-Object Sectrometer (IRMOS)	SF 1 [CR]	0.021	
		NAS +X 4	0.608	
	Mid-Infrared AO System (MIRAO)	SF 1 [CR]	0.024	
		NAS -X 4	0.115	
	Mid-Infrared Echelle Spectrometer (MIRES)	SF 1 [CR]	0.671	
		NAS -X 4		
	Near Infrared Echelle Spectrometer (NIRES-R)	SF 1 [CR]	0.605	
		NAS -X 4	0.010	
	NFIRAOS Upgrade	SF 1 [CR]	0.010	
		NAS -X 4	0.010	
	NFIRAOS Side Instrument (NSI)	SF 1 [CR]	0.605	
		NAS -X 4	0.010	
	Planet Formation Instrument (PFI)	SF 1 [CR]	0.031	
		NAS -X 4	0.021	
	WFOS GLAO upgrade	SF 1 [CR]	0.100	
[REQ-1-OAD-4876]	**Operations**		0.082	
	Communication and Information Systems (CIS)	SF 1 [CR]	0.590	
	Common Software (CSW)	SF 1 [CR]	0.020	
	Data Management System (DMS)	SF 1 [CR]	0.023	
	Executive Software (ESW)	SF 1 [CR]	0.019	
	Site Conditions Monitoring System (SCMS)	SCT	0.010	
		SF 1 [CR]	0.010	
	US-ELTP (UPP.SOSS and DPS)	SF 1 [CR]	0.020	

Note: (1) Via TCS. (2) TUS. (3) Re-used M2S

[REQ-1-OAD-4885] The TIO System latency from the computer room to end point devices shall be less than 5 ms for each telescope-mounted subsystem, as shown in Table 3-42: Latency for Subsystems Terminating in a CIS or Subsystem Switch.

Table 3-42: Latency for Subsystems Terminating in a CIS or Subsystem Switch

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

Discussion: For CIS-specific testing, the Netperf application can be used to determine bi-directional data performance (see figure below). For operational use, applications will utilize CSW and therefore a major allocation is expected to go to the CSW components (command, events, telemetry).

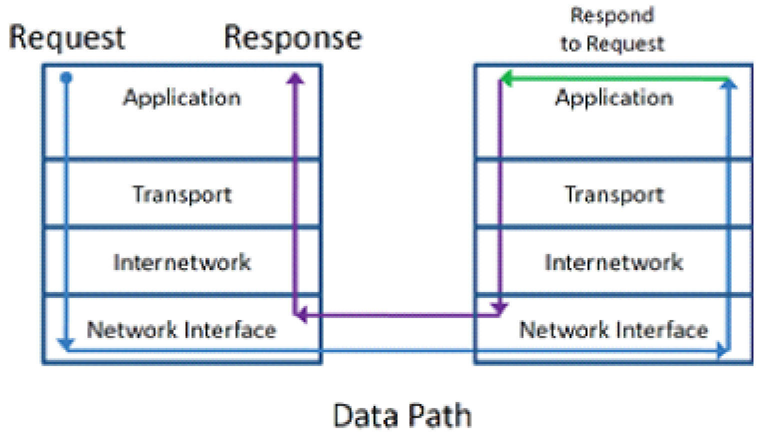

Figure 3-3: Bi-directional data performance

3.19 PRESET AND ACQUISITION TIME

Definition: The term *"preset"* refers to commanded "blind" motion of an actuator, or assembly of actuators, to a given position based on a specific input (Look-Up-Tables, coordinates, encoder position, etc.). If not explicitly denoted, preset motions involving different subsystems are triggered in parallel.

Preset is the process of (i) slewing the Telescope and Enclosure to point to the sky coordinates of a requested observation, and (ii) configuring all subsystems to execute the acquisition process.

Definition: The term "*acquisition*" refers to the execution of a coordinated sequence of functions that prepares the system for a science exposure. In contrast to preset, the motions are not blind and the involved subsystems typically require receiving star light.

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

> *Discussion: (RD44) illustrates and defines example preset and acquisition sequences for Seeing-Limited and Diffraction-Limited modes (NFIRAOS NGSAO and NFIRAOS LGS MCAO) of TIO.*

3.19.1 PRESET TIME

> *Discussion: TIO Preset Sequences Workflows are detailed in (RD44). The 1-minute average and 3-minute maximum preset times are allocated to subsystem as shown in Table 3-43: Preset Time Decomposition for Seeing-Limited and Diffraction-Limited (NGSAO and NFIRAOS LGS MCAO Mode). The LGSF terms do not apply for NGSAO and Seeing-Limited mode. This sequence includes pointing from any one position on the sky to any other in a way ensuring the uninterrupted execution of the next observation, and settle control loops and structural dynamics sufficiently to be ready for object acquisition.*

Table 3-43: Preset Time Decomposition for Seeing-Limited and Diffraction-Limited (NGSAO and NFIRAOS LGS MCAO Modes)

Requirement ID	Description	avg (s)	max(s)
[REQ-1-OAD-8729]	Preset Time	60	180
[REQ-1-OAD-8735]	Facilities	60	180
	Enclosure (ENC)	60	180
[REQ-1-OAD-8730]	Telescope	60	180
	M1 Control System (M1CS)	30	75
	M2 System (M2S)	30	60
	M3 System (M3S)	30	60
	Telescope Control System (TCS)	2	5
	Telescope Structure (STR)	60	180
	Instrumentation	60	140
[REQ-1-OAD-8739]	Difraction-Limited	60	140
	Adaptive Optics Executive Software (AOESW)	15	18
	InfraRed Imaging Spectrometer (IRIS) *	42	35
	Laser Guide Star Facility (LGSF) **	17	60
	Narrow Field Near Infrared AO System (NFIRAOS)	47	45
[REQ-1-OAD-8731]	Seeing-Limited	45	60
	Wide Field Optical Spectrometer (WFOS)	45	60
[REQ-1-OAD-8738]	Operations	2	5
	Executive Software (ESW)	2	5
	Reserve	0	0

Note: * The requirements for MODHIS will be identical to those of IRIS
**** LGSF only applicable for LGS MCAO mode**

3.19.2 Guide Star Acquisition Time

Refer to (RD48) for the acquisition time allocations for both Seeing-Limited and Diffraction-Limited modes (NFIRAOS LGS MCAO/NGSAO Modes). These allocations outline the time distribution for subsystems and individual steps/tasks and are derived from the workflows specified in (RD44). Table 3-44 assumes fully automated operation without user interactions, with requirements applicable only under these conditions. Note that the LGSF terms do not apply to the NGSAO mode.

Table 3-44: Guide Star Acquisition Time Decomposition for Seeing-Limited and Diffraction-Limited (NFIRAOS NGSAO/ LGS MCAO) Modes

Requirement ID	Description	avg (s)	max (s)
[REQ-1-OAD-8701]	Difraction-Limited Guide Star Acquisition Time	240	420
[REQ-1-OAD-8702]	Seeing-Limited Guide Star Acquisition Time	120	180
N/A	Facilities	0	0
	Enclosure (ENC)	0	0
[REQ-1-OAD-8740]	Telescope	30	41
	M1 Control System (M1CS)	30	30
	M2 System (M2S)	0	0
	M3 System (M3S)	0	0
	Telescope Control System (TCS)	6	6
	Telescope Structure (STR)	2	5
	Instrumentation		
[REQ-1-OAD-8745]	Difraction-Limited	185	349
	Adaptive Optics Executive Software (AOESW)	52	52
	Narrow Field Near Infrared AO System (NFIRAOS)	109	177
	InfraRed Imaging Spectrometer (IRIS) *	50	80
	Laser Guide Star Facility (LGSF) **	56	79
[REQ-1-OAD-8751]	Seeing-Limited	60	120
	Wide Field Optical Spectrometer (WFOS)	60	120
[REQ-1-OAD-8744]	Operations	25	27
	Reserve	0 30	3 19

Note: * The requirements for MODHIS will be identical to those of IRIS
**** LGSF only applicable for LGS MCAO mode**

4 SYSTEM SPECIFICATION

4.1 GENERAL SYSTEM REQUIREMENTS

4.1.1 ENVIRONMENTAL REQUIREMENTS

The definitions used in the following sections define the level of performance that must be achieved when equipment is exposed to the listed environmental conditions.

4.1.1.1 ENVIRONMENTAL REQUIREMENTS APPLYING TO ALL SUBSYSTEMS

"Equipment inside the enclosure" refers to any subsystems inside the enclosure that are protected from external environmental conditions.

The values identified for wind speed inside the enclosure 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.

For inside the enclosure, wind speeds should be considered using the air density resulting from the lowest temperature and lowest pressure for the conditions.

4.1.1.1.1 OBSERVING PERFORMANCE CONDITIONS

Observing Performance Conditions: subsystems 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.

[REQ-1-OAD-1210] Subsystems shall meet their Observing Performance requirements over the ranges specified in Table 4-1.

Table 4-1: Observing Performance Conditions

Observing Performance	
Condition	**Range**
Temperature	-5 to +9 °C
Humidity	between 0 and 95% at temperatures between -5 to +9 °C
Wind Speed	7.2 m/s (peak) at Observatory Floor 2.6 m/s (nominal) at Nasmyth/M1/M3 8.2 m/s (peak) at Nasmyth/M1/M3 1.3 m/s (nominal) at Top End/M2 9.7 m/s (peak) at Top End/M2 18m/s (1 minute average velocity at 20m elevation) at ENC/SUM/SCMS*
Temperature Gradients	within the 99.9% night-time values defined in Table 4-5
Pressure	600-618 hPa
Ozone	50 parts per billion

*for unprotected equipment

4.1.1.1.2 FACILITY PERFORMANCE CONDITIONS

Facility Performance: the Summit Facilities, Enclosure, and any subsystems 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.

[REQ-1-OAD-1215] Subsystems shall meet their Facility Performance requirements over the ranges specified in Table 4-2.

Table 4-2: Facility Performance Conditions

Facility Performance	
Condition	**Range**
Temperature	-10 to +13 °C
Humidity	0 and 95% at temperatures between -10 and +13°C 0 and 100% (condensing conditions) for unprotected equipment*
Wind Speed	15 m/s at Observatory Floor 10 m/s at Nasmyth/M1/M3 20.5 m/s at Top End/M2 30m/s (3s gust at 20m elevation) at ENC/SUM/SCMS*
Temperature Gradients	within the 99.9% night-time values defined in Table 4-5
Pressure	600-618 hPa
Ozone	50 parts per billion

*for unprotected equipment

4.1.1.1.3 Component Functional Conditions

Component Functional Conditions: any mechanical, electrical, or electromechanical components of a subsystem must be capable of functioning over this range of conditions.

[REQ-1-OAD-1225] Subsystems shall meet their Component Functional requirements over the ranges specified in Table 4-2.1.

Table 4-2.1: Component Functional Conditions

Component Functional	
Condition	**Range**
Temperature	-13 to +25 °C
Humidity	0 and 95% at temperatures between -10 to +13°C
Wind Speed	n/a
Temperature Gradients	within the 99.9% night-time values defined in Table 4-1
Pressure	600-1015 hPa
Ozone	n/a

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

4.1.1.1.4 Survival Conditions

Survival Conditions: All subsystems 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 the inspection period and without replacing any parts. No prior warning is available for this condition and subsystems cannot assume that their equipment is manually switched to an off or standby state prior to arrival of these conditions.

[REQ-1-OAD-1230] Subsystems shall meet their Survival requirements over the ranges specified in Table 4-3.

Table 4-3: Survival Conditions

Survival	
Condition	**Range**
Temperature	-16 to +30 °C
Humidity	0 and 100% (condensing conditions) at temperatures between -10 to +13°C
Wind Speed	Long duration, <10 min expoure: 15 m/s at Observatory Floor 10 m/s at Nasmyth/M1/M3 20.5 m/s at Top End/M2 Short duration, <30s expoure: 18 m/s at Observatory Floor 12 m/s at Nasmyth/M1/M3 24.6 m/s at Top End/M2 83.7m/s (3s gust at 20m elevation) at ENC, SUM, SCMS*
Temperature Gradients	up to the 99.9% values for all data defined in Table 4-5
Pressure	590-1025 hPa
Ozone	n/a

*for unprotected equipment

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

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*

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

4.1.1.1.5 DUST

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

Table 4-4: Median Dust Levels at Mauna Kea Site

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

4.1.1.1.6 TEMPERATURE GRADIENTS (SHORT TERM)

Table 4-5: Temporal Temperature Gradients Inside and Outside Enclosure

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

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

4.1.1.1.7 TEMPERATURE VARIATION (LONG TERM)

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

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

4.1.1.2 ENVIRONMENTAL CONDITIONS FOR SUBSYSTEMS WITH UNPROTECTED EQUIPMENT (ENC, SUM, SCMS)

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

[REQ-1-OAD-1235] Subsystems with unprotected equipment shall meet their requirements over the ranges specified in Table 4-6.

Table 4-6: Environmental Conditions for Unprotected Equipment

Environmental Conditions for Subsystems with Unprotected Equipment			
Condition	**Observing Performance**	**Facility Performance**	**Survival**
Temperature Gradients	within 99.9% values defined in Table 4-5	within 99.9% values defined in Table 4-5	Up to max level as defined in Table 4-5
Rainfall	n/a	0.04m/hour	0.04m/hour
Precipitation	n/a	in the presence of snow, hail, and rainfall	
Lightning	n/a	protection per NFPA 780	protection per NFPA 780
Snow/Ice	n/a	150 kg/m2 snow and ice load (vertical projection) after removal of ice and snow from critical areas	snow loads up to 150kg/m2 ice loads up to 68kg/m2 (can act concurrently)

4.1.1.3 Environmental Requirements Inside Utility Room

[REQ-1-OAD-1251] The Summit Facilities Utility Room equipment shall meet requirements over the ranges specified in Table 4-7.

Table 4-7: Environmental Conditions for the SUM Utility Room

	Environmental Conditions for the SUM Utility Room	
Condition	**Operational Range**	**Survival Range**
Temperature	0°C to 25°C	-16°C to 35°C (equipment may be assumed non-operational from -16 to 0°C)
Humidity	0-95%	up to 100%, condensing conditions (equipment may be assumed non-operational at levels >95%.)

4.1.1.4 Environmental Requirements Inside Computer Room

[REQ-1-OAD-1261] The Summit Facilities Computer Room equipment shall meet requirements over the ranges specified in Table 4-8.

Table 4-8: Environmental Conditions for the SUM Computer Room

	Environmental Conditions for the SUM Computer Room	
Condition	**Operational Range**	**Survival Range**
Temperature	15°C to 22°C	-16°C to 45°C (power off state)
Temperature Rate of Change	20°C/hour	
Humidity	20-80% with a maximum dew point of 17°C	8-80% with a maximum dew point of 27°C (power off state)

The operational range defines how well the conditions inside the computer room have to be controlled at any time that equipment located there is expected to be operational. The survival range defines the conditions that equipment must sustain in the event that power is lost to the observatory and the air conditioning systems for the computer room are inoperable.

4.1.1.5 Electromagnetic Interference/Electromagnetic Compatibility

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

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

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

4.1.2 Other General Requirements

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

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

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

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

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

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

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

4.2 Telescope

4.2.1 Optical Design

Discussion: TIO optical design is a Ritchey Chrétien (R-C) configuration as detailed in (RD74).

Discussion: Positive surface radius of curvature, and field curvature, are concave towards the incoming light to the surface. In the TIO 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.

Table 4-9: TIO Optical Parameters

Description	Value/Tolerance	Note
Entrance pupil primary mirror	Diameter ≥ 30 m	
Final focal length and plate scale	450 m ± 2.6 m, and 0.458366 arcsec/mm ± 0.0026 arcsec/mm	(D)
Nominal back focal distance	16.5 m ± 0.02 m	
M1 vertex radius of curvature	+60.000000 m ± 0.032 m	(P)
M1 conic constant (k1)	-1.00095348 (±0)	(P)
M1 to M2 distance separation (d)	27.0937500 m ± 0.026 m	(D)
M2 vertex radius of curvature	-6.227687857 m ± 0.021 m	(P)
M2 conic constant (k2)	-1.31822813 (±0.054dk2 ± 0.00047)	(P)
M3 curvature	0 ± 34 x 10^{-6}/m	(P)
Medial field curvature	3.00923 ± 0.01 m	(D)
Unobstructed field of view (FOV) delivered to foci.	20 arcmin	
Unvignetted FOV based on clear apertures of M2 and M3	15 arcmin	

Note: P = a primary dimension; tolerances apply to the fabricated parts.
D = Derived parameter; the value may fall in this range depending on the as-manufactured primary dimensions.

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

[REQ-1-OAD-1050] TIO final focal length and plate scale^{D} shall be 450m (+/-2.6m) and 0.458366 arcsec/mm (+/-0.0026 arcsec/mm), respectively.

Discussion: ^{D} = Derived parameter; the value may fall in this range depending on the as-manufactured primary dimensions.

[REQ-1-OAD-1052] TIO M1 vertex radius of curvature^{P} shall be +60.000000m (+/-0.032m).

Discussion: ^{P} = a primary dimension; tolerances apply to the fabricated parts.

[REQ-1-OAD-1054] TIO M1 conic constant (K_1)^{P} shall be -1.00095348 (+/-0).

Discussion: ^{P}= a primary dimension; tolerances apply to the fabricated parts.

Discussion: No tolerance is specified for the M1 conic constant as it should be used as a basic dimension in the individual segment prescriptions

[REQ-1-OAD-1056] TIO M1 to M2 distance separation (d)^{D} shall be 27.0937500m (+/-0.026m).

Discussion: ^{D} = Derived parameter; the value may fall in this range depending on the as-manufactured primary dimensions.

[REQ-1-OAD-1058] TIO M2 vertex radius of curvature (k_2)^{P} shall be -6.227687857m (+/-0.021m).

Discussion: ^{P} = a primary dimension; tolerances apply to the fabricated parts.

[REQ-1-OAD-1060] TIO M2 conic constant^{P} shall be -1.31822813 (with a tolerance of $0.054dk_2$+/-0.00047).

Discussion: ^{P} = a primary dimension; tolerances apply to the fabricated parts.

Discussion: The M2 conic constant tolerance depends on the achieved tolerance on the M2 radius of curvature, dk_2.

[REQ-1-OAD-1062] TIO M3 curvature^{P} shall be 0 with a tolerance of +/- 34 x 10^{-6}/m.

Discussion: ^{P} = a primary dimension; tolerances apply to the fabricated parts.

[REQ-1-OAD-1010] TIO M3 shall be located in front of the primary mirror, to steer the telescope beam to Nasmyth foci.

[REQ-1-OAD-1064] TIO Medial Field curvature^{D} shall be 3.00923 (+/-0.01m).

Discussion: ^{D} = Derived parameter; the value may fall in this range depending on the as-manufactured primary dimensions.

[REQ-1-OAD-1066] TIO unobstructed field of view delivered to foci shall be 20 arcmin.

[REQ-1-OAD-1068] TIO unvignetted field of view (FOV) based on clear apertures of M2 and M3 shall be 15 arcmin.

Discussion: Clear apertures should maintain 15 arcminutes unvignetted field of view under all tolerance conditions.

[REQ-1-OAD-1015] TIO nominal back focal distance shall be 16.5 m with a tolerance of +/-0.02m.

Discussion: The back focal distance is defined as the distance or back relief from the M1 vertex to focus in the absence of the M3.

[REQ-1-OAD-1020] TIO 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] TIO stray light control shall be provided by a baffle around M2 and M3 and in the instrument designs.

[REQ-1-OAD-1026] TIO baffle size of the M2 and M3 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] TIO entrance pupil shall have a maximum of 4% obscuration due to the shadow of the secondary mirror and its support structure and follow the pattern shown in (AD41).

4.2.2 Aerothermal Considerations

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

Table 4-10: Maximum Allowable Cross Sectional Area of Telescope Top End

Requirement ID	Sub-System	Maximum Transverse Cross Sectrional Area (m^2)	
[REQ-1-OAD-1090]	M2S	4.0	
[REQ-1-OAD-1092]	LGSF Top End	4.0	
[REQ-1-OAD-1094]	LGSF Beam Transfer Tube	6.0	
[REQ-1-OAD-1096]	Telescope Structure	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 (STR)

4.2.3.1 General

The telescope structure provides support for the telescope optics and their associated systems, instruments and adaptive optics systems, and provide services and auxiliary systems as additionally specified in this document.

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

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

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

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

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

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

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

Discussion: The height of:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

4.2.3.1.1 SEISMIC ACCELERATIONS

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

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

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

[REQ-1-OAD-1287] Under all operating conditions and configurations, subsystems which are mounted on the telescope structure shall withstand the seismic accelerations defined in 'Table 4-11: Seismic limits for telescope-mounted subsystems' such that:

- After a 10-year return period earthquake, the subsystems can resume normal operations after inspection by the normal operations staff.

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

Table 4-11: Seismic Limits on Telescope Structure Mounted Subsystems

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

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

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

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

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

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

[REQ-1-OAD-1291] Derating of seismic loading for 200- or 1000-year return period earthquakes for equipment in temporary configurations whose failure can damage the M1, M2, M3 or present worse than a marginal hazard to personnel shall use the acceleration scaling factors in Table 4-12: Seismic Acceleration Scaling Factors for Temporary Configurations - Personnel/Optics Safety.

Table 4-12: Seismic Acceleration Scaling Factors for Temporary Configurations-Personnel/Optics Safety

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

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

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

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

[REQ-1-OAD-1294] Derating of seismic loading for 200- or 1000-year return period earthquakes for equipment in temporary configurations not covered by [REQ-1-OAD-1291] shall use the acceleration scaling factors in Table 4-13: Seismic Acceleration Scaling Factors for Temporary Configurations.

Table 4-13: Seismic Acceleration Scaling Factors for Temporary Configurations

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

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

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

4.2.3.2 TELESCOPE AZIMUTH STRUCTURE

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

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

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

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

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

4.2.3.3 TELESCOPE ELEVATION STRUCTURE

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

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

Discussion: The maximum deflections of the interface planes between the telescope and the M2S and LGSF laser launch telescope are not to exceed the values given in 'Table 4-14: Maximum allowable deflection of the telescope top end". These limits apply at any observing temperature combined with any elevation angle between 0 and 65º.

Table 4-14: Maximum allowable deflection of the telescope top end

Requirement ID	Direction	Maximum Allowed Deflection
[REQ-1-OAD-1322]	Axial motion along the primary mirror optical axis relative to the M1 vertex	+/-4mm
[REQ-1-OAD-1323]	Tilt relative to the M1 optical axis about M2CRS x axis	+/-2.5mrad
[REQ-1-OAD-1326]	Tile relative to the M1 optical axis about the M2CRS Y axis	+/-0.5mrad
[REQ-1-OAD-1324]	Translation perpendicular to the M1 optical axis	+/-15mm

4.2.3.4 TELESCOPE PIER

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

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

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

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

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

4.2.3.5 CABLE WRAPS

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

[REQ-1-OAD-1345] The cable wraps shall accommodate the distribution of all utilities, VTCW, HBS, power and grounding, CIS, CRYO, REFR, lighting, fire alarm, FCA, and safety network to the telescope structure as defined in (AD96).

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

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

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

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

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

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

4.2.3.6 MOUNT CONTROL SYSTEM AND DRIVES

[REQ-1-OAD-1375] The mount control system as implemented on the telescope shall exhibit a torque disturbance rejection transfer function relative to open loop, that is equal to or better than that shown in 'Figure 4-1: Bound on mount control torque rejection with respect to open-loop' below.

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

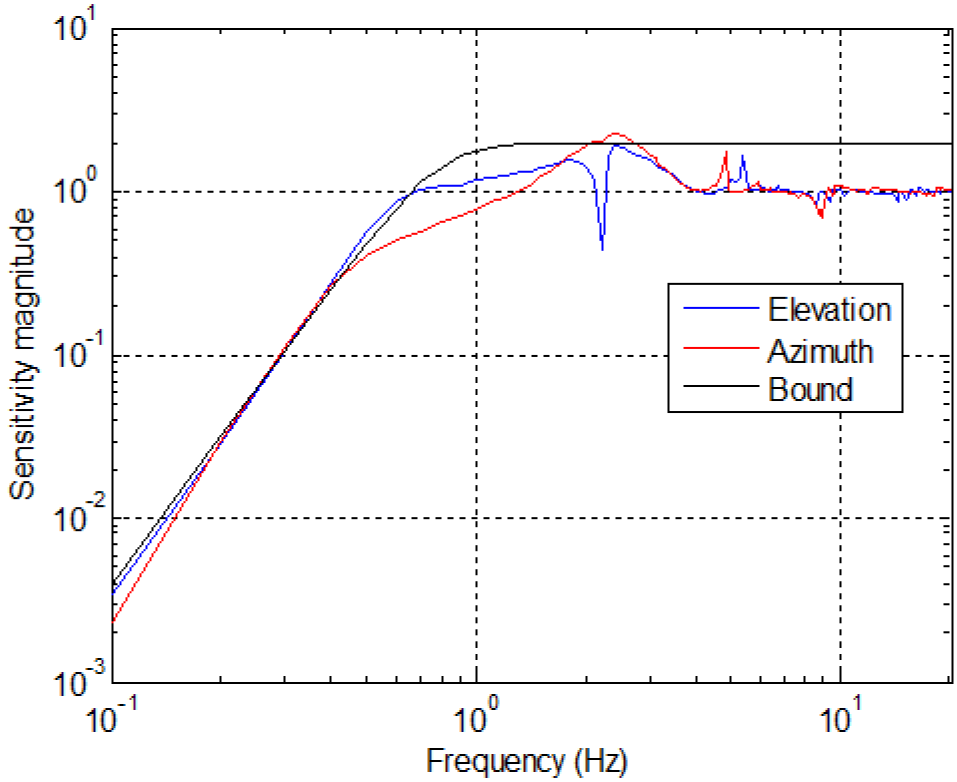

Figure 4-1: Bound on mount control torque rejection with respect to open-loop. The mount control rejection achieved with the current design is shown for comparison.

4.2.3.6.1 Telescope Azimuth Axis Slewing

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

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

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

4.2.3.6.2 Telescope Elevation Axis Slewing

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

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

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

4.2.3.7 Nasmyth Platforms and Instrumentation Support

4.2.3.7.1 Performance

[REQ-1-OAD-1380] The telescope shall deliver the image with jitter due to wind effects, relative to an instrument mounted on the Nasmyth platform, less than or equal to the PSD shown in '*Figure 4-2: Allowable image jitter as seen by an instrument mounted on the Nasmyth Platform*' below.

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

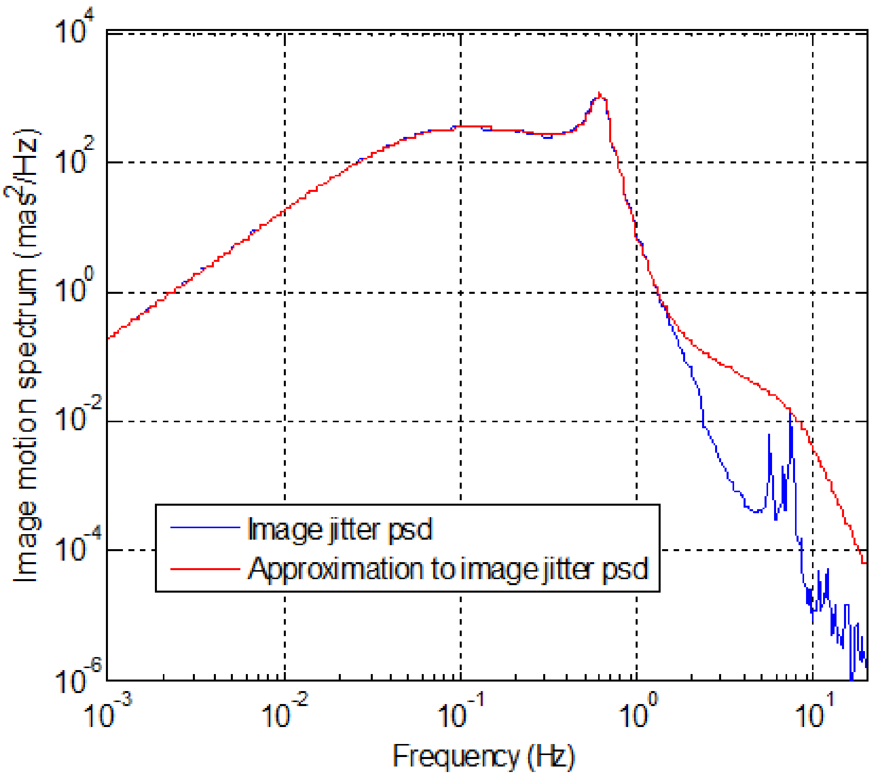

Figure 4-3: Allowable image jitter as seen by an instrument mounted on the Nasmyth Platform

Discussion: The image jitter below 10 Hz is primarily due to wind. The requirement is derived from a model of the wind loads, the telescope structure, and the telescope control system based on the design as of June 2007, and documented in TIO.SEN.TEC.07.017 (RD23). The allowable wind-induced image jitter power spectrum as seen by an instrument on the Nasmyth platform is given in the figure, with the amplitude scaling described below. The approximation, useful for analysis, is

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

where k is chosen to scale the overall amplitude. For the 75th percentile wind and upwind (0° azimuth, 30° zenith) orientation used to generate the above spectrum, then f_0 = 0.105 Hz, f_1 = 0.625 Hz, f_2 = 1.5 Hz, f_3 = 8 Hz and ζ_0 = 1.25, ζ_1 = 0.1, ζ_2 = 0.5, ζ_3 = 0.5. Changes in the overall amplitude will also shift the frequency response, but this effect is relatively small - the most significant influence on the shape of the response results from the control systems and is thus independent of conditions (orientation or wind speed). The image jitter is predominantly one-

dimensional; at least 5 times larger in rotation about x than rotation about y. The median, 75th, 85th and 95th percentile overall image jitter due to wind is 13, 28, 45, and 90 mas respectively.

4.2.3.7.2 Configuration

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

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

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

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

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

<u>+X Nasmyth Platform:</u>

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.

<u>-X Nasmyth Platform:</u>

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

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

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

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

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

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

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

[REQ-1-OAD-1410] At First Light, the Nasmyth Platforms shall provide support for the following instruments, each at their own foci: NFIRAOS with the NSCU, feeding IRIS and MODHIS, at the 174.5 degree position on the -X platform, WFOS at the 0 degree position on the +X platform, and APS at the 180 degree position on-axis and beside NFIRAOS.

Discussion: The Nasmyth sides are designated -X and +X corresponding to directions in the Azimuth Coordinate Reference System. The foci locations are designated by their angular position, where 0 degrees is on the +X platform aligned with the telescope elevation axis, increasing counterclockwise as viewed from above.

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

[REQ-1-OAD-1415] The Nasmyth Platforms shall be upgradeable to support the following First Decade instruments, each at their own foci and with their required field of view: IRMOS, MIRES, PFI, NIRES, HROS.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

4.2.3.7.3 Instrument Mounting Points

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

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

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

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

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

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

4.2.3.7.4 SERVICES

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

4.2.3.7.5 ACCESS TO PLATFORMS AND INSTRUMENT LOCATIONS

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

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

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

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

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

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

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

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

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

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

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

[REQ-1-OAD-1482] All instruments shall not block the pathways on the 4F Nasmyth platforms (per AD103) used for personnel and equipment to transit between the +Y and -Y ends of the Nasmyth areas.

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

4.2.3.7.6 ACCESS TO INSTRUMENTS

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

4.2.3.7.7 ACCESS BETWEEN PLATFORMS

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

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

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

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

4.2.3.7.8 Instrument Handling, Installation and Removal

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

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

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

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

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

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

Discussion: Activities such as in situ welding, cutting and grinding are considered incompatible with this environment, they must ne avoid and it will required TIO approval. Activities will be planned, and equipment will be designed in such a manner that any damage to the telescope optics is highly unlikely.

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

4.2.3.7.9 Requirements for Regular Maintenance and Servicing of Instruments

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

4.2.3.7.10 Floor Space and Storage Requirements

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

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

4.2.3.7.11 Safety and Personnel Considerations

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

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

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

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

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

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

4.2.4 M1 Optics System (M1S)

4.2.4.1 General

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

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

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

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

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

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

[REQ-1-OAD-1685] The segment and the portions of the SSA that will stay with it in the coating chamber shall be compatible with the vacuum and coating environment, and shall not show any degradation after 30 re-coating cycles.

[REQ-1-OAD-1690] The segments shall be dimensionally stable such that the relative heights of the segment edges comply with the error budget term for SOPD Segment Out of Plane Displacement [REQ-1-OAD-0406] for periods of at least 30 days without updates from the APS.

[REQ-1-OAD-1692] The STR shall provide access to the primary mirror cell from each of the Nasmyth platforms when the telescope is zenith pointing.

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

4.2.4.2 Telescope Mirror Optical Coating Requirements

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

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

Discussion: 'Table 3-3: Subsystems Throughput after Fresh Optical Coatings' lists the requirements for the optical coatings on each of the M1, M2 and M3 mirror surfaces.

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

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

[REQ-1-OAD-1606] The M1, M2, and M3 Optical Coatings shall have ΔR / Wavelength of < 0.003/nm over a wavelength range of 0.31 - 28 µm.

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

[REQ-1-OAD-1603] The M1, M2, and M3 Optical Coatings shall have a Maximum Emissivity per Surface of 0.015 over a wavelength range of 0.7 - 28 µm.

4.2.4.3 SEGMENTATION

[REQ-1-OAD-1700] The primary mirror of the system shall be segmented as shown in '*Figure 4-3: Layout of the segmented primary mirror, as projected on the X-Y plane of the Elevation Coordinate System (ECRS)*' below; it contains 492 segments.

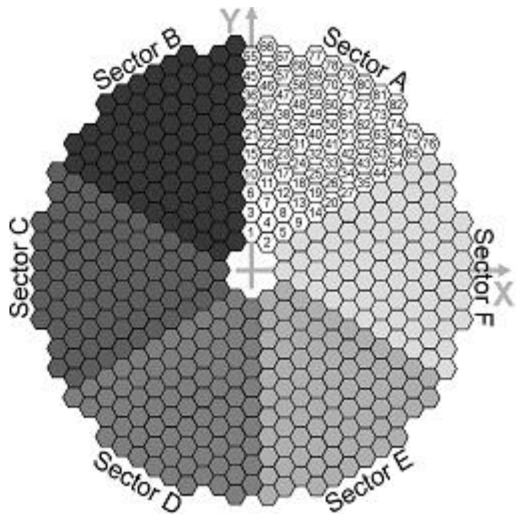

Figure 4-3: Layout of the segmented primary mirror, as projected on the X-Y plane of the Elevation Coordinate System (ECRS). The capital letters denote identical sectors rotated by 60 degrees relative to each other.

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

Discussion: The nominal gap between segments is 2.5mm, and each segment has a 0.5mm bevel. Therefore the optical gap between segments is 3.5mm. For the 1386 gaps between segments, the total pupil obscuration is 0.56%.

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

[REQ-1-OAD-1735] The telescope structure and primary mirror cell shall be designed such that relative in-plane motion between any two adjacent segments results in a segment gap change of less than 0.54 mm under all Observing Performance conditions, and less than 1.0 mm under all Facility Performance conditions.

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

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

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

Table 4-15: Combination of cases under which segment to segment contact must not occur

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

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

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

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-1775] The radial scaling coefficient, α, of [REQ-1-OAD-1750] shall be 0.1650.

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

4.2.4.4 Positioning

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

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

4.2.4.5 M1 Optics Handling

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

M1 General Segment Lifting Fixture (GSLF) that interfaces to the MSA; (3) M1 Segment Storage Cabinet (SSC) for storage of 82 spare M1 segments; (4) M1 Segment Handling Cart Restraint (SHC Restraint) as a means to tether the loaded or unloaded carts in the staging bays; (5) M1 Segment Lifting Jack to raise segments from the fixed frame and allow removal from the telescope.

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

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

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

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

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

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

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

4.2.5 M2 System (M2S)

4.2.5.1 M2S General

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

[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).

4.2.5.2 M2S Removal, Cleaning and Coating

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

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

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

[REQ-1-OAD-1850] As a goal, the M2 system shall be designed to allow in-situ washing of the mirror. Catchments shall be provided to catch all the fluids used in the washing operation, for proper disposal. No washing fluids shall be allowed to drip onto the primary mirror or tertiary mirror.

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

4.2.5.3 M2S Control

The M2 System includes a low level control system to control the M2 positioner.

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

[REQ-1-OAD-1860] In addition to any other motion requirements, the mechanical range of motion of the M2 system shall be sufficient to accommodate any combination of the telescope top end deflections as specified in 'Table 4-9: Maximum allowable deflection of the telescope top end'.

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

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

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

4.2.5.4 M2S Optical Quality

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

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

4.2.6 M3 System (M3S)

4.2.6.1 M3S General

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

The M3 incorporates alignment features that allow its position and orientation to be accurately and quickly measured by the Global Metrology System (GMS).

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

4.2.6.2 M3S Removal, Cleaning and Coating

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

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

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

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

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

[REQ-1-OAD-1995] The M3 assembly shall be serviceable either using the aerial servicing platform with the telescope horizon pointing or in telescope zenith-pointing orientation by personnel who ascend into the center of the assembly through the rotation bearing of the M3 positioner.

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

4.2.6.3 M3S Control

[REQ-1-OAD-2000] The M3 System shall provide two degree of freedom motion of the tertiary mirror relative to the telescope structure. The required mechanical range of motion shall be sufficient to redirect a beam of light from the secondary mirror towards the Nasmyth platform instrument locations per [REQ-1-OAD-1398]. The motion shall be achieved over a telescope zenith angle range of 0 to 65 degrees. All instrument optical axes are located in a plane perpendicular to the ACRS z-axis and coincident with the ECRS origin.

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

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

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

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

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

4.2.6.4 M3S Optical Quality

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

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

4.2.7 Primary Mirror Control System (M1CS)

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

Discussion: The static stiffness relative to its neighbours is defined by the slope of the force versus displacement curve for forces applied normal to, and at the center of, the front surface of a segment properly installed in the telescope and displacement of the segment relative to its 6 neighbours. Higher stiffness provides additional benefit. The compliance is dominated by the Primary Segment Assembly (including SSA and actuators) and the top chord of the mirror cell; the rest of the mirror cell does not contribute significantly to the relative stiffness as defined below and can be neglected for this calculation.

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

Discussion: The bandwidth is defined as the frequency where the sensitivity is -3dB. The wind rejection characteristics of the M1 system are defined by the temporal and spatial character of the wind and the wind rejection capability of the M1CS. Both of these parameters are complex and difficult to define in a concise manner. Defining a static stiffness of the M1 system along with a M1CS bandwidth provides a reasonable approximation to the comprehensive requirement. Since the wind disturbance has finite content up to, and even beyond 1 Hz, defining a static stiffness number doesn't define the complete response. Below 1 Hz the stiffness characteristics of the relevant structural components won't vary greatly; on the other hand, the stiffness of the actuator may vary considerably over this range compromising the wind disturbance rejection as predicted by a static stiffness model. For this reason, performance prediction models will utilize more accurate models of M1 wind rejection. Higher bandwidths provide additional benefit and should be considered if achievable with little extra cost.

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

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

Discussion: The requirement between 1 and 5 Hz is simply a linear relationship on a log-log scale joining the requirements at 1 and 5 Hz. There is no stiffness requirement for frequencies above 20 Hz. These numbers are guidelines. [REQ-1-OAD-2100] states that the static stiffness of the combined segment support is to be no less than 10 N/um in the z direction. There are advantages to make the actuators as stiff as possible up through 20 Hz. Presently the disturbance environment between 1 and 20 Hz is not well understood.

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

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

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

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

4.2.8 Alignment and Phasing System (APS)

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

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

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

Additionally, APS possesses the functionality of an acquisition camera, which is utilized for pointing, acquisition, and tracking tests at AIV, as well as during engineering nights.

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

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

Discussion: In Alignment Maintenance Mode and Post Segment Exchange Mode, the initial M1, M2, and M3 optics are not to exceed the error requirements shown in 'Table 4-16: Alignment Maintenance Mode and Post Segment Exchange Mode Capture Range'.

Table 4-16: Alignment Maintenance Mode and Post Segment Exchange Mode Capture Range

Requirement ID	Optical Element	Maximum Error for alignment maintenance mode capture range	Maximum Error for post segment exchange capture range	Units
[REQ-1-OAD-2260]	M1			
	M1 Segment Tip/Tilt	+/- 1	+/- 20	arcseconds in one dimension on the sky
	M1 Segment Piston	+/- 1	+/- 30	microns (surface)
	M1 Surface Shape	+/- 0.25	+/- 0.5	arcseconds relative in one dimension on the sky between Shack-Hartmann subapertures 20cm apart.
[REQ-1-OAD-2266]	M2			
	M2 Tip/Tilt	+/- 5		arcseconds in one dimension on the sky
	M2 Piston	+/- 2		mm (surface)
	M2 X/Y Decenter	+/- 100		microns
[REQ-1-OAD-2274]	M3			
	M3 Tip/Tilt	+/- 60		mm (pupil mis-alignment at M1) in X and Y

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

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

[REQ-1-OAD-2330] The APS shall be able to perform all function necessary for on-axis alignment and M1CS calibration in 180 minutes when all optics are within the post-segment exchange specifications.

[REQ-1-OAD-2331] APS shall be able to transition from its standby state and be ready to perform any of its alignment and phasing routines within ten (10) minutes.

4.2.9 Cleaning System (CLN)

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

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

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

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

4.2.10 Engineering Sensors (ESEN)

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

4.2.11 Site Conditions Monitoring System (SCMS)

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

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

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

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

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

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

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

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

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

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

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

4.2.12 Test Instruments (TINS)

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

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

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

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

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

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

4.3 INSTRUMENTATION

4.3.1 GENERAL

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

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

[REQ-1-OAD-2705] TIO Instrumentation (Instruments/AO Systems) shall incorporate all hardware necessary for calibration.

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

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

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

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

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

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

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

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

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

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

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

4.3.2 First Light

4.3.2.1 NFIRAOS Subsystem

4.3.2.1.1 General

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

4.3.2.2 LGSF

4.3.2.2.1 General

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

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

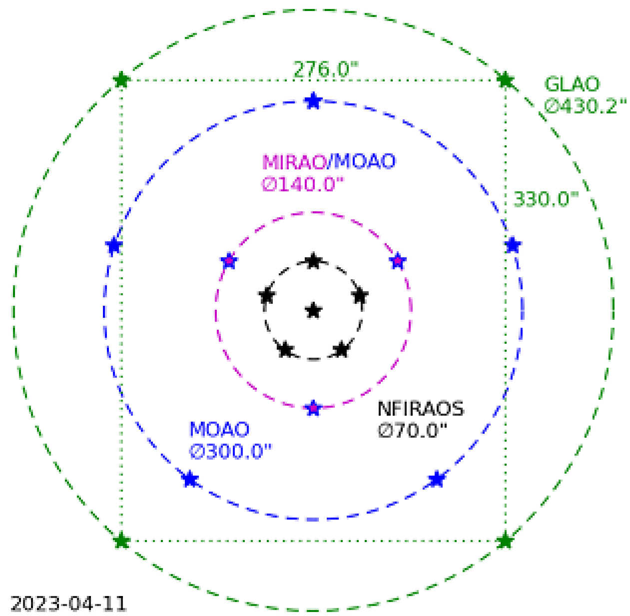

Figure 4-4: LGSF asterisms supporting different AO modes: ***NFIRAOS*** *(black) 1 on axis, 5 on a 35 arcsec radius;* ***MIRAO*** *(magenta) 3 on a 70 arcsec radius;* ***MOAO*** *(blue) 3 on a 70 arcsec radius, 5 on a 150 arcsec radius;* ***GLAO*** *(green) 4 on a 276 arcsec by 330 arcsec rectangle centered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

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

Discussion: This signal level may be reduced by ~65% if a laser pulse format that enables dynamic refocusing (in order to eliminate LGS elongation) is utilized.

[REQ-1-OAD-2917] The LGSF shall include all necessary alignment, calibration and diagnostic features required to meet its performance requirements.

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

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

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

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

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

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

[REQ-1-OAD-2939] LGSF shall provide a fast tip/tilt control of the Laser Guide Star (LGS) position on the sky to maintain their centering within the wavefront sensor field of view and minimize the errors due to sensor non-linearity.

[REQ-1-OAD-2937] In addition to any other motion requirements, the LGSF shall be capable of correcting for any combination of the deflections at the telescope top end as specified in 'Table 4-9: Maximum allowable deflection of Telescope Top End'.

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

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

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

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

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

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

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

[REQ-1-OAD-2955] The LGSF system shall be upgradeable to provide Laser Guide Stars with the signal level and image quality consistent with the wavefront error budget of an upgraded NFIRAOS [REQ-1-OAD-2745].

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

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

4.3.2.2.2 LGSF ACCESS

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

[REQ-1-OAD-2992] Access shall be provided to those components of the LGSF Beam Transfer Optics Elevation Optical Path which are located along the -XECRS, +YECRS vertical column including the intersection with the top ring, when the telescope is horizon pointing.

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

4.3.2.3 ADAPTIVE OPTICS EXECUTIVE SOFTWARE

4.3.2.3.1 GENERAL

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

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

[REQ-1-OAD-3005] The AO Executive Software shall be upgradeable to control the first decade AO system upgrades.

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

[REQ-1-OAD-3010] NFIRAOS shall offload tip, tilt, focus, coma, M1 scalloping modes, and up to 100 M1 modes to the Telescope Control System.

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

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

4.3.2.4 IRIS

4.3.2.4.1 General

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

4.3.2.5 WFOS

4.3.2.5.1 General

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Discussion: The field need not be continuous.

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

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

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

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

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

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

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

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

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

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

4.3.2.5.2 WFOS Desirable Features

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

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

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

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

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

4.3.2.6 MODHIS

4.3.2.6.1 General

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

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

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

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

[REQ-1-OAD-3260] The MODHIS science channel shall provide wavelength coverage over the 0.98 µm - 2.46 µm range.

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

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

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

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

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

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

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

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

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

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

[REQ-1-OAD-3287] The MODHIS spectrograph internal image quality shall not degrade the theoretical spectral resolving power by more than 10% across the bandpass.

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

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

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

4.3.3 First Decade

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

4.4 Services

4.4.1 Power, Lighting and Grounding

4.4.1.1 Power

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

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

Discussion: Typical loads supported by the backup generator include:

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

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

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

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

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

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

4.4.1.2 Lighting

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

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

- Telescope elevation
- Telescope azimuth
- Telescope fixed structures

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

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

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

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

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

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

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

4.4.1.3 Bonding/Grounding

The bonding/grounding system is used for the protection of mission critical equipment and personnel against abnormal voltage surge levels and elevated potentials due to lightning, static electricity, induced radio frequency (RF) and electromagnetic interference (EMI) and noise, and conductive surface touch and step voltage potentials as a result of abnormal electrical feeder and branch circuit phase to phase and phase to ground fault current events and levels.

4.4.2 Coolant

[REQ-1-OAD-4660] Chilled water shall be supplied to the observatory at the temperatures defined in '*Table 4-18: Observatory Chilled Water Supply*'

Table 4-18: Observatory Chilled Water Supply

Description	Temperature (ºC)	Comments	Anticipated Uses
Fixed Temperature Chilled Water (FTCW)	7	Chosen at operating temperature for standard chiller equipment	Majority of facility cooling including computer room, mirror coating equipment, CRYO and REFR equipment
Fixed Temperature Chilled Water, low temperature (FTCW-L)	-15		Enclosure air handlers and hydrostatic bearing system
Variable Temperature Chilled Water (VTCW)	See comments	Temperature approximately 5 degrees C below the desired enclosure temperature for the next night's observing. The offset below the enclosure temperature set point may vary depending on the set point.	LGSF electronics on the Laser Platform as well as STR drives and motors.

Discussion: 'Chilled water' refers to a water/glycol mixture appropriate to prevent freezing over the range of site temperatures. This includes both 'fixed' and 'variable temperature' chilled water types.

Discussion: To mitigate the risk of damage to optics and electronics from potential leaking, phase-change refrigerant cooling is used to remove waste heat from instruments and other electronics on the telescope, where possible.

[REQ-1-OAD-4670] The normal operating pressure of the chilled water supplies listed in '*Table 4-18: Observatory Chilled Water Supply*' above will be 5 bar.

[REQ-1-OAD-4675] The maximum pressure drop through any single chilled water heat exchanger shall be less than 1 bar.

[REQ-1-OAD-4610] TIO Instrumentation Cooling Subsystems (CRYO/REFR) defined in OAD Section 2.2.1.3 shall operate and meet all requirements for at least 50 years with preventive maintenance.

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

[REQ-1-OAD-4730] In the event of a failure of the normal power supply, the following cooling systems shall be maintained:

- Cooling to the summit facility computer room
- Refrigerant cooling
- Variable temperature chilled water

Discussion: It is expected that the variable chilled water temperature will be maintained at an elevated temperature, possibly by using the enclosure air handlers to cool it.

4.4.2.1 Refrigerant (CO2)

[REQ-1-OAD-4740] For optical enclosure cooling, the refrigerant evaporating temperature (REF-SZ) shall not exceed -35°C for steady state and -40°C for cooldown.

[REQ-1-OAD-4741] For electronics cooling, the refrigerant evaporating temperature (REF-A) shall be within 2°C of the ambient cooling set point.

Discussion: The ambient cooling set point (REF-A) is selected whenever feasible to be above the anticipated dew point in the observatory. For the purposes of design subsystem teams can assume that the refrigerant evaporating temperature is never set to a value below the local dew point.

4.4.2.2 CRYOGEN

[REQ-1-OAD-4748] Cryogenic cooldown heat removal for a single instrument shall not exceed 400 MJ, removed over a time constant of not less than 68,000 s.

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

[REQ-1-OAD-4750] Cryogenic cooling of instruments to temperatures between 77 K and 200 K shall use liquid nitrogen in boil-off mode.

[REQ-1-OAD-4751] The cryogenic cooling system shall provide intermittent daytime filling of instrument LN2 reservoirs from the CRYO LN2 reservoirs on the Nasmyth platforms.

Discussion: LN2 filling will occur either once or twice daily so that the instruments can be maintained at low temperatures at all times. Refilling once per day is sufficient if adequate space is available within the instrument's LN2 reservoir.

[REQ-1-OAD-4752] The cryogenic cooling system shall generate LN2 at a sufficient rate to supply the steady cooling requirements of the full TIO instrument suite, cool down one instrument, and replenish the minimum LN2 storage capacity within 40 days.

[REQ-1-OAD-4753] The cryogenic cooling system shall provide sufficient LN2 storage capacity on the Nasmyth platforms to supply the steady state cooling requirements of the full TIO instrument suite for a period of at least 5 days.

[REQ-1-OAD-4754] The cryogenic cooling system shall provide sufficient LN2 storage capacity on the Nasmyth platforms to cool down one instrument, while supplying the steady state cooling requirements of the remaining TIO instrument suite, with LN2 remaining in Nasmyth storage at the time of maximum depletion during cooldown sufficient to provide steady state cooling and replace generation for 1 day.

[REQ-1-OAD-4755] The cryogenic cooling system shall provide sufficient LN2 storage capacity in the SUM facility to supply the steady state cooling requirements of the full TIO instrument suite for a period of at least 48 hours.

[REQ-1-OAD-4756] The cryogenic cooling system shall transfer the daily generated amount of LN2 to the Nasmyth platform LN2 reservoirs within 4 hours during uninterrupted daytime operation.

Discussion: Filling of the LN2 reservoirs on the Nasmyth platforms can be performed at the same time as filling the instrument LN2 reservoirs.

4.4.3 COMPRESSED AIR

[REQ-1-OAD-0998] The normal operating pressure of the FCA listed in '*Table 4-26: FCA Loads*' shall be above 6 bar to each selected telescope subsystem or instrument.

4.4.4 COMMUNICATIONS AND INFORMATION SERVICES (CIS)

The CIS encompasses the IT architecture (hardware, software, and cabling) necessary to implement the generalized communications backbones and establish connection to Internet. The four networks described below (ENET, CNET, PNET, and SNET) comprise a fiber-based distribution system out to various network distribution junction boxes located on the telescope structure and the summit facility control room, laboratory, utility room, and site conditioning and monitoring system. An additional network, the INET, is not part of the CIS but may be referenced in this document. CIS will also include a communications backbone for the Headquarters facility which will include a computer room, remote control room, and offices.

Enterprise Network (ENET): The ENET includes connectivity to the Internet, remote access from partner locations (US, China, India, Japan, and Canada) and backup or disaster recovery facilities, corporate communication, email servers, Domain Name System (DNS) servers, and IT business systems.

Common Network (CNET): CNET is the common software (CSW) based network. It includes common infrastructure network, management network (IPMI), and reference clock (PTP). The CNET network extends between the computer room and locations in the observatory. It is where the majority of subsystem monitoring and control takes place.

Point-to-Point Network (PNET): The PNET is a CIS-provided physical network infrastructure for dedicated fiber point-to-point network from the computer room to a specific subsystem.

Safety Network (SNET): The SNET runs the Observatory Safety System (OSS) fiber network. It contributes to the enforcement of a safe operational environment and the minimization of the risk to safety of personnel and equipment within the TIO Observatory. The OSS provides the cabling for the SNET, while CIS provides the sizing of the SNET fibers.

The CIS network will employ a collapsed core architecture with the core and distribution layers located in the Summit facility data center, and access layer components providing connectivity at each of the significant observatory locations:

- Azimuth Wrap Distribution
- +X/-X Nasmyth Platform Distribution
- +X/-X Elevation Wrap Distribution
- -X Laser Platform
- Top End
- Utility Room
- SCMS Tower
- Observatory Floor
- M1 Coating Room
- Control Room
- Computer Room

4.4.4.1 CIS GENERAL

[REQ-1-OAD-4800] The TIO observatory-wide CIS network shall run on top of a communication protocol stack that has a physical IT communications network.

Discussion: The CIS Network LAN reference design is Ethernet based on TCP/IP protocols.

[REQ-1-OAD-4802] CIS shall minimize any cross-talk or interference from power sources or supplies.

[REQ-1-OAD-4825] CIS shall provide the means to connect to the nearest Internet service point, whether by physical connection or microwave links, to establish internet connectivity.

[REQ-1-OAD-4845] The CIS shall provide fiber infrastructure and access ports for the following networks:

- ENET: Enterprise Network
- CNET: Common Software (CSW) based Network
- PNET: Point to Point Network
- SNET: Safet Network (OSS)

[REQ-1-OAD-4850] The CIS shall support standard Internet services (e-mail, Web, video conferencing, voice-over-IP, etc.).

4.4.4.2 CIS Security

[REQ-1-OAD-4888] The CIS shall provide a security and monitoring system that includes still and video cameras, sensors, and identification systems for the purposes of access monitoring, remote monitoring of subsystems, and remote inspection after an earthquake.

[REQ-1-OAD-4890] The CIS shall allow only authorized users to access Observatory networks.

[REQ-1-OAD-4892] The CIS shall protect the Observatory from any external traffic on the public internet.

4.4.5 Fire Alarm

The SUM subsystem is responsible for providing the end-to-end fire alarm system, including equipment such as detection, warning devices (audible and visible), fire alarm management control system and panel, and fire suppression equipment including water storage. The overall fire alarm system has the ability to detect smoke or heat in most areas of the observatory. The SUM fire alarm system interfaces with the STR and ENC mounted components of the fire alarm systems.

The STR (TUS) subsystem designs the telescope fire alarm system, including routing (including through cable wrap), mounting locations for equipment, and interfaces with the SUM fire alarm system.

The ENC subsystem covers routing and mounting locations for fire alarm system components mounted to the rotating Enclosure. It also provides safety-rated communication across the rotating interface for the fire alarm signal and interfaces with the SUM fire alarm system. There is no fire suppression capability anywhere inside the Enclosure.

4.4.6 HBS Oil

HBS oil is continuously supplied to the azimuth and elevation hydrostatic bearings.

[REQ-1-OAD-5000] HBS oil shall be supplied to the observatory with maximum allowed particle count per 1 ml of oil for each particle size as described in '*Table 4-19: HBS Oil Cleanliness'.*

Table 4-19: HBS Oil Cleanliness

Range code	Particle size (µm(c))	Particles per milliliter
17	4	640-1300
15	6	160-320
12	14	20-40

4.5 Facilities

4.5.1 Enclosure

4.5.1.1 General

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

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

[REQ-1-OAD-5056] The enclosure shutter shall open or close within 2 minutes at any cap orientation.

[REQ-1-OAD-5057] The enclosure shall have an aperture opening and shutter of sufficient size to not vignette the 20 arcminute diameter field of the telescope during observations, plus additional clearance of 1 degree radius outside the field of view in all directions.

Discussion: The telescope must quickly reposition over small distances without requiring the enclosure to move at the same rate. With the enclosure stationary, the telescope must be able to move 1° in any direction from the center of the enclosure aperture without vignetting the 20 *arcminute diameter optical field. Note that for moves close to 1 degree, margin can be gained by pre-biasing the enclosure pointing in the direction of the planned telescope move.*

[REQ-1-OAD-5058] The enclosure aperture opening shall have a continuous and unlimited range of azimuth motion (no cable wraps) and zenith motion range from 0 to 65 degrees zenith angle.

[REQ-1-OAD-5060] The enclosure azimuth and cap axes shall be designed to operate with maximum acceleration and deceleration rates of 0.05 deg/s^2 and a maximum velocity of 1.15 deg/s.

[REQ-1-OAD-5065] The enclosure shall be capable of pointing the aperture opening to a target on the sky over the required range of motion within a peak error of 10 arcmin in each axis on the sky.

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

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

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

[REQ-1-OAD-5092] The observatory shall provide a secure environment for equipment.

[REQ-1-OAD-5105] Except when observing or when necessary in servicing and maintenance mode, the enclosure shall be parked such that the top end servicing platform is aligned with the telescope top end and the shutter is pointing north.

Discussion: [REQ-1-OAD-1270] defines the telescope parked position.

4.5.1.2 ENCLOSURE GEOMETRY

[REQ-1-OAD-5150] No part of the inner enclosure shall be within the volume defined in drawing TIO.FAC.ENC-ENV (AD70).

[REQ-1-OAD-5161] The ENC shall use the geometry parameters as shown in the TIO Enclosure Geometry Drawing TIO.ENC.GTY-0001 (AD75).

Discussion: The 30m primary mirror aperture as defined by the perimeter of the mirror is located 3.5 - 1.875 = 1.625 m below the elevation axis. The height of the aperture opening defined by the flaps is 32.5 m above the primary aperture. A 31.25 m opening gives an oversize in radius of tan-1{0.625/32.5} = 66 arcmin.

Discussion: The external radius of the enclosure is 33 meters per (AD75).

We need 10 arcmin for the science FOV radius, and about 10 arcmin for pointing and tracking, which leaves slightly less than 50 arcmin of radius or 100 arcmin of diameter for telescope tracking with the enclosure held fixed. At a sidereal rate of 15 degrees/hour, 100 arcmin of diameter oversize represents about 400 seconds of tracking with a strategy of fixing the enclosure 50 arcmin ahead of the telescope then letting the telescope track until the enclosure is 50 arcmin behind.

Discussion: The enclosure design includes vent openings with a minimum total vent area of 1500 m^2. The shape and location of the vent openings is defined in the TIO Enclosure Geometry Drawing TIO.ENC.GTY-0001 (AD75).

Discussion: The enclosure design includes 94 vents (42 x 3.4 m x 3.6 m vents, and 52 x 5.0m x 4.0 m vents). The useful vent opening area is somewhat less than the maximum defined by the vent openings to account for bracing, vent door frames and other obstructions (conservative estimate, 1,500 m²).

4.5.1.3 SLEWING

4.5.1.3.1 ENCLOSURE BASE AXIS SLEWING

[REQ-1-OAD-5162] In observing mode, the enclosure shall be capable of making all base axis moves rapidly, such that they can be completed, including smooth ramping profiles and settling time, faster than an equivalent move with a trapezoidal velocity profile with acceleration and deceleration rate of 0.25 degrees/s^2 and a maximum velocity of 1.25 degrees/sec.

Discussion: "Observing mode" for the enclosure indicates that the wind speed is within the observing performance conditions and that there are no snow and ice accumulations on the enclosure.

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

[REQ-1-OAD-5164] The maximum slewing rate of the enclosure base axis shall not exceed 1.25 degrees/sec.

4.5.1.3.2 Enclosure Cap Axis Slewing

[REQ-1-OAD-5168] In observing mode, the enclosure shall be capable of making all cap axis moves rapidly, such that they can be completed, including smooth ramping profiles and settling time, faster than an equivalent move with a trapezoidal velocity profile with acceleration and deceleration rate of 0.15 degrees/s^2 and a maximum velocity of 1.75 degrees/sec.

Discussion: "Observing mode" for the enclosure indicates that the wind speed is within the observing performance conditions and that there are no snow and ice accumulations on the enclosure.

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

[REQ-1-OAD-5170] The maximum slewing rate of the enclosure cap axis shall not exceed 1.75 degrees/sec.

4.5.1.4 Wind, Thermal and Environmental Management

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

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

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

[REQ-1-OAD-5195] The area averaged RSI insulation value of the enclosure including the fixed base shall be at least 6 m2K/W. This insulation value shall be provided between the enclosure interior and the interstitial space.

Discussion: This insulation value is averaged over the entire enclosure interior surface including the vent doors, shutter rail and other areas which may have lower insulation values than the bulk areas of insulation covering the interior walls.

[REQ-1-OAD-5197] Vent doors (including door seal conductance but not infiltration) shall provide an averaged RSI insulation value of at least 4 m2K/W.

[REQ-1-OAD-5198] Any heat loads related to operation of the enclosure shall be dissipated to the enclosure interstitial space.

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

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

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

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

Discussion: Aperture flaps increase the effective diameter of the enclosure for protection of the telescope top end from wind buffeting.

Discussion: The enclosure incorporates aperture flaps with geometry as per the TIO Enclosure Geometry Drawing TIO.ENC.GTY-0001 (AD75).

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

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

[REQ-1-OAD-5215] The external surface of the enclosure shall have the following properties:

- Emissivity < 0.4
- Absorptivity < 0.2
- Emissivity not less than absorptivity

[REQ-1-OAD-5217] For thermal purposes, the emissivity of the internal surface of the enclosure shall be < 0.4.

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

[REQ-1-OAD-5220] The enclosure shall include a vent to remove air at a rate of 4.7m^3/s from the top of the enclosure during daytime operation of the observatory air conditioning system.

Discussion: Thermal modelling of the enclosure daytime environment assumes that 20% of the total air volume output by the air handlers is vented from the enclosure. This prevents a thermal gradient forming over the primary mirror when the telescope is in its daytime parked position (horizon pointing).

4.5.1.5 SUMMIT FACILITY FIXED BASE

[REQ-1-OAD-1265] The summit facility shall provide vibration isolation between the foundations of each of the Telescope pier, Enclosure pier, and Summit Facilities.

[REQ-1-OAD-5255] The summit facility fixed base floor structure shall support HS 20-44 truckloads.

[REQ-1-OAD-5257] The observing floor shall be flat and continuous in the area between the outer radius of the telescope fixed walkway and the inner radius of the fixed enclosure walkway.

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

[REQ-1-OAD-5258] The observing floor shall be free from obstructions in the area between the outer radius of the telescope fixed walkway and the inner radius of the fixed enclosure walkway with the exception of the following items:

- M2/M3 coating chamber rails
- Air handlers
- Fixed base elevators
- Platform lifts and stairs to access telescope and enclosure fixed walkways

Discussion: The sector extending clockwise and counterclockwise from the main entrance into the enclosure is to be kept clear for vehicular access, M2 and M3 operations and transferring large components into the enclosure.

[REQ-1-OAD-5260] The summit facility fixed base shall provide an access door to the exterior of the facility at grade with an opening of at least 4.88 m wide by 5.03 m high for equipment and component movement.

Discussion: The size restrictions for components that can be transferred into the enclosure via these doors is defined in TIO.SEN.TEC.11.014 (RD29).

Discussion: The size of component that can be lifted to the Nasmyth platform from the enclosure floor is limited by the outside radius of the pier walkway and the inner radius of the fixed base walkway. The width and length are related by the following equation:

$$W = \sqrt{\left(729 - \left(\frac{L}{2}\right)^2\right)} - 20.4$$

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

[REQ-1-OAD-5267] Two entrances at least 1 m wide by 1.9 m high shall be provided in the pier wall to allow personnel access to the area enclosed by the pier.

Discussion: At least one of these doorways may need to be an 'emergency exit' only to prevent personnel using the area within the pier as a throughway from one side of the telescope to the other.

[REQ-1-OAD-5270] The summit facility fixed base shall provide a tunnel from the facilities mechanical and electrical plant to the pintle bearing area housing the telescope cable wrap for delivery of utility services to the telescope and telescope mounted sub-systems.

[REQ-1-OAD-5272] An emergency egress route shall be provided from the pintle bearing/cable wrap area that allows personnel to exit to the observing floor outside the telescope pier in the event of a fire or other hazard occurring in the service tunnel.

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

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

[REQ-1-OAD-5285] The Summit Facilities shall provide an enclosed space within the enclosure to store and individually access the equipment used for optics handling.

Discussion: The purpose of this area is to house handling carts in a semi-clean environment, with or without segments mounted on the cart (e.g. in preparation for a segment exchange). In this area, the carts can be restrained such that no damage can occur to a segment during a seismic event.

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

[REQ-1-OAD-5296] Two elevators and stairways that meet the location and space requirements of TIO.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 Seismic and Snow/Ice Loads

[REQ-1-OAD-5306] Under all operating conditions and configurations, the ENC shall withstand the representative time series of site-specific seismic accelerations as described in (RD16) such that:

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

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

Discussion: The Enclosure also meets building code requirements per (RD60) for collapse prevention at the 2500-year return period MCE level earthquake.

Discussion: The levels of a 1000-year return period earthquake have a 5% probability of being exceeded in a 50-year period.

[REQ-1-OAD-5309] Under all operating conditions and configurations, Enclosure and Summit Facilities floor-mounted equipment shall withstand the seismic accelerations at the levels defined in 'Table 4-20: Seismic Limits on Floor-mounted Equipment within ENC/SUM' such that:

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

Table 4-20: Seismic Limits on Floor-mounted Equipment within ENC/SUM

Subsystems	Maximum Accelerations (g)					
	10-year return period		200-year return period		1000-year return period	
	Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical
Floor-mounted equipment within SUM/ENC	0.1	0.1	0.3	0.2	0.5	0.4

Discussion: These values are calculated using the average of the maximum accelerations from each of the seismic time histories for 1000-year and 10-year, provided by (RD16). The 200-year values were calculated using a factor of 0.58 applied to the 1000-year values as recommended in (RD16).

Discussion: The levels of a 1000-year return period earthquake have a 5% probability of being exceeded in a 50-year period.

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

- rotation of the enclosure cap or base.
- operation of the aperture flaps.
- operation of the aperture without snow or ice falling inside the enclosure.
- operation of the vents.
- the ability to safely observe.

- opening of the shutter.

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

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

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

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

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

[REQ-1-OAD-5420] The process of removal of ice and snow accumulations to enable safe observing shall be able to be accomplished with a crew of 4 people within an 8 hour daytime period once the aperture flaps can be opened. An area is considered critical if snow, ice or water can reach the inside of the enclosure from that area through an open observing slit or vent.

Discussion: The primary means of removing snow and ice accumulation from the dome will be passive. The enclosure exterior will be a smooth as possible to promote snow and ice shedding. When possible, the closed shutter will be pointed towards the sun to further promote snow and ice melting.

4.5.1.7 Enclosure Servicing and Maintenance

4.5.2 Summit Facilities

4.5.2.1 General

[REQ-1-OAD-5440] Under all operating conditions and configurations, the SUM shall withstand the time history response spectra of site-specific seismic accelerations as described in (RD16) such that:

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

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

Discussion: The Summit Facilities also meets building code requirements per (RD60) for collapse prevention at the 2500-year return period MCE level earthquake.

Discussion: The levels of a 1000-year return period earthquake have a 5% probability of being exceeded in a 50-year period.

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

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

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

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

[REQ-1-OAD-5503] A backup communications system independent of other observatory systems shall be available in case of emergencies.

4.5.2.2 Mirror Maintenance

[REQ-1-OAD-5505] A mirror stripping and coating facility sufficient to process the M1 mirror segments shall be located adjacent to the enclosure to minimize mirror transportation.

Discussion: A full sector of 82 spare segments is provided, due to the optical prescription. Efficient access to this storage is necessitated by the frequency and time limits of M1 segment exchanges.

[REQ-1-OAD-5507] A mirror stripping and coating facility sufficient to process the M2 and M3 mirrors shall be located either adjacent to or within the enclosure to minimize mirror transportation.

[REQ-1-OAD-5510] The M1 mirror coating and stripping facility shall be equipped with an overhead crane.

Discussion: It is anticipated that the M2 and M3 coating chamber will be located in an area accessible by the enclosure mounted crane or hoist.

[REQ-1-OAD-5515] The M1 mirror coating area shall be built and equipped to be capable of providing a class 10,000 clean room environment.

[REQ-1-OAD-5520] The Summit Facilities shall provide space to store and access the spare quantity of M1 mirror segments either adjacent to the mirror stripping and coating facility or within the enclosure.

4.5.2.3 Operations Spaces

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

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

[REQ-1-OAD-5551] The computer room shall provide class A1 environmental conditions (per RD60: ASHRAE 90577) and be capable of operating in the recommended range when required.

4.5.2.4 Lab & Shop Spaces

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

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

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

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

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

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

4.5.2.5 Personnel Spaces

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

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

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

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

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

4.5.2.6 Shipping & Receiving

[REQ-1-OAD-5615] The Summit Facilities shall provide a platform lift in the shipping and receiving area with the following characteristics: 2 ton capacity, 1.0 m x 2.4 m platform area, capable of rising to 1.6 m above floor level.

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

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

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

4.5.2.7 Mechanical Plant

[REQ-1-OAD-5620] A mechanical plant will be provided to house the mechanical equipment required at the summit facilities.

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

[REQ-1-OAD-5630] The summit facility mechanical plant shall incorporate chillers, to be used in the daytime with the air conditioning system in the fixed base, with sufficient capacity to remove the heat loads listed in *'Table 3-2: Heat Dissipation Inside Summit Facilities and Enclosure'* 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] TIO shall provide air conditioning with a total flow of 23.6 m^3/s at the following operating points with 80% of air being re-circulated:

Table 4-21: Nozzle Temperatures

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

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

[REQ-1-OAD-5637] The maximum outlet temperature of the Summit Facilities exhaust shall not exceed 15°C above the ambient nighttime temperature at the exit of the vent.

Discussion: As a goal, the temperature delta should be 10°C. There is no requirement on the daytime limit to the temperature of the exhaust air. It is assumed that the fluid cooler runs at lower flow rates in the daytime to conserve power which results in higher temperatures.

4.5.2.8 ELECTRICAL PLANT

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

4.5.2.9 ROADS & PARKING

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

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

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

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

4.5.2.10 GROUNDING AND LIGHTNING PROTECTION

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

[REQ-1-OAD-5685] The external lightning protection system shall comply with (RD60: NFPA 780).

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

4.5.2.11 FIRE PROTECTION AND SAFETY

[REQ-1-OAD-5690] A fire suppression system shall be supplied throughout the summit facilities building.

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

[REQ-1-OAD-7000] The CIS shall incorporate a video system to allow operations staff to monitor the enclosure environment.

4.5.3 HEADQUARTERS

4.5.3.1 GENERAL

[REQ-1-OAD-5745] TIO Headquarters Facility shall be established within two (2) hours drive of the summit.

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

4.5.3.2 ADMINISTRATION

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

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

4.5.3.3 REMOTE CONTROL ROOM

[REQ-1-OAD-5800] A remote control/observing room including two full observing consoles shall be provided at the headquarters building.

4.5.3.4 Lab & Shop Spaces

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

[REQ-1-OAD-5820] The Headquarters engineering workshop shall be equipped with overhead bridge cranes with sufficient hook height for associated component movements.

4.5.3.5 Warehouse Storage

[REQ-1-OAD-5830] Storage and capacity shall be provided at the headquarters that is sufficient to house the equipment, tools and spares used to support sea level technical work.

Discussion: It is anticipated that the majority of the storage space required for observatory spares will be in rented warehouse space.

4.5.3.6 Shipping & Receiving

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

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

4.5.3.7 Electrical Plant

[REQ-1-OAD-5865] An emergency generator shall be provided to ensure that remote observing can take place in the event of a power outage.

4.5.3.8 Roads and Parking

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

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

4.6 Lifetime, Servicing and Maintenance

4.6.1 Lifetime

[REQ-1-OAD-5010] TIO Observatory Facilities Subsystems defined in OAD Section 2.2.1.1 shall operate and meet all requirements for at least 50 years with preventive maintenance.

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

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

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

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

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

4.6.2 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°

4.6.3 Maintenance

[REQ-1-OAD-6280] TIO shall implement and maintain a comprehensive maintenance system, which includes scheduling and details of both predictive and preventative maintenance, component and assembly replacement, and alignment procedures.

[REQ-1-OAD-6282] A failure database shall be established by the end of construction, and maintained throughout operations, which allows the logging of errors of the system and its subsystems, including corrective actions taken.

4.6.4 Crane Systems

Discussion: Cranes, lift, and deployable maintenance platforms are needed for executing logistics and maintenance activities in the Enclosure, Enclosure Fixed Base, the Summit Facilities Building, and on the Telescope Structure. RD71 TIO Cranes, Lifts, and Deployable Maintenance Platforms documents the locations and key characteristics of each.

4.6.4.1 Cranes and Hoists provided by Summit Facilities

[REQ-1-OAD-6260] Any maintenance locations in the Summit Facilities shall be accessible by lifts and cranes.

Discussion: RD71 documents the locations and key characteristics of lift and/or crane.

[REQ-1-OAD-6272] Any maintenance and storage locations in the Enclosure Fixed Base shall be accessible by lifts and cranes.

Discussion: RD71 documents the locations and key characteristics of lift and/or crane.

4.6.4.2 Cranes and Hoists provided by Enclosure

[REQ-1-OAD-6200] Any maintenance locations in the interior of the enclosure and components of the telescope shall be accessible by personnel lifts and freight cranes.

Discussion: RD71 documents the locations and key characteristics of lift and/or crane.

[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 TIO.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-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.

4.6.4.2.1 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 TIO.FAC.ENC.TEP-ENV (AD71).

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

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

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

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

4.6.4.3 Cranes and Hoists provided by Structure

The STR provides cranes, hoists, or equivalent handling systems for: (1) a man lift on the azimuth structure to access the M3 mirror during its removal or installation; (2) the Segment Handling System (STR SHS) to lift and position primary mirror segments; and (3) servicing elements of the LGSF laser system and beam transfer optics within the -X ECRS elevation journal.

4.6.4.3.1 Elevation Platform Crane/Hoist

[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.

4.6.4.3.2 ASP Lift

[REQ-1-OAD-1297] A man lift shall be mounted on the azimuth structure to enable personnel to access to the M3 mirror during M3 removal or installation (with the telescope horizon pointing).

4.6.4.3.3 Segment Handling Crane

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

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

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

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

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

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

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

• 2000 installation or removal operations during construction,

• 10 routine segment exchanges during a single 10-hour day, once every two weeks for fifty years (13,000 segment exchanges),

• a proof test (at two times rated load) every six months for 50 years.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

4.7 Environmental, Safety and Health Requirements

The safety priorities of any subsystem needs to be: (i) protection of persons, (ii) guarding the technical integrity of the observatory and other equipment potentially affected by the operation of the observatory, and (iii) protection of scientific data, in this order.

The environmental protection, safety and health aspects of the TIO 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 TIO Safety Architecture document (RD18) allocates these functions to the appropriate TIO subsystems and identifies the requirements that apply to each function. The collection of subsystems and components that provide these functions is referred to as the 'TIO Safety Architecture'.

The Functional Safety Architecture is the part of the TIO Safety Architecture responsible for providing emergency stops, hazard detection and interlocks. The Functional Safety Architecture involves any subsystem connected to the Observatory Safety System (OSS) as well as the OSS itself. Requirements applying to the entire Functional Safety Architecture are contained in section 4.7.1.1

The OSS is responsible for monitoring and in some cases imposing interlocks across the Functional Safety Architecture. It monitors and provides the appropriate response to e-stops. It also provides the seismic detection function and, in some cases, may participate in the provision of the other safety functions. Section 4.7.2.1 contains requirements that apply only to the OSS.

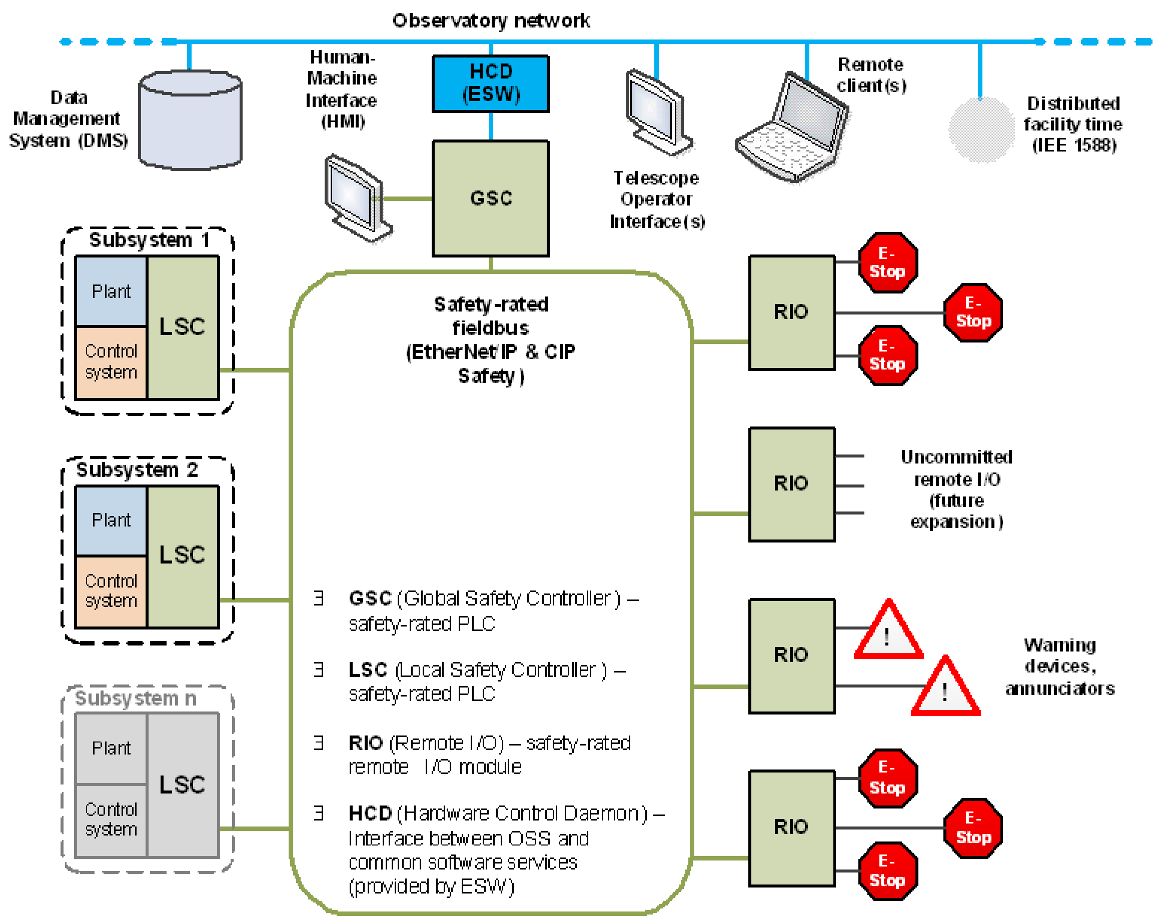

Figure 4-5: Functional Safety Architecture.

Discussion: GSC, field bus RIOs and e-stops are contained within OSS subsystem. Items within dotted lines are responsibility of connected subsystems.

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] TIO shall incorporate fixed, automatic, or other protective safety devices into the design of subsystems identified in hazard analysis.

Discussion: The hazard analysis is an output of the process defined in (AD80). The safety priorities of the subsystems are: (i) protection of persons, (ii) guarding the technical integrity of the observatory and other equipment potentially affected by the operation of the observatory, and (iii) protection of scientific data, in this order.

[REQ-1-OAD-6901] The OSS and other sub-systems in the Functional Safety Architecture (those requiring a safety related control function to mitigate a hazard and/or those sub-systems providing safety related telemetry to the OSS) shall comply with (RD60: IEC 62061).

*Discussion: **(RD60: IEC 62061)** requires that a functional safety management plan be followed to ensure that safety functions are designed, implemented and verified properly. TIO has developed a Functional Safety Plan (RD46) that can be applied by any sub-system that is covered by **(RD60: IEC 62061)**. It is recommended that sub-systems in the Functional Safety Architecture follow this document or an equivalent functional safety plan as agreed by TIO.*

Discussion: The decision as to whether a sub-system requires a safety related control function to mitigate an SRCF is based on the sub-systems hazard analysis conducted per RD40.

[REQ-1-OAD-6902] Any sub-system whose hazard analysis identifies a hazard that needs to be mitigated by a 'Safety Related Control Function (SRCF)' per (RD60: IEC 62061) shall provide a Local Safety Controller to implement the SRCF.

Discussion: (RD60: IEC 62061) considers a safety related control function to be a function that maintains a safe condition or prevents an increase of risk and is implemented by an electrical or electronic control system. The local safety controller is connected to the OSS as shown in Figure 4-5: Functional Safety Architecture

[REQ-1-OAD-6903] The Local Safety Controller provided by the sub-system shall follow the use the hardware defined in AD85.

Discussion: A typical LSC comprises the components shown in 'Figure 4-6: Illustration of the components that comprise a local safety controller' below.

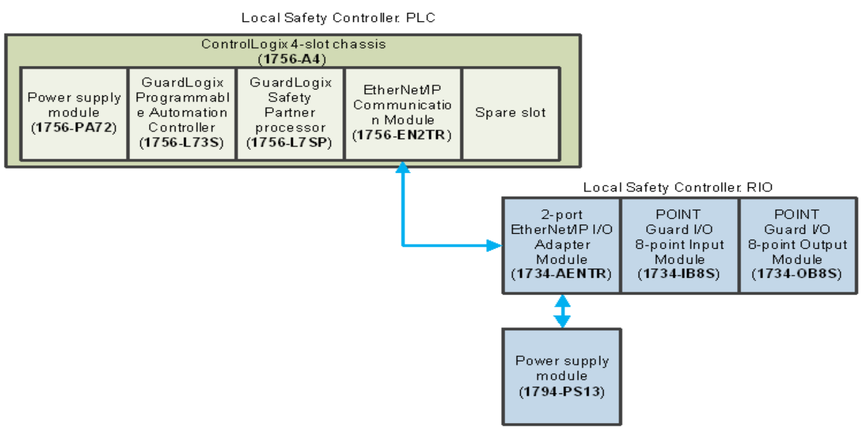

Figure 4-6: Illustration of the components that comprise a local safety controller

[REQ-1-OAD-6904] Each LSC shall provide a local user interface.

[REQ-1-OAD-6905] Upon detecting a hazardous fault or condition, a subsystem shall independently and immediately take action to alert personnel and mitigate the hazard without any interaction with, or the presence of, the OSS.

[REQ-1-OAD-6908] Sub-systems required to enter an interlocked state due to hazards occurring in other areas of the observatory shall respond to interlocks imposed by the OSS by implementing behaviour as agreed in the appropriate sub-system to OSS ICD.

[REQ-1-OAD-6910] Upon detecting a hazardous fault or condition and imposing the appropriate interlock, a subsystem shall provide the OSS with Safety Status information.

Discussion: (a) All Global SRCF information must be reported from an LSC to the GSC via the interlock events. (b) All local SRCF information, modes and hardware status for an LSC must be reported from an LSC to the GSC via the safety status (as per the architecture & ICD) (c) An LCS *does not publish SRCF information via common software and HCD. Only the GSC does this via a HCD.*

[REQ-1-OAD-6912] A special mode implemented via a sub-system's LSC and associated HMI shall be used when recovery from an interlocked condition requires the temporary inhibition of interlocks.

Discussion: An example of this would be when telescope axis motion is interlocked by passing an over travel limit. To move back into its normal operating range under power the interlock would temporarily need to be suspended and other restrictions such as local control, velocity limits etc. imposed to maintain safety whilst operating in this mode.

[REQ-1-OAD-6906] All safety-related communication between the OSS GSC, the sub-system LSCs, and all Remote I/O shall be via a safety-rated EtherNet/IP & CIP Safety network provided by the OSS (or by the responsible sub-system for connections between an LSC and remote I/O module).

[REQ-1-OAD-6907] Sub-systems incorporating a Local Safety Controller (LSC) shall comply with the requirements contained in the Local Safety Controller Design Requirement Document (AD84).

[REQ-1-OAD-6911] The OSS Global Safety Controller and Local Safety Controllers used by sub-systems shall be developed following the OSS Developer's Guide (AD85).

4.7.1.2 ACCESS CONTROL AND TRAPPED KEY SYSTEM

[REQ-1-OAD-7601] Barriers and/or gates shall be used to prevent access to areas where hazards to personnel may be caused by release of stored energy during normal operations.

Discussion: Normal operations include maintenance. Release of stored energy is terminology used in (RD60: OSHA 29 CFR 1910); its sources may be hydraulic, electrical, mechanical, pneumatic, chemical, or thermal. Hazards caused by release of stored energy include crushing, pinching, electric shock, etc.

[REQ-1-OAD-7602] Access to the hazardous areas shall only be possible when all sources of hazardous energy have been locked out using an energy isolating device.

Discussion: 'Energy isolating device' is terminology used by (RD60: OSHA 29 CFR 1910). It is expected that for TIO these will usually be devices locking out electrical power.

[REQ-1-OAD-7613] Operating modes supporting special operating procedures that allow entry without isolating energy sources shall be defined and included in the functions of sub-system local safety controllers.

Discussion: These special operating procedures need to be agreed by TIO on a case-by-case basis.

[REQ-1-OAD-7603] Trapped key devices shall be used that allow each person entering a hazardous area to carry a personal safety key with them that guarantees that sources of hazardous energy affecting that area are isolated.

[REQ-1-OAD-7604] The gates preventing access to hazardous areas shall be locked at all times when entry/exit is not in progress, and may only be unlocked from the outside using a personal safety key.

[REQ-1-OAD-7605] Exiting any hazardous areas shall, in normal circumstances, be achieved using a push button to unlock the gate.

[REQ-1-OAD-7606] When a personal key is used to gain access to a hazardous area, or the push button is used to exit the area, the gate shall unlock only for a period sufficient to allow a person to enter or exit, and shall re-lock after that period has elapsed or after each person as entered or exited the hazardous area (except in emergency situations as described in [REQ-1-OAD-7607]).

[REQ-1-OAD-7607] In emergency situations, it shall be possible to open every gate from the inside using a manual override that unlocks the gate and keeps it unlocked.

[REQ-1-OAD-7608] The system shall monitor and display the status of all lockouts implemented by trapped keys and the removal of trapped keys from any key exchange devices.

[REQ-1-OAD-7609] The design of the trapped key system shall be consistent with that described in the Observatory Safety Access Summary (AD91) and figure 'Trapped Key System Schematic' below.

Discussion: AD91 defines the interlocks and other safety devices required when accessing hazardous areas, as well as the recommended hardware to be used in the trapped key system. Figure 4-7: 'Trapped Key System Schematic' below shows the typical trapped key system schematic required by AD91.

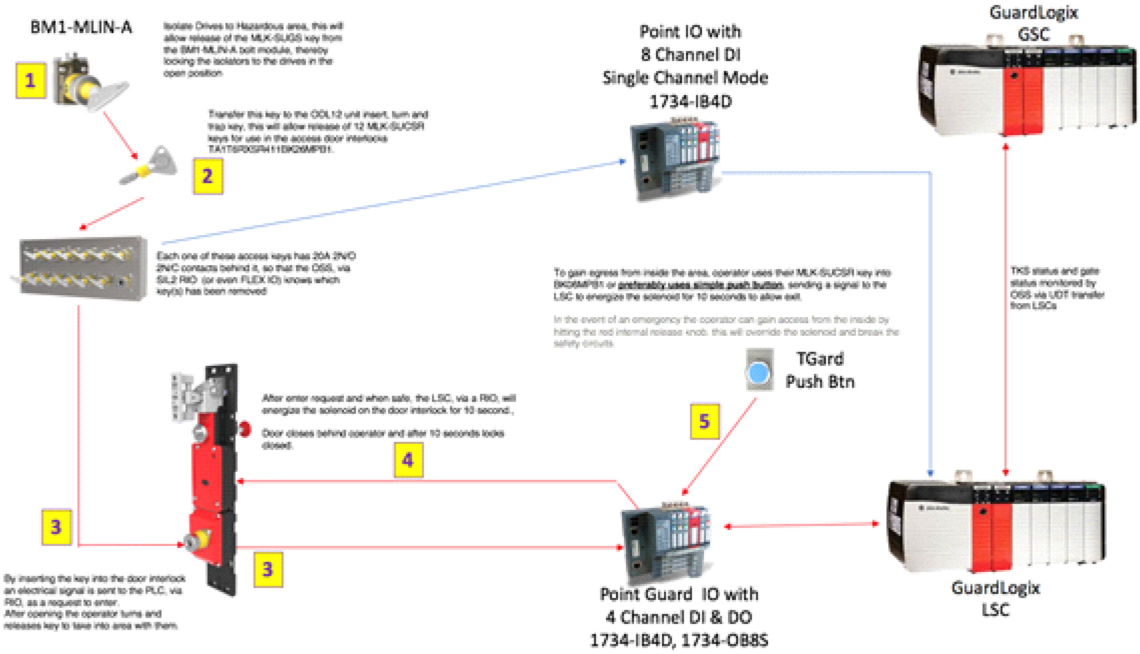

Figure 4-7: Trapped Key System Schematic

4.7.1.3 ENVIRONMENTAL REQUIREMENTS

4.7.1.3.1 RESTRICTION OF HAZARDOUS SUBSTANCES IN ELECTRICAL & ELECTRONIC EQUIPMENT (ROHS)

[REQ-1-OAD-6950] Except when safety would be compromised, cost would be significantly increased, schedule would be significantly prolonged, performance would be significantly degraded, electrical and electronic commercial-off-the-shelf (COTS) equipment contained in TIO 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 TIO 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 TIO 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 TIO Project Management that cost, schedule and performance trade-offs merit the use of these materials. Infrared detectors are an example of devices that would merit the use of ROHS restricted materials.

[REQ-1-OAD-6954] Electrical and electronic equipment that contains ROHS restricted materials shall be labeled, with details of restricted materials contained within, on a side or surface that is visible under normal maintenance conditions.

Discussion: Verification of this requirement will be at minimum by inspection during acceptance testing.

4.7.2 Observatory Safety System

This section contains requirements applicable to the Observatory Safety System.

4.7.2.1 Observatory Safety System (OSS), General

[REQ-1-OAD-7050] The Observatory Safety System shall be implemented as an independent PLC based system whose operation does not rely on the availability of any other sub-systems other than power.

[REQ-1-OAD-7052] The OSS shall provide different operational modes that support:

- Observing Operations
- Maintenance Operations
- Fault and Interlock Recovery

[REQ-1-OAD-7051] The OSS shall provide fault, interlock and emergency stop monitoring and control in a manner consistent with the TIO System Level Hazard Analysis Document (AD37).

Discussion: The TIO System Level Hazard Analysis document (AD37) identifies the possible faults and hazardous conditions associated with interactions between the sub-systems of the observatory and defines the necessary interlocks that have to be managed by the OSS in order to enforce functional safety under these circumstances.

[REQ-1-OAD-7053] The OSS shall be able to detect hazardous faults or conditions that are not associated with a particular sub-system.

Discussion: An example would be a gate switch that is triggered when accessing a certain area of the telescope for servicing purposes. In that case, it makes sense to allow the OSS to directly read such a switch and act upon it.

[REQ-1-OAD-7054] The OSS shall have the capability to detect earthquakes and respond by implementing and enforcing any interlocks on sub-systems that are required to maintain safety under these conditions.

[REQ-1-OAD-7059] The OSS shall have a Hardware Control Daemon (HCD) that allows OSS information to be communicated via the common services framework using a read-only OSW compliant interface.

[REQ-1-OAD-7061] The OSS shall include a simple user interface accessible via both a PanelView and the ESW via the OSS HCD (Hardware Control Daemon), that displays an indication of the state of the safety system and allows the user to:

- Reset interlocks
- Query which sub-systems have generated interlock requests
- Query which sub-systems are interlocked via interlock demand signals

Discussion: The user interface should be simple and functional. This is particularly important as it may have to be used in emergency situations where the ability to perform necessary tasks quickly is paramount. A remote interface should also be provided so that the same (or similar) interface is accessible over the network. In this case, access controls should be incorporated to prevent unauthorized use.

[REQ-1-OAD-7062] The OSS shall provide an indication to the Data Management System (DMS) and the Executive Software (ESW) of the status of any interlocks raised by either the OSS Global Safety Controller (GSC) or any sub-system Local Safety Controller (LSC).

[REQ-1-OAD-7063] Whenever the OSS alerts the ESW and/or the DMS to an interlock event, it shall include in the notification any relevant engineering information pertaining to the interlock condition (e.g. the sub-system that raised the interlock request, the time the event occurred, etc.).

Discussion: This data is limited to the information that is related to the receipt of an interlock request or the implementation of an interlock demand. It is not intended that the OSS provide or *distribute telemetry from connected sub-systems. The sub-system is responsible for providing the telemetry data to the DMS and ESW by other means.*

[REQ-1-OAD-7064] The OSS shall provide and control independent audible and visual warning devices located throughout the summit facility as per the Hazard Analysis.

4.7.2.2 Observatory Safety System, Interlocks

Definitions:

- Interlock event - communication from a local safety controller to the global safety controller, used by the global safety controller to impose interlock demands on other sub-systems
- Interlock demand - communication from the global safety controller to a local safety controller to implement interlocks or permissives
- Interlock - an interlock is an action taken to stop an ongoing process, or prevent a process or action from starting

[REQ-1-OAD-7065] The OSS shall continuously monitor the fault states of all connected devices and subsystems and, upon detection of faults or hazards, impose appropriate interlocks on other connected subsystems per the TIO System Level Hazard Analysis (AD37).

Discussion: This implies that all subsystems shall be able to receive an interlock demand signal from the OSS and provide an interlock event signal to it, transmitted exclusively via the EtherNet/IP safety fieldbus.

[REQ-1-OAD-7080] The OSS shall have the capability to latch an interlock until it is manually reset via the user interface.

Discussion: This is expected to be the normal behaviour, there may be exceptions where this is not desirable. These will be identified in the System Hazard Analysis.

[REQ-1-OAD-7081] The re-setting of sub-system interlocks shall be via a secure interface to the global safety controller.

[REQ-1-OAD-7085] Reset of the interlock demands generated by the OSS shall only be possible provided the interlock request is no longer present.

[REQ-1-OAD-7086] The OSS shall ensure that the system enters a safe state on system startup or if there is a power or network failure.

4.7.2.3 Emergency Stop (E-Stop)

[REQ-1-OAD-7100] The OSS shall implement an emergency stop (E-Stop) system that operates without reliance on any other subsystem.

[REQ-1-OAD-7105] The OSS shall be responsible for continuously monitoring all emergency stops throughout the observatory. In the event of an emergency stop being triggered, it is responsible for ensuring that appropriate action is taken to enforce safety and reduce risk.

Discussion: The emergency stops described in the requirement above initiate action via the OSS to place all subsystems in a safe state, and are distinct from any local devices such as switches or buttons that shut off power or stop motion of an individual machine or device.

Discussion: In general, a system would be made safe when an emergency stop is triggered. This is not the only thing that could be done however; for example, the GSC could have a means of controlling circuit breakers so that power to a particular section of the facility could be removed under GSC control. The need for such action would be determined by the TIO system-level hazard analysis (AD37).

[REQ-1-OAD-7110] Emergency stop devices shall be conveniently and appropriately located throughout the Observatory as necessary to ensure adequate coverage and access in the event of an emergency.

Discussion: Emergency stop devices should be located in and near areas where hazards may occur or be detected. The guiding principle should be that of common sense; locate emergency stops where they are easy to locate and operate in the event of an emergency and where they will *not be accidentally activated. The distributed I/O capabilities of the RIO modules make this task relatively easy.*

[REQ-1-OAD-7112] The OSS shall provide any emergency stop devices and connect them to the nearest interface to the OSS, except for e-stops on the ENC.

Discussion: The OSS provides remote I/O modules at suitable locations to ensure that all emergency stops can be connected to it. The OSS provides the e-stops, the mounting hardware and the necessary cabling and connectors to make the interface at the nearest remote I/O module.

[REQ-1-OAD-7113] OSS E-stop devices shall adhere to ISO 1385 (AD102).

Discussion: This requires OSS E-stop switches to have a red actuator with a yellow background behind the actuator so they are distinguishable from equipment local stops or other similar devices.

[REQ-1-OAD-7115] All subsystems and equipment interlocked by the OSS shall be capable of withstanding multiple emergency stop occurrences without damage.

[REQ-1-OAD-7120] The OSS shall immediately identify and report the location of any triggered emergency stop.

Discussion: To speed fault recovery, the OSS reports the location of any triggered emergency stop. It correctly identifies the triggered device and reports the location even when more than one device has been activated.

4.7.3 Telescope Safety

4.7.3.1 General

[REQ-1-OAD-7200] The elevation structure of the telescope shall have the capability to be physically restrained to inhibit motion or damage, even under Infrequent Earthquake Conditions, for any servicing or maintenance operation where a mass imbalance of the elevation axis is expected.

[REQ-1-OAD-7202] The elevation structure shall include locking devices that prevent motion during servicing operations when the telescope is zenith pointing or horizon pointing.

Discussion: The majority of major servicing operations will be performed with the telescope zenith pointing (e.g.M1 segment removal) or horizon pointing (e.g. M2 and M3 removal). Locking mechanisms will be engaged during these operations.

[REQ-1-OAD-7205] The telescope shall incorporate earthquake stops on the elevation and azimuth axes that are capable of restraining the system during an Infrequent earthquake event.

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

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

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

Discussion: Exiting the STR from any regularly accessed location on the telescope is expected within 90 seconds.

[REQ-1-OAD-7230] Under an emergency stop condition, azimuth motion shall be stopped as quickly as possible without exceeding a deceleration rate of 2 degrees/sec^2.

Discussion: For a maximum azimuth speed of 2.5deg/s, the stopping time, stopping distance and deceleration at the edge of the Nasmyth platform are:

Table 4-22: Telescope Azimuth Stopping Deceleration, Time and Distance

Azimuth deceleration rate	Stopping time	Stopping distance at Nasmyth platform edge (R=27.5m)	Deceleration at Nasmyth Platform edge
deg/s^2	sec	m	g
2	1.25	0.75	0.098

[REQ-1-OAD-7233] The elevation travel limit system shock absorbers and mechanical stops shall decelerate the elevation structure such that the maximum deceleration is no greater than 2.5 deg/s2.

[REQ-1-OAD-7235] Under an emergency stop condition, elevation motion shall be stopped as quickly as possible without exceeding a deceleration rate of 2.0 degrees/sec^2.

Discussion: For a maximum elevation speed of 1 deg/s, the stopping time, stopping distance and deceleration at the elevation journal and the top end are:

Table 4-23: Telescope Elevation Stopping Deceleration, Time and Distance

Elevation deceleration rate	Stopping Time	Stopping distance at elevation journal (R=10.7m)	Deceleration at elevation journal	Stopping distance at top end (R=27.5m)	Deceleration at top end
deg/s^2	sec	m	g	m	g
2	0.5	0.05	0.038	0.12	0.098

4.7.4 Enclosure Safety

4.7.4.1 General

[REQ-1-OAD-7300] The Enclosure shall incorporate an emergency lighting system to illuminate the interior of the enclosure and emergency exit paths during a power failure or E-stop occurrence.

4.7.4.2 Enclosure Safety System

[REQ-1-OAD-7350] The Enclosure Safety System shall monitor and protect the system and personnel under the conditions identified in the TIO Enclosure Hazard Analysis process.

Discussion: These conditions may include Enclosure cap, base and shutter over-speed; enclosure cap, base and shutter drive over-current; enclosure control system failure; seismic events; unstowed cranes; over temperature conditions; deployable platforms not correctly stowed.

4.7.5 Laser Guide Star Facility

[REQ-1-OAD-7500] The System shall follow the safety rules defined for the class 4 lasers used in the LGSF system.

[REQ-1-OAD-7505]: The Laser Guide Star Facility Safety System shall monitor the LGSF systems and the associated environment in order to enforce safety of both personnel and the facility and to mitigate the risks and hazards associated with the system identified in the TIO 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 SOFTWARE AND CONTROL ARCHITECTURE

5.1 OBSERVATORY CONTROL ARCHITECTURE

Definition: Active optics is the aggregate of sensors, actuators, and control algorithms (software and hardware) working together to maintain proper telescope optical performance during observations. The active optics system is not a subsystem, but rather the interaction of various subsystems.

Definition: Telescope Optical Feedback System (TOFS) is the functional component of active optics that is utilizing continuous optical measurements of starlight to maintain proper telescope optical performance. TOFS is not a subsystem, but rather the interaction of various subsystems, as described in the Telescope Optical Feedback System Architecture and Specification document (RD40).

5.1.1 POINTING, OFFSETTING, TRACKING, GUIDING AND DITHERING

Definition: Pointing is the blind operation establishing the initial alignment of the telescope and instrument foci to the sky. Pointing is not supported by optical feedback (like acquisition camera or WFS) as its very objective is to establish the appropriate conditions for closing any optical loop. Pointing is aided by the pointing model to achieve the required accuracy. The pointing model is a Look-Up-Table (LUT) based or best fit estimated correction to the theoretical commands to the mount actuators. The pointing model comprises the relevant imperfections of the telescope and its control systems for various environmental and operating conditions, most prominently temperature and elevation angle. It also contains astrometry corrections.

Definition: Offsetting is the process of moving from one pointing to another over a small angular distance.

Definition: Tracking i.e. following the virtual sky motion without the aid of any sky reference is a special sequence of pointing, possibly with pre-calculated trajectory. Tracking relies on calculating mount coordinates from the sky coordinates of the target, and correcting them with the pointing model. It is understood that a significant portion of tracking error comes from the imperfect smoothness of the required motion.

Definition: Guiding is defined as tracking with closed loop control based on optical position feedback from a guide star.

Definition: Dithering is the process of repetitively offsetting between two or more pointings.

Discussion: TIO establishes the alignment of the telescope and instrument foci relative to the sky primarily by means of mount actuators setting the telescope azimuth and elevation angles, and the tertiary mirror steering the beam to the instrument foci.

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

[REQ-1-OAD-8015] The Telescope Optical Feedback System (TOFS) shall improve the alignment of the telescope relative to the sky by means of closed optical loop guiding.

[REQ-1-OAD-8020] Guiding shall correct residual image motions by reconstructing image motion (OPD tip/tilt) into mount elevation and azimuth angles.

[REQ-1-OAD-8025] The bandwidth for the closed optical guide loop shall be at least 0.1 Hz.

[REQ-1-OAD-8030] In seeing limited operation, guiding errors shall be directly calculated from the slopes of a guiding NGS WFS or the centroids of a guide camera by the Active Optics Reconstructor & Controller (aORC), which is part of the Telescope Control System (TCS) (See '*Figure 5-1: Control architecture for seeing limited observations*' below).

Discussion: The role of the aORC is (i) to read the WFS and guide camera, (ii) compute the required telescope modes with the appropriate sampling rate, and (iii) send setpoint updates to the telescope local control loops (MCS, M1CS, M2CS). The number of algorithmic operations required is relatively small and a single processor computer should be able to perform the work.

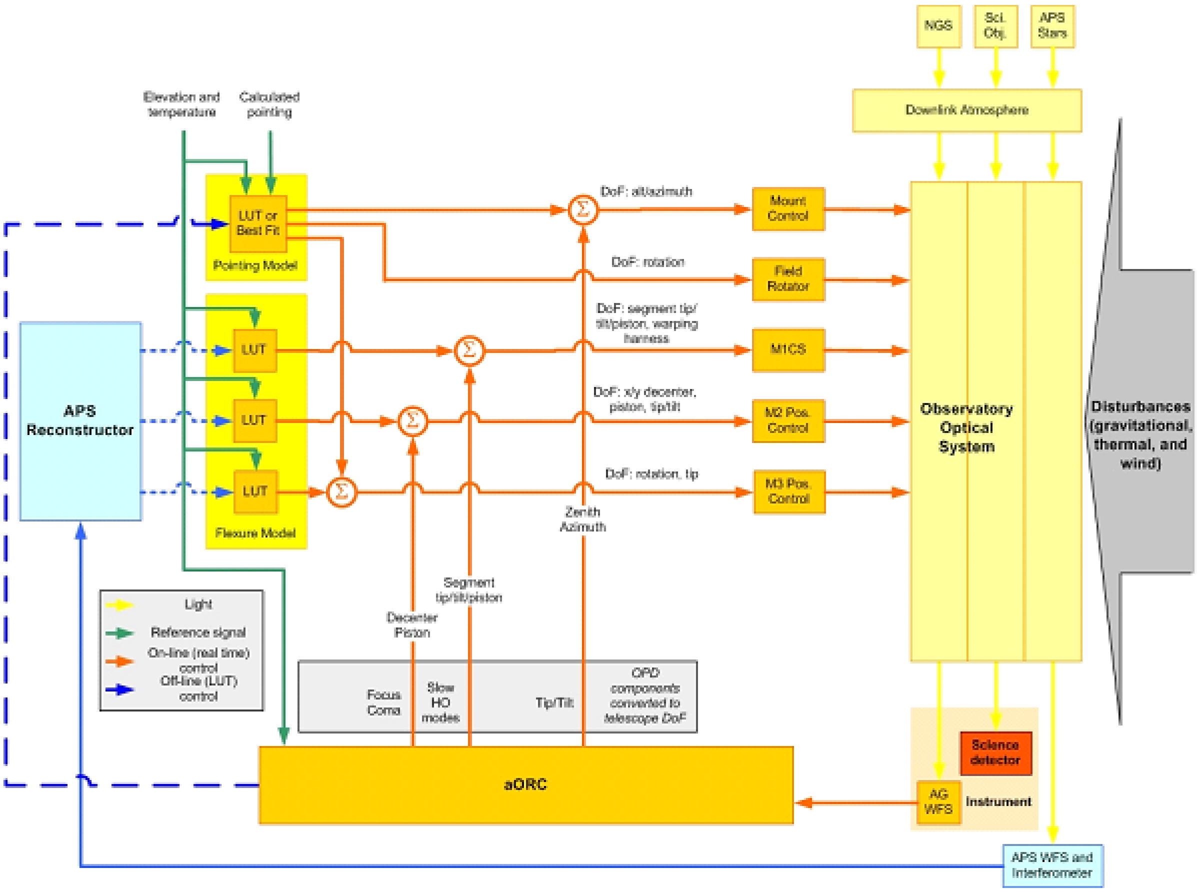

Figure 5-1: Control architecture for seeing limited observations.

[REQ-1-OAD-8035] In adaptive optics operation, guiding errors shall be computed by averaging the AO fast tip/tilt mirror commands or, if AM2 is used, by averaging the AM2 tip/tilt modes. In both cases, the guiding errors are computed by the AO RTC (see '*Figure 5-2: Control Architecture for adaptive optics observations*' below).

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

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

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

[REQ-1-OAD-8052] The observatory shall guide/track at any rate up to 1.1 times the sidereal rate.

Discussion: TIO is required to track solar system targets, using “fixed” natural guide stars as the guiding reference. This is a maximum of 16.5 arcsec/s on the sky. This results in a maximum speed in azimuth of 895 arcseconds/second and a maximum elevation speed of 15.5 arcseconds/second.

[REQ-1-OAD-8055] During dithering, the deviation of the telescope mount and NGS WFS probes from the profile commanded by the TCS shall not exceed +/- 0.25 arcseconds.

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

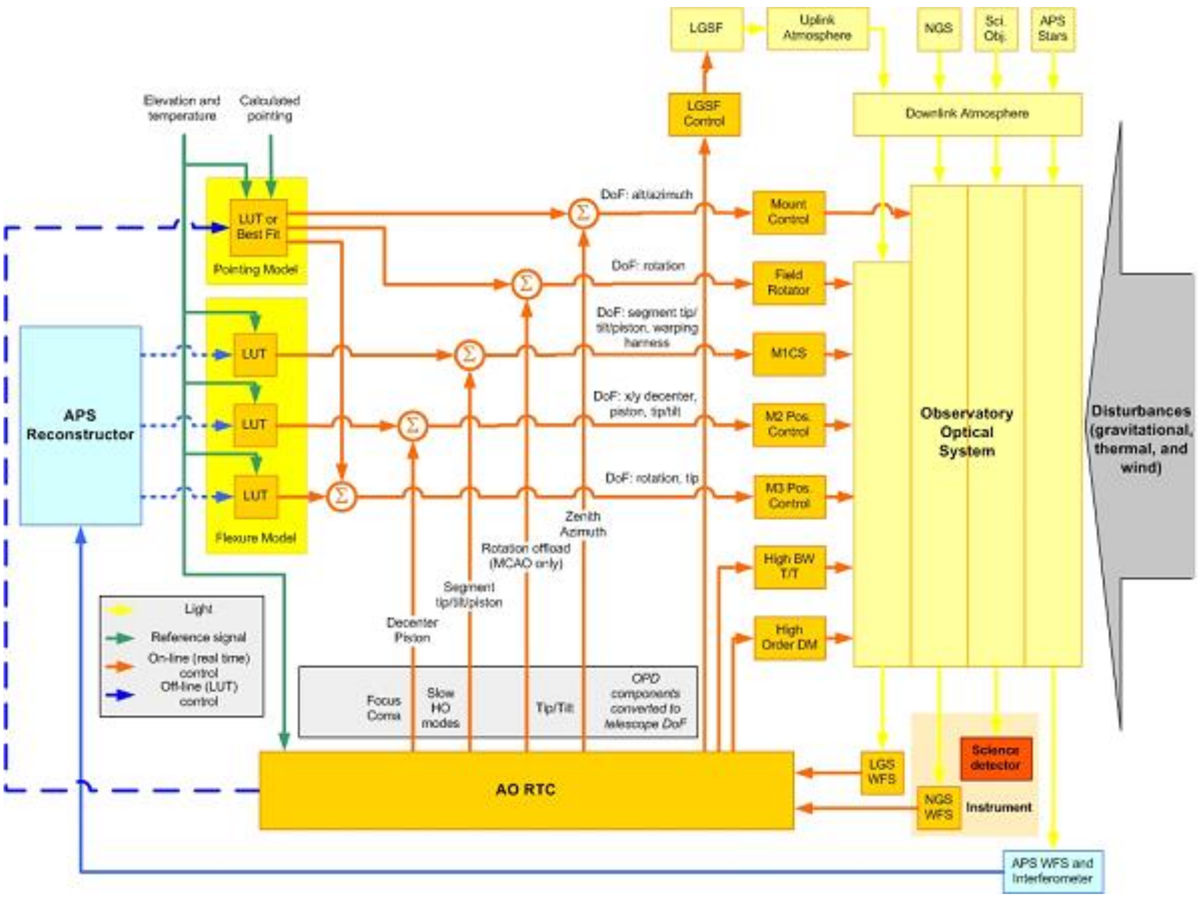

Figure 5-2: Control Architecture for adaptive optics observations

[REQ-1-OAD-8060] The telescope shall be able to validate pointing independent of an instrument.

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

5.1.2 FIELD DE-ROTATION

[REQ-1-OAD-8100] Field de-rotation opto-mechanical components shall be the responsibility of the instruments or adaptive optics systems.

[REQ-1-OAD-8105] Field de-rotation shall be a "blind" i.e. open optical loop operation driven by the rotation command calculated by the pointing model in the telescope control system (see 'Figure 5-1: Control architecture for seeing limited observations' and 'Figure 5-2: Control Architecture for adaptive optics observations' in the previous section).

Discussion: Since the calculation of field rotation requires RA, Dec, and sidereal time as inputs, this model is a part of the observatory. This results in a testable interface to instruments via mechanical angle commands.

[REQ-1-OAD-8110] Instruments and AO systems that need higher field de-rotation accuracy than the seeing limited requirements shall provide the means to calibrate their de-rotator, and/or correcting rotation errors by real time optical feedback.

Discussion: It is understood that detecting rotation errors requires an extension to the guiding/AO sensors, allowing off-axis measurements. It is also understood that relatively wide field adaptive optics systems, like an MCAO system, can provide rotation error off-loads.

5.1.3 Atmospheric Dispersion Compensation

[REQ-1-OAD-8200] The telescope control system (TCS) shall provide pointing model open-loop telemetry for instrument atmospheric dispersion compensator (ADC) operation.

[REQ-1-OAD-8210] TIO shall provide ADC compensation, applied either by the AO system or instrument, as agreed.

5.1.4 Active and Adaptive Optics Control Architecture

5.1.4.1 General

[REQ-1-OAD-8300] TIO shall maintain the shape of the M1 optical surface and the alignment of M1, M2, and M3 relative to each other, i.e. the collimation of the telescope by means of active optics compensation of thermal, gravitational, and vibration disturbances (see 'Figure 5-1: Control architecture for seeing limited observations' and 'Figure 5-2: Control Architecture for adaptive optics observations' in the previous section).

Discussion: The most prominent vibration disturbance is expected to be wind buffeting.

[REQ-1-OAD-8310] TIO shall validate wavefront control independent of an instrument.

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

[REQ-1-OAD-8320] The Telescope Optical Feedback System (TOFS) shall meet all performance requirements without degrading the sky coverage of the seeing limited science instruments: 95% for WFOS at the galactic pole.

[REQ-1-OAD-8330] The Telescope Optical Feedback System (TOFS) shall operate and meet performance requirements even when not all primary mirror segments are installed.

5.1.4.2 Active Optics Actuators

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

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

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

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

[REQ-1-OAD-8412] The warping harness shall be capable of correcting low order errors present in each segment by the amount shown in the table below.

Table 5-1: Warping Harness Performance Parameters

Noll Zernike Mode		Correctable Zernike Amplitude on a 1.44m circle (nm RMS)	Correctable Zernike Amplitude on a hexagonal segment (nm RMS)	Correction Factor
Mode Name	#			
Focus ($Z_{2,0}$)	4	1067	911	17.3
Astigmatism ($Z_{2,+2}$)	5	1575	1331	24.5
Astigmatism ($Z_{2,-2}$)	6	1671	1410	24.4
Coma ($Z_{3,+1}$)	7	348	312	2.8
Coma ($Z_{3,-1}$)	8	222	200	2.8
Trefoil ($Z_{3,+3}$)	9	840	571	7.5
Trefoil ($Z_{3,-3}$)	10	936	813	24.9
Spherical ($Z_{4,0}$)	11	291	264	2.5
Secondary astigmatism ($Z_{4,+2}$)	12	707	639	1.4
Secondary astigmatism ($Z_{4,-2}$)	13	666	602	1.4

Discussion: The above correction factors and amplitudes are based on applying correction using 10 SVD modes. This is the baseline control scheme for the segment warping harness.

[REQ-1-OAD-8415] The active optics system shall adjust M2 position in 5 DoF (tip, tilt, piston, x and y decenters) by means of a hexapod.

[REQ-1-OAD-8425] The active optics system shall adjust M3 position in 2 DoF (tip and rotation about the telescope optical axis) by means of 2 actuators.

5.1.4.3 Active Optics Sensors

[REQ-1-OAD-8500] The active optics system shall measure M1 segment position relative to neighboring segments by means of sensors attached to all shared segment to segment edges.

[REQ-1-OAD-8510] The M1 segment position sensing system shall be capable of operating with less than a full complement of segments installed.

Discussion: Alignment and Phasing System Requirements can be found in Section 4.1.9.

The Alignment and Phasing System (APS) is responsible for measuring the alignment and shape of M1, M2, and M3, and for operating in conjunction with the respective telescope control and mirror actuator systems to adjust the alignment and figuring of the mirror segments. In particular, the APS will measure and generate commands for adjusting:

- *M1 Segments in piston tip and tilt*
- *M1 Segment surface figure*
- *M2 Five degrees of rigid body motion (piston, tip, tilt, and x- and y-decenter)*
- *M3 Two degrees of rigid body motion (tip, tilt)*
- *AM2: Five degrees of segment rigid body motion (piston, tip, tilt, and x- and y decenter) for each of up to 6 segments.*

5.1.4.4 Compensation Strategy

[REQ-1-OAD-8600] The adaptive optics system, or in absence of it an “on-instrument” low order NGS WFS, shall provide time averaged wavefront errors to the Telescope Optical Feedback System (TOFS).

Discussion: This is necessary to limit drifts in the active optics system and correct for uncertainties due to the not completely resolved temperature distribution of the environment, structure, and glass.

[REQ-1-OAD-8605] The OPD information supplied to the TOFS shall be the same in both seeing limited and near diffraction limited observations.

[REQ-1-OAD-8610] OPD focus shall be reconstructed into M2 piston.

[REQ-1-OAD-8620] OPD coma shall be reconstructed into M2 decenter.

Discussion: Both focus and coma is primarily controlled by LUT developed through APS measurements (see appendix 'Table 7-4: Mount and active optics actuators and corresponding sensors with control bandwidths). TOFS provides adjustments for system uncertainties due to unmapped drift between APS measurements.

[REQ-1-OAD-8630] In seeing limited operations higher order OPD information including focus and coma shall be directly calculated from the slopes of the Low Order NGS WFS in the seeing limited instruments, by the Active Optics Reconstructor & Controller (aORC).

Discussion: It is expected that the wavefront sensing and guiding functions can be combined into a single sensor.

[REQ-1-OAD-8635] In adaptive optics operation higher order OPD information including focus and coma shall be computed by averaging the ground conjugated deformable mirror commands, or, if AM2 is used, by averaging the AM2 modes. In both cases, the higher order OPD information are computed by the AO RTC.

[REQ-1-OAD-8640] In adaptive optics operations, the OPD information shall be scaled into telescope modes (degrees of freedom) that are transferred to the Telescope Control System.

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

[REQ-1-OAD-8650] In steady state conditions, the telescope system shall meet the image quality requirements over periods up to 300s without corrections from the optical feedback system.

[REQ-1-OAD-8655] The Low Order NGS WFS in the seeing limited instruments shall be either adjacent to the entrance window of the instrument, or preferably located inside the instrument.

[REQ-1-OAD-8670] The AO RTC shall collect the measurements from the various NGS and LGS WFS and compute the commands to the wavefront correctors. (Deformable Mirrors, Tip Tilt Mirrors or Tip Tilt platform, AM2 modes when AM2 is used as an AO woofer).

Discussion: Details of the early light facility AO system (NFIRAOS) are listed in Section 4.2.

[REQ-1-OAD-8675] The control architecture for near diffraction limited observations shall be as shown in 'Figure 5-2: Control Architecture for adaptive optics observations' below [REQ-1-OAD-8055].

Discussion: The architecture is an extension of the active optics control architecture. New features include (i) the control of high order DMs and high bandwidth tip/tilt stages using measurements from NGS and LGS wavefront sensors, (ii) offloads from these components to M1, M2, and the mount, and (iii) pointing and centering control of the beam transfer and projection optics in the LGS facility.

5.1.5 PRESET AND ACQUISITION

[REQ-1-OAD-8700] The Executive Software shall coordinate the preset and acquisition processes.

[REQ-1-OAD-8705] TIO instruments and AO systems shall provide their sensors for guiding.

Discussion: TIO doesn't include a facility acquisition and guiding system.

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

- If it is feasible to design the field of view of the guide WFS large enough to accommodate telescope pointing repeatability (1 arcsec), the acquisition can be made in a single pointing step. Even in this case though, it may be necessary to re-align the wavefront sensors relative to the instrument after the initial acquisition.

- If it is technically or financially not feasible to use large enough FOV guide WFS, the instrument shall provide an at least 20 arcsec acquisition camera. After acquiring the guide star on the camera, telescope blind offset places the guide star on the WFS.

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

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

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

[REQ-1-OAD-8725] TIO TCS shall command the position of the guiders or wavefront sensors (WFS).

Discussion: This includes any type of guide star mechanism such as AGWFS, ODGW, OIWFS and PWFS.

5.1.5.1 Preset and Acquisition Sequences for Different System Configurations

5.1.5.2 Science Target Acquisition Time

Definition: The guide star acquisition process delivers the telescope ready for science observation to the predefined Pointing-Origin position. Pointing-Origin is defined as the [x,y] position in the focal plane that receives the image of the target. If additional adjustments specific to a science observation are needed, these are covered by the science target acquisition time requirements.

[REQ-1-OAD-3096] IRIS science target acquisition time for IFU, in NGSAO or LGS MCAO shall take less than 2 minutes, after the guide star acquisition has been completed.

[REQ-1-OAD-3098] IRIS science target acquisition time for the Full Array Imager, in NGSAO or LGS MCAO shall take less than 0.5 minutes, after the guide star acquisition has been completed.

[REQ-1-OAD-3344] WFOS science target acquisition time for multi-slit masks, in seeing-limited, shall take less than 3 minutes, after the guide star acquisition has been completed.

[REQ-1-OAD-3346] WFOS science target acquisition time of a single target onto a long slit, in seeing-limited, shall take less than 1 minute, after the guide star acquisition has been completed.

5.2 Observatory Software Architecture

TIO Software Architecture (OSA) is split into two parts called the Program Execution System Architecture (PESA) and Observation Execution System Architecture (OESA). The OESA includes the software that runs at the telescope and controls other hardware systems in order to gather and quick look science data. The PESA includes all software needed to prepare for observing at the telescope and all software used following observing to process and distribute science data.

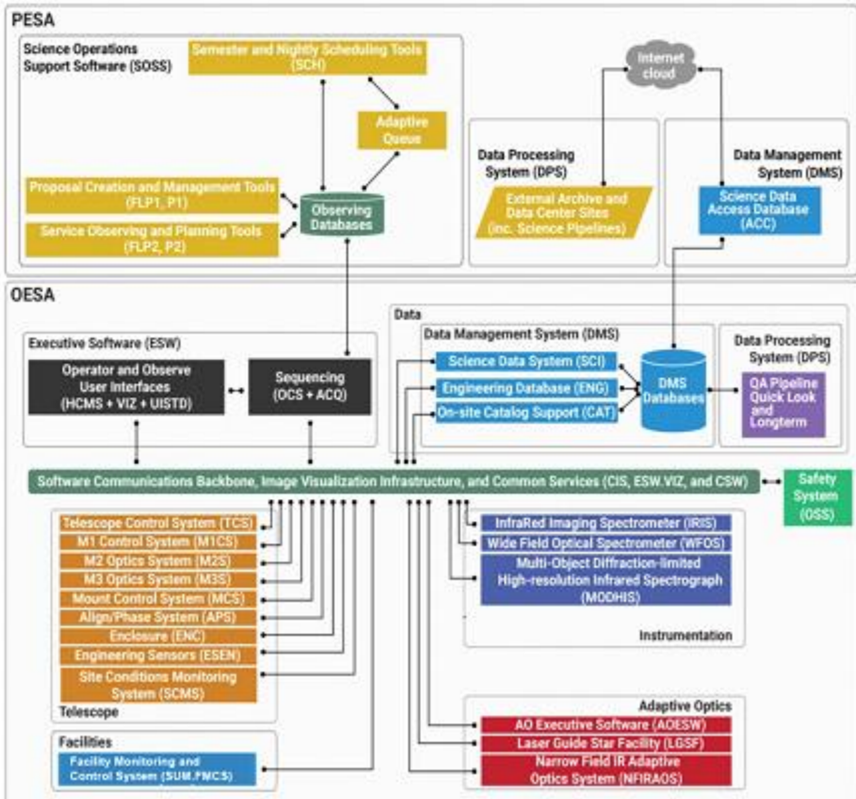

Figure 5-3: Observatory Software Architecture (OSA) Subsystem Decomposition

Discussion: The OSA subsystems are also partitioned into six logical groups of related functionality called Principal Systems to aid reasoning about the software system as shown in 'Figure 5-4: OSA partitions software subsystems into Principal Software Systems' below and 'Figure 5-3: Observatory Software Architecture (OSA) Subsystem Decomposition' above. The observatory subsystems that implement these functions are called out in 'Table 5-5: OSA subsystem allocation into Principal Software Systems'.

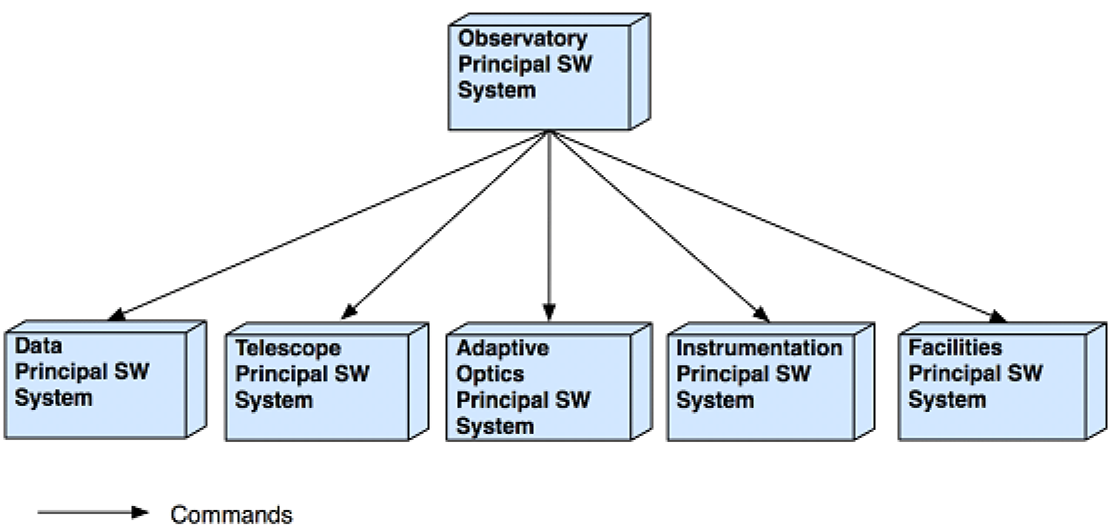

Figure 5-4: OSA partitions software subsystems into Principal Software Systems

[REQ-1-OAD-9351] The OSA principal systems shall be implemented per the Observatory Subsystem Allocation subsystem elements as shown in 'Table 5-5: OSA subsystem allocation into Principal Software Systems' and 'Figure 5-3: Observatory Software Architecture (OSA) Subsystem Decomposition'.

Table 5-5: OSA subsystem allocation to Principal Software Systems

System	Principal Software System	OESA/PESA
Enclosure (ENC)	Telescope	OESA
Summit Facilities (SUM) -Facilities Control and Mgmt System (FCMS)	Facilities	OESA
Observatory Headquarters (HQ)	N/A	N/A
Telescope Structure (STR) -Mount Control System (MCS)	Telescope	OESA
M1 Optics System (M1)	N/A	N/A
M2 System (M2)	Telescope	OESA
M3 System (M3)	Telescope	OESA
Optical Cleaning Systems (CLN)	N/A	N/A
Optical Coating System (COAT)	N/A	N/A
Test Instruments (TINS)	N/A	N/A
Optics Handling Equipment (HNDL)	N/A	N/A
Alignment and Phasing System (APS)	Telescope	OESA
Telescope Control System (TCS)	Telescope	OESA
M1 Control System (M1CS)	Telescope	OESA
Observatory Safety System (OSS)	N/A	OESA
Engineering Sensors (ESEN)	Telescope	OESA
Narrow Field Near Infrared On-Axis AO System (NFIRAOS) (including NSCU)	Adaptive Optics	OESA
Laser Guide Star Facility (LGSF)	Adaptive Optics	OESA
Adaptive Optics Executive Software (AOESW)	Adaptive Optics	OESA
Refrigerant Cooling System (REFR)	N/A	N/A
Cryogenic Cooling System (CRYO)	N/A	N/A
InfraRed Imaging Spectrometer (IRIS)	Instrumentation	OESA
Wide Field Optical Spectrometer (WFOS)	Instrumentation	OESA
Multi-Object Diffraction-limited High-Resolution Infrared Spectrograph (MODHIS)	Instrumentation	OESA
Communications and Information Systems (CIS)	N/A	N/A
Common Software (CSW)	Observatory	OESA
Data Management System (DMS)	Data	OESA/PESA
Executive Software (ESW)	Observatory	OESA
Science Operations Support Systems (SOSS)	Observatory	PESA
Data Processing System (DPS)	Data	OESA/PESA
Site Conditions Monitoring System (SCMS)	Telescope	OESA

[REQ-1-OAD-9009] OSA subsystem command-and-control shall be strictly hierarchical as indicated by the arrows in 'Figure 5-4: OSA partitions software subsystems into Principal Software Systems'.

Discussion: This limits command communication to flow from Observatory Controls to the other principal systems.

Discussion: Observatory Controls is responsible for coordinating and synchronizing activities occurring in different principal systems.

Discussion: The Observatory Software Architecture is defined with the intent that command rates between Observatory Controls and other principal systems is slow (e.g. less than 100 *commands/sec between subsystems). All faster communication takes place within the individual principal systems and may use CSW services or other mechanisms based on requirements.*

[REQ-1-OAD-9850] The OSA shall include all software necessary to implement the first light observing mode called Visitor Observing Mode.

Discussion: Individual users (or teams) are assigned specific blocks of time no shorter than one half night. During their assigned time, users have complete responsibility for how they use and configure the telescope and instruments.

Discussion: OSW provides software tools that support the proposal process for Visitor Observing Mode. OSW provides tools for planning observations prior to arrival at this telescope. Observers can use the user interface programs and tools provided at the telescope (or a remote observing site) to configure the telescope systems and instrument to obtain science data. Instrument user interfaces load sequences which are executed to control and coordinate the telescope software and hardware systems. The observing process creates entries in observatory databases to associate the science data created with the observer's program. The created science data flows to the local data storage system and is available via a data access web site.

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

Discussion: Service observations are executed by TIO Science Operations Staff on behalf of PIs from a combined list of observation descriptions from all partners.

Discussion: OSW provides software tools that support the proposal process for observers. OSW provides tools for planning observations prior to arrival at this telescope. The planning tools are required for observers to enable later execution by TIO staff. Information sufficient for execution is stored in the observatory databases. Staff members use the user interface programs and tools provided at the telescope (or a remote observing site) to extract the information and configure the telescope systems and instrument to obtain science data. The tool loads a sequence, which is executed to control and coordinate the telescope software and hardware systems. The entries in observatory databases are updated to associate the science data created with the observer's program. The created science data flows to the local data storage system and is available via a data access web site.

[REQ-1-OAD-9854] The OSA shall include an observing mode called Adaptive Queue Observing Mode to ensure that this mode is available without significant re-design as part of the Service Observing Mode.

Discussion: Adaptive Queue Observing mode means onsite conditions are used to optimize the scheduling of observations on the telescope. This mode is not a first light observing mode, but it is required that our software system allow it in the future without significant rewrite of code. The majority of changes required are scheduling tool and observing database updates.

[REQ-1-OAD-9856] The OSA design shall include all software necessary to support Target of Opportunity (ToO) observations during time allocated for both Visitor and Service Observing Mode programs.

Discussion: The TIO 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 TIO 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 TIO software framework as provided by TIO Common Software and described in TIO 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 TIO software system on-site and make it operational.*
- *Minimize time and effort needed to maintain and extend the TIO software system during operations.*

Discussion: This is verified by showing compliance reports comparing the subsystem design with the TIO Software Design Document.

[REQ-1-OAD-9715] Each OSA software subsystem shall be compliant with the TIO Software Quality Assurance Plan and Software Development Process (AD79).

Discussion: This requirement can be verified by each subsystem demonstrating adherence to the TIO standard tools, languages, and operating system as defined in Appendix A of AD79.

Discussion: Adherence to the TIO Software Quality Assurance Plan and Software Development Process (AD79) ensures that TIO software subsystems are consistent with the approved TIO software systems engineering standard that includes software quality assurance, project management, requirements management, testing and configuration management supporting processes.

[REQ-1-OAD-9953] OSA software subsystems that require a private non-relational database or technical datastore shall integrate with the Observatory Databases through an HTTP-based interface.

Discussion: The HTTP-based interface will be defined by DMS ENG and implemented by the subsystem. See 'Figure 5-6: Observatory database architecture' in Section 5.3.

[REQ-1-OAD-9027] OSA software subsystems shall use Graphical user interfaces (GUIs) as the default for all normal scientific and technical operations.

Discussion: User interface standards development and support are part of the Common Software and ESW requirements.

[REQ-1-OAD-9029] OSA software subsystems shall provide engineering GUIs if they include:

- Low-level technical software parameter settings that are modifiable during operations.
- Low-level engineering functions that are occasionally executed by an expert user.
- Are required to operate in standalone mode.

[REQ-1-OAD-9740] The combined set of OSA software subsystems shall be implemented such that, without warning, they can be removed from the TIO operational environment then re-installed and restored to their operational state in less than eight (8) hours.

Discussion: The restoration of the OSA subsystems will be solely based on information stored on the central configuration server supplemented by various high-level installation kits (e.g. operating system, common software packages, etc.).

5.2.1 Observation Execution System Architecture (OESA)

This section contains general OESA requirements that pertain to all software that is part of the OESA. Section 5.4 contains detailed Observatory Software requirements for Common Software, Executive Software, and the Data Management System that supplement the requirements in this section.

[REQ-1-OAD-9000] The OESA shall enable efficient observation of astronomical objects as well as efficient command, control, and monitoring of all observatory functions.

[REQ-1-OAD-9003] OESA shall consist of a set of software subsystems that interact through a software connectivity backbone that is implemented in a software Subsystem called Common Software (CSW) layered on top of a physical communications network Subsystem called

Communications and Information Systems (CIS) (see '*Figure 5-3: Observatory Software Architecture (OSA) Subsystem Decomposition*').

Discussion: The subsystems of the OESA form a distributed, concurrent application. The communication is decomposed into a set of communication common services, which are discussed later in this document.

[REQ-1-OAD-9300] Each OESA software subsystem shall consist of one or more lower-level software components.

Discussion: A software component is a software entity that encapsulates a set of related functions or data.

Discussion: Software subsystems generally consist of multiple lower-level software components that collectively provide the subsystem functionality. The requirements in this section pertain to subsystems as well as their lower-level components.

[REQ-1-OAD-9365] Any OESA software subsystems that contain hardware and software, such as instruments and telescope subsystems, shall be structured in a TIO-standard way consisting of an observing mode-oriented sequencer, assemblies and hardware control daemons.

Discussion: An example of this structure is shown in 'Figure 5-5: Standardized software components for subsystems with hardware and software' below.

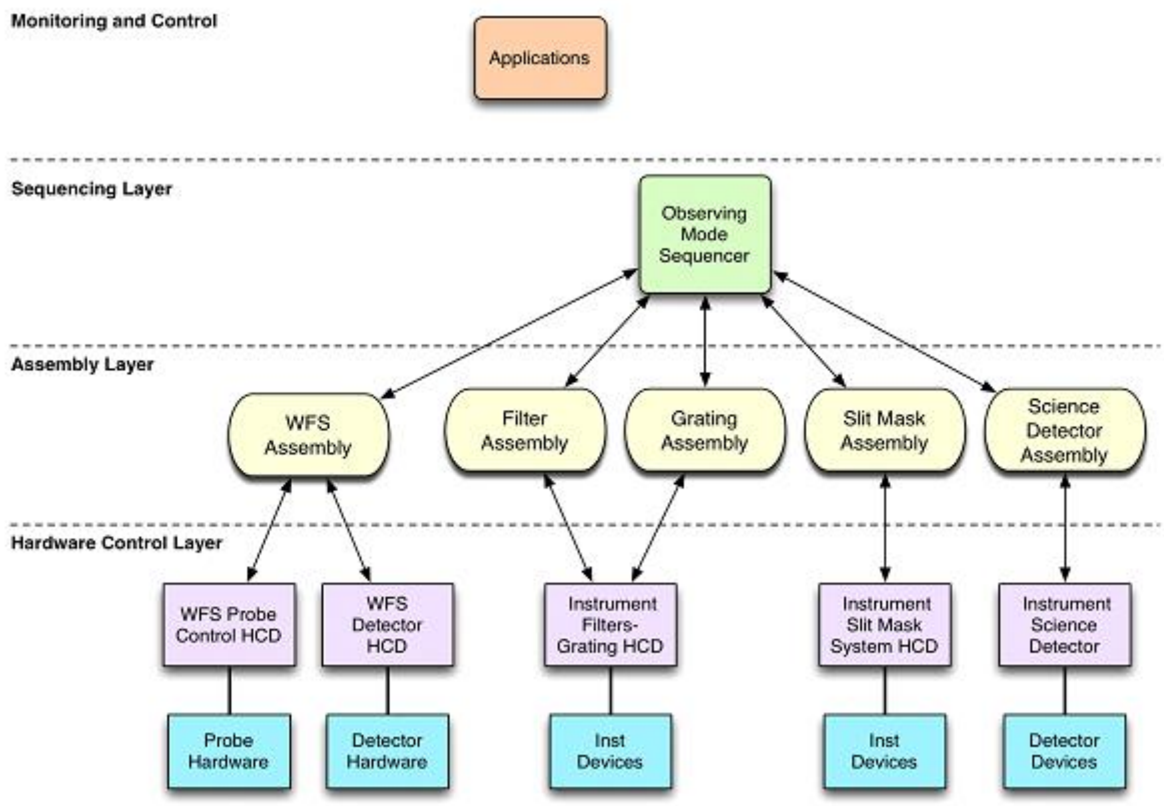

Figure 5-5: Standardized software components for subsystems with hardware and software

Discussion: The lowest layer in the software system, called the Hardware Control Layer, consists of all the controllable hardware that is available for use by higher levels of software. A sea of similar software components called Hardware Control Daemons (HCD) interfaces to hardware devices. The Assembly Layer exists just above the Hardware Layer. Software at this layer consists of components called Assemblies with two roles. The first role is to allow the grouping of HCDs into higher-level entities. This is required when individual hardware devices must be considered as a unit or requiring processing. The second role of components in the Assembly Layer is to provide more sophisticated hardware control functionality that integrates devices across different

HCDs to produce higher-level devices or add uniformly useful capabilities. The Sequencing Layer contains components called sequencers because they control and synchronize the actions of the HCDs and Assemblies. A Sequencer uses a script that to coordinate and synchronize the Assemblies and HCDs. The Monitoring/Control Layer is the layer of software that contains the user interface programs that are used to observe with the telescope.

[REQ-1-OAD-9330] Each OESA subsystem or component shall integrate and communicate with the other principal systems of the OESA using only the integration services and other software provided by the TIO Common Software (CSW) subsystem (see 'Table 5-8: TIO Common Software services definitions' below [REQ-1-OAD-9200]).

Discussion: This requirement constrains the software principal systems to use only the TIO Common Software for integration with OESA.

[REQ-1-OAD-9021] Each OESA software subsystem user interface shall support the tasks of the user types shown in 'Table 5-6: Software subsystem user types' below.

Table 5-6: Software subsystem user types

User Type	Description
Observing Assistant	A TIO staff person at the telescope site who is responsible for controlling and monitoring the TIO telescope and software system on behalf of other system users.
PI-Directed Observer	A TIO 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 TIO telescope, TIO Support Facility or at an approved remote observing facility.
Pre-Planned Queue User	A TIO 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 TIO 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 TIO telescope or the TIO 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: The TIO common look-and-feel defined for graphical user interfaces is described in ESW.UISTD (RD72).

[REQ-1-OAD-9309] Each OESA software subsystem shall initialize itself with a default configuration and make itself ready for operation without further human intervention in less than one (1) minute.

Discussion: See 'Figure 5-5: Standardized software components for subsystems with hardware and software'. This requirement also applies to all components within a subsystem.

[REQ-1-OAD-9306] Any OESA software component that controls hardware shall provide a simulation mode so that the component can be tested in an environment without the hardware.

Discussion: This requirement provides the ability to test the software in a standard environment that does not require the presence of hardware devices or controllers, or other subsystem software.

Simulation for components that control hardware, such as HCDs, must either provide a simulation mode itself or, preferably, simulate the hardware device or controller (see Figure 5-6).

The level of simulation must be such that it realistically tests the system. Tests for the simulated component must be the same tests run for the non-simulated version of the component.

For unit and component tests, interfaces with other subsystems must be simulated. For integration tests, other subsystems running in either real or simulated mode may be used, if available.

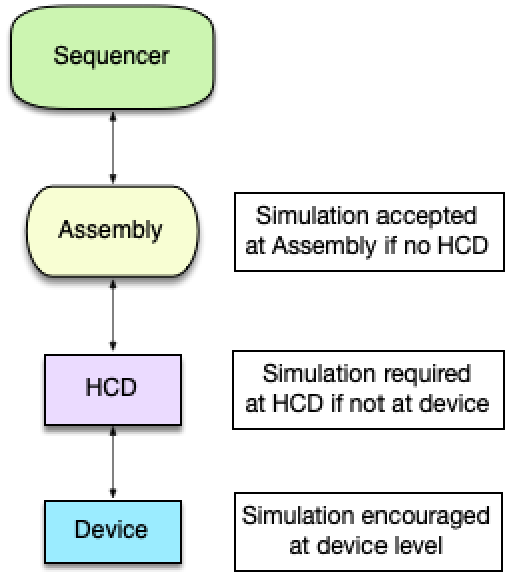

Figure 5-6: Simulation levels

[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 TIO software system.

Discussion: This requirement also applies to each component within a subsystem. See [REQ-1-OAD-9300] and [REQ-1-OAD-9365] and their discussions for the definition of a component.

[REQ-1-OAD-9305] Any TIO software subsystem platform, when operating at full capacity, shall have an available margin in computational power of 30% or more.

Discussion: This requirement is to ensure that delivered computer systems have enough reserve computational capacity to allow future reasonable changes during AIV and the first few years of operations that may impact CPU/core performance.

Discussion: For many systems, the requirement can be met by demonstrating that the average load at full capacity is 70% or less on all CPUs or cores. Where this approach does not apply, the system should provide another method for demonstrating that the 30% margin is achieved.

Discussion: An example of operating at full capacity includes performing maximum computations.

[REQ-1-OAD-9307] The OESA software subsystems shall allow remote/programmatic control of power to controllers and devices over the CIS network using TIO standard hardware.

Discussion: This is to support cold starts and to have the ability to remotely control power to equipment in panels that are heated, etc. This is distinct from devices being on UPS or conditioned power. The TIO standard hardware is the Eaton IPC34XX-NET series. For example, the IPC-3402-NET 16A 8 outlet Intelligent Power Controller. These controllers provide web interfaces for browser control. If this standard hardware does not satisfy subsystem requirements, other hardware can be substituted with TIO SE permission.

5.2.2 PROGRAM EXECUTION SYSTEM ARCHITECTURE (PESA)

This section contains general PESA requirements. For more details, see section 5.4.4 for Science Operations Support System requirements and section 5.4.5 for Data Processing System requirements.

Due to construction resource limitations, much of the PESA implementation is not included in the scope of the construction project and is deferred until early operations. The PESA and subsystem design must take that constraint into account.

[REQ-1-OAD-9100] The PESA shall be implemented to enable efficient management of astronomical programs from proposal creation to data delivery based on the end-to-end observing workflow.

Discussion: The end-to-end observing workflow is described in the TIO Observation Workflow (RD44) and the TIO OSW OCDD (RD45).

[REQ-1-OAD-9405] The PESA software subsystems and tools shall support the operations workflow and operations modes of the TIO OSW OCDD (RD45).

[REQ-1-OAD-9400] PESA subsystems shall follow the same user interface standards and guidelines as OESA subsystems unless it is determined that they are not sufficient.

[REQ-1-OAD-9403] Unless otherwise noted, PESA subsystems shall follow the same communication stack solutions as OESA subsystems. However, PESA systems acting as web services may work synchronously with a request-response communication model.

Discussion: This requirement acknowledges that the PESA applications will have different requirements than OESA applications and different solutions and approaches may be needed.

5.3 Observatory Database Architecture

The reference design for the Observatory Database Architecture is shown in '*Figure 5-7: Observatory database architecture*'.

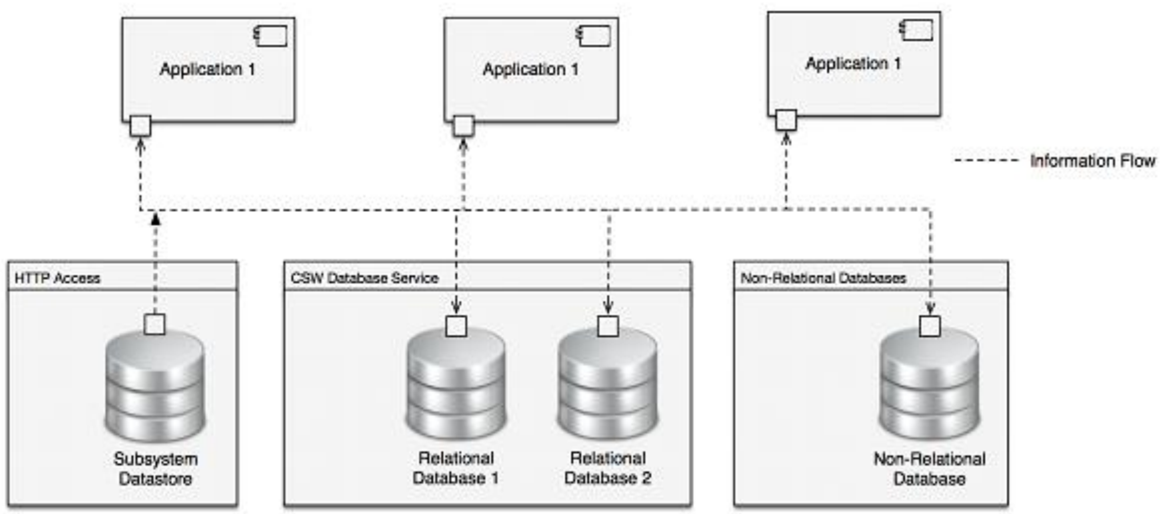

Figure 5-7: Observatory Database Architecture

[REQ-1-OAD-9106] All Observatory and observing-related information shall be stored in one or more databases, consistent with the architecture shown in '*Figure 5-7: Observatory Database Architecture*'.

Discussion: 'Figure 5-7: Observatory Database Architecture' shows that individual applications can access one or more databases.

[REQ-1-OAD-9500] The observatory databases shall be designed, as a minimum, to the following use cases as shown in 'Table 5-7: Observatory Database Use Cases'.

Table 5-7: Observatory Database Use Cases

Use Case	Database
Proposal and planning information supporting pre-planned queue observing	SOSS Observing DB
Long-term Schedules	SOSS SCH DB
Locations of science data produced by science instruments	SOSS Observing DB, DMS ACC DB
Associations of science data and observations	SOSS Observing DB, DMS ACC DB
Telemetry data produced by technical systems	DMS ENG DB
Logging (history) data from all subsystems	CSW DB
Astronomical catalogs required on site	DMS CAT DB
System Configuration Database	
User contact information, authentication, and authorization data	CIS DB
RTC Database	
M1CS Database	
APS Database	

[REQ-1-OAD-9501] The observatory Databases shall provide one or more persistent data stores for observatory information as shown in 'Figure 5-6: Observatory Database Architecture'

[REQ-1-OAD-9943] All observatory subsystems shall store their configuration information in a central observatory configuration database.

Discussion: It is planned that the observatory configuration can be loaded into subsystems from the configuration database during system initialization. This may be the operational model for the initializing the observatory each evening. A consequence is that engineering GUI's that allow direct modification of subsystem parameters should have a “save to configuration database” function to facilitate the persistence of desired changes.

Discussion: Local storage of configuration data by subsystems is not permitted.

[REQ-1-OAD-9942] The configuration of each observatory subsystem, and therefore the entire observatory, shall be accessible from a central observatory configuration database.

Discussion: This includes pointers to initialization files, look-up tables, hardware state. For example, the configuration of the primary mirror (segment serial numbers etc.) should be retrievable from this database. Also, the LUT for M2 internal calibration should be retrievable.

Discussion: Some subsystems, such as APS and M1CS, will have very detailed data models that don't lend themselves well to the flat file structure planned for the configuration service. These data models may have follow a two step creation process, first generated as files (from queries to the DMS engineering database, for example) and stored on the configuration service before being loaded into the subsystem.

[REQ-1-OAD-9950] The observatory shall maintain a searchable status and alarms database, that includes both current and historical data.

Discussion: Since health and alarms are events that are logged to the engineering database, this could be implemented through queries to the existing database.

[REQ-1-OAD-9504] Each subsystem using its own database shall use standard choices for database technologies identified by TIO.

Discussion: This requirement recognizes that a single database technology is not appropriate for all TIO issues and that a single database provides a bottleneck for operations and development. It also recognizes that the number of database technologies must be controlled.

Discussion: Some applications require update-oriented data – small (few byte to several KB) data objects oriented towards an update-many, read-many, fast access model (e.g. status flags, mutable business objects). Other applications need to store bulk data – large (several to many

MB) data objects oriented towards a write-once, read-many, slow access model (e.g. science detector pixel data).

Discussion: The use of standardized database system choices will allow combining databases during operations as needed.

[REQ-1-OAD-9909] Subsystems that store technical data locally shall provide an HTTP query interface to enable retrieval of data from local database.

[REQ-1-OAD-9524] If access and or update to a subsystem database is required by other subsystems, an Application Programmer Interface shall be provided by the subsystem containing the database that describes the available data structures and operations.

Discussion: In some cases, a database within a subsystem may need to be accessed by another subsystem.

[REQ-1-OAD-9526] When used between subsystems, database Application Programmer Interfaces shall be implementation neutral whenever possible.

Discussion: Some complex database interfaces may be too complicated to allow an implementation neutral API.

5.4 Observatory Operations Software

[REQ-1-OAD-9701] TIO Operations Subsystems defined in OAD Section 2.2.1.4 shall operate and meet all requirements for at least 50 years with preventive maintenance.

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

5.4.1 Common Software

Common Software is the software subsystem that provides the infrastructure for integrating all TIO software subsystems and their components. This section defines TIO Common Software.

The TIO Common Software includes (but is not necessarily limited to):

- Middleware APIs and/or Service APIs and supporting libraries
- Software templates for building software components
- Build process and other specifications for developing components
- A strategy and support for testing and automating tests of components
- Standard choices for (if appropriate):
  - Data and meta-data structures
  - Programming languages
  - Development environment (OS, hardware, compilers…)
  - Deployment environment (OS, hardware)
  - Associated documentation

[REQ-1-OAD-9712] Whenever possible, the TIO 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 TIO 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 TIO 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, TIO 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 TIO-standardized software Hardware Control Daemons for these systems (see [REQ-1-OAD-9365]).

Discussion: Examples are (but not limited to) the various low-level facility mechanical plant and electrical plant equipment and enclosure HVAC systems. Examples might be: FCS, SUM, STR, M2, M3, ENC and MCS.

5.4.1.1 Specific Common Software Requirements

[REQ-1-OAD-9028] The CSW shall include libraries and/or editors to support component and GUI development.

Discussion: Common Software will provide developers of user interfaces with solutions and demonstrations of common integration tasks. User interface templates and standards are part of ESW.

[REQ-1-OAD-9039] CSW shall implement support for automatic startup and shutdown of OESA subsystems and components as required by [REQ-1-OAD-9740].

[REQ-1-OAD-9200] The CSW shall include the set of software communication and integration services listed in 'Table 5-8: TIO Common Software services definitions' below with a general description of their functionality

Discussion: Each Common Software service provides functionality needed to integrate the OESA components.

Discussion: This table is the current list of common software services, which may change as the software design evolves.

Discussion: Software with the functionality of Common Software services are often known as middleware in the software development arena.

Table 5-8: TIO Common Software services definitions

Name	Task
Single Sign-on Service	Centrally manage user authentication/access control
Connection and Command Service	Support for subscribing to, receiving, sending and completing commands in the form of configurations
Location Service	Locate and connect to components within the distributed system
Event Services	Provide an event publish/subscribe infrastructure to support events, telemetry, alarms and health
Configuration Service	Manage system and component configuration changes
Logging Service	Capture/store log information
Database Service	Common access to centralized, relational database
Time Service	Provides access to standards-based, precise and accurate time

[REQ-1-OAD-9312] CSW shall provide support for the use of the CSW services listed in '*Table 5-8: TIO 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 TIO 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 TIO-defined data structures containing health, status, alarms and events using the Common Software Event and Alarm Services.
- Each OESA software subsystem or component shall perform a health evaluation and transmit health information (i.e., a heartbeat) at least once per second.
- For the purposes of later diagnosis and analysis, each OESA software subsystem or component shall have the ability to transmit time-stamped logging information using the Common Software Logging Service.
- For the purposes of process control and synchronization, each software subsystem shall be able to transmit or receive events.
- For the purposes of fault detection, each OESA software subsystem or component shall have the ability to transmit an alarm using the Common Software Alarm Services when a situation occurs that prevents normal operations or abnormal condition occurs.

[REQ-1-OAD-9213] Each CSW service shall have an Application Programming Interface (API). It is a goal to make each API service implementation neutral, i.e. it shall be possible to change how a service is implemented without needing to make extensive code modifications to subsystems using that service.

Discussion: The API is used by the developers of components to interact with the TIO system and other TIO components.

5.4.1.2 Specific Common Software Service Definitions

[REQ-1-OAD-9223] The Single Sign-on (SSO) Service shall enable OESA users to authenticate once and gain access to authorized operations. For each user, one or more authorization roles shall be maintained.

Discussion: Single Sign-on is used in a variety of situations in the software system such as looking up an observer's personal information during planning, limiting access to control system functions, and making sure that one observer cannot view the science data of another observer.

[REQ-1-OAD-9226] The Connection and Command Service shall enable one software component to create a connection to another in order to perform command and control of a specific set of OESA subsystems for specific operations.

Discussion: When one component in the OESA needs to control the activities of another with a command, it uses the Connection and Command Service.

[REQ-1-OAD-9229] The Location Service shall provide a service that allows one software component to find other registered components for the purpose of creating connections for inter-process communication.

Discussion: The Connection and Command Service may include the functionality of the Location Service. In this case, a separate Location Service is not needed.

[REQ-1-OAD-9237] The Configuration Service shall manage a database containing *configuration files* and a historical record of changes made to those files. Clients use the Configuration Service to store and retrieve versions of configuration files.

Discussion: The configuration files stored in the Configuration Service are used for a variety of use cases in the software system including storing user interface parameters, look-up tables and default values for components that are used during their initialization.

[REQ-1-OAD-9900] The CSW configuration service design architecture shall be scalable in order to store the data necessary for operations, for the lifetime of the observatory, provided that periodic updates are made to storage, processing hardware, and database software.

[REQ-1-OAD-9238] The Logging Service shall allow software processes or components to record diagnostic or explanatory messages (with time-stamps) local to the process or component or to a central, shared log storage system or database.

[REQ-1-OAD-9247] The Database Service shall provide access to a relational database system that components or processes may use to create specialized databases that store complex relational data for which the Configuration Service is inadequate.

Discussion: Simple models can be stored with historical version access in the Configuration Service. The Database Service provides a shared Database Management System, but processes or components are responsible for their database design.

Discussion: Database Service provides one form of storage capability for software systems that require this kind of storage as required by [REQ-1-OPSRD-4130].

[REQ-1-OAD-9250] The Time Service shall provide software components and processes with access to precise and accurate time (based on RD60: IEEE 1588 V2) and a GPS-based time base.

Discussion: The Time Service provides synchronization between parts of the software system to an accuracy of ~100 microseconds without a hardware board and ~100 nanoseconds with a hardware board.

[REQ-1-OAD-9251] The TIO standard time provided by the time service and to be used as the baseline by other systems within the OESA and PESA is International Atomic Time (TAI).

5.4.1.2.1 EVENT SERVICE DEFINITIONS

[REQ-1-OAD-9232] The CSW Event Services shall enable the publication of events or messages indicating a change of state, completion of task, etc. and the subscription to events from specific registered processes.

Discussion: The Event Services support a variety of use cases in the software system including distribution of demands as event streams from the Telescope Control System, keeping the user interfaces up to date with the latest status values and events that signal significant activities that occur in the software system.

Discussion: An event stream scenario includes the telescope pointing kernel calculating demands for another component at a periodic rate (e.g. example is 20 Hz).

[REQ-1-OAD-9257] After an event publishing component has initialized, the CSW Event Service shall immediately provide the most recently published value of an event to a newly subscribing component.

Discussion: Dependent systems subscribing to events are dependent on getting initial values for events.

[REQ-1-OAD-9258] The CSW Event Service shall provide a component the most recent value of an event, including an accurate time of occurrence, upon request. The component does not need to be a subscriber of the event to request the most recent value of the event.

Discussion: The implementation of this requirement must address the following edge cases: 1) If no value is available, the CSW Event Service will provide an invalid response. 2) If an old value exists, the CSW Event Service will provide it to the subscriber. Subscribers are responsible for checking the time stamp of the events they consume before making decisions based on the value of the event.

[REQ-1-OAD-9259] When an event publisher has not yet published an event value because it has not initialized, the CSW Location Service shall enable a subscribing component to determine that the publisher is not currently available.

Discussion: The subscribing subsystem can use the CSW Location Service to resolve the status of the publishing subsystem or even track the status of the publishing subsystem. This enables the subscribing system to determine how to proceed with their initialization when event publishers have not yet initialized.

5.4.2 EXECUTIVE SOFTWARE SUBSYSTEM

Executive Software (ESW) is the observatory software subsystem that provides the framework and support for command, control and synchronization of components during observing activities including target and science data acquisition.

An Observation Block (OB) is a description of an observation as a set of named parameters and their values that is provided by the observer during planning or observing. Examples of information contained in an OB:

- Targets (science, wavefront sensors)
- System configurations (instrument, telescope, AO system)
- Workflow information (observer, program and scheduling information)

[REQ-1-OAD-9354] The ESW shall support the end-to-end observatory workflow as shown in '*Figure 5-9: The TIO Operations Plan observing workflow*', including the future use of conditions-based scheduling (Adaptive Queue).

5.4.2.1 Executive Software Observatory Control System (ESW OCS)

[REQ-1-OAD-9353] The ESW OCS sequencer shall be responsible for the coordination and synchronization of subsystems.

Discussion: This requirement states the most important functionality of ESW is to provide a software system for the coordination and sequencing of the other subsystems.

[REQ-1-OAD-9806] The ESW OCS sequencer shall support the PI-directed and Pre-planned observing modes by accepting Observation Blocks as an input created by a user interface program or a database of Observation Blocks (Observation Block Generators) as shown in 'Figure 5-8: The ESW sequencing system accepts Observation Blocks (OBs) created by Observation Block Generators' below.

Discussion: Observation descriptions are generated by users using a variety of interface tools and submitted to the ESW for execution. Based on those descriptions, the OESA orchestrates a sequence of system actions to accomplish the described observation. Science datasets are the primary output of this process.

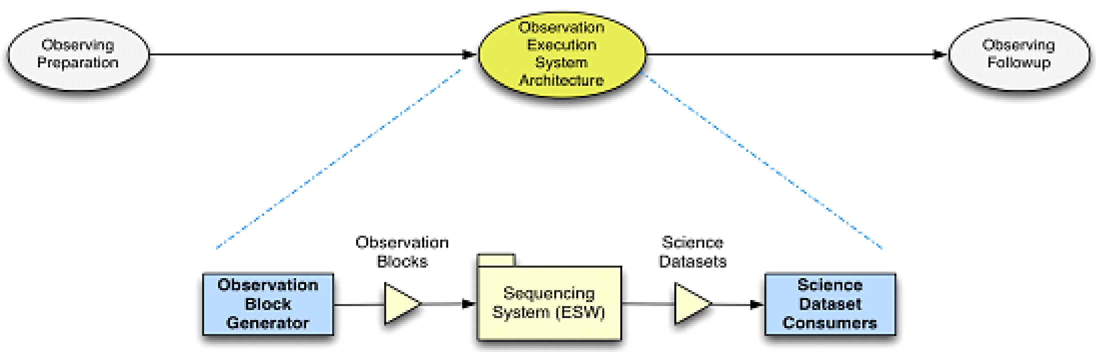

Figure 5-8: The ESW sequencing system accepts Observation Blocks (OBs) created by Observation Block Generators. The Sequencing System uses the OB to execute the observation resulting in one or more datasets, which are consumed by Science Dataset Consumers.

[REQ-1-OAD-9314] The ESW OCS shall define and develop the Observation Block describing the information created by observing user interfaces and observation planning tools (Observation Block Generators).

[REQ-1-OAD-9006] An ESW OCS sequencer shall be able to orchestrate a complete observation, including observatory configuration, target acquisition, and science data acquisition.

Discussion: This requirement sets the scope of ESW sequencing to include this functionality.

Discussion: This coordination will be accomplished in concert with a set of lower tier sequencers. See 'Figure 5-9: Observation execution system architecture sequencer hierarchy.'

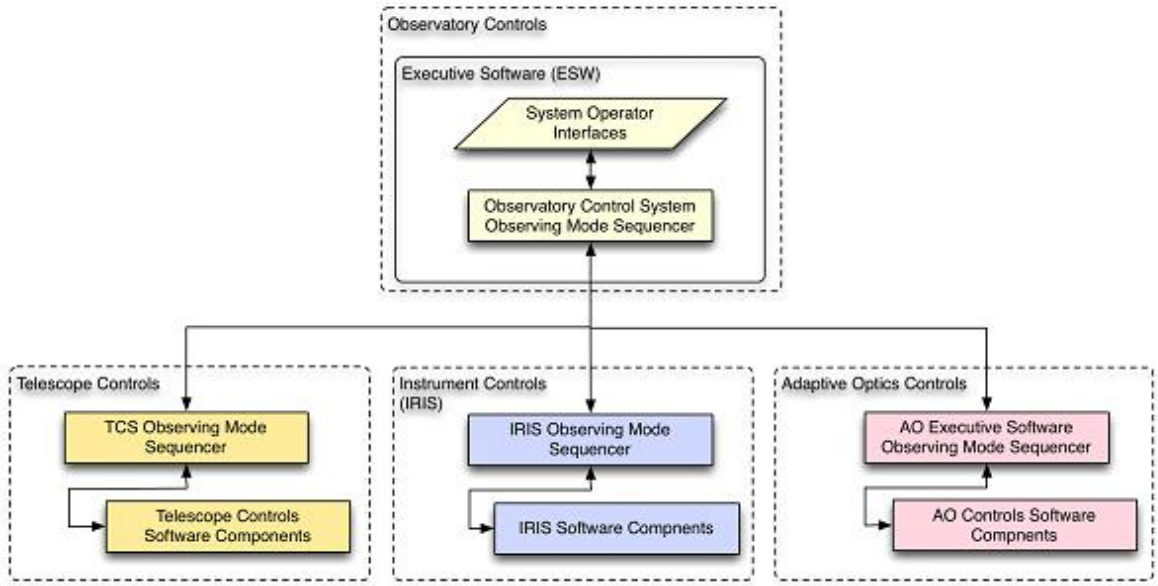

Figure 5-9: Observation execution system architecture sequencer hierarchy

[REQ-1-OAD-9012] The ESW OCS sequencer shall establish an appropriate command-and-control hierarchy depending on the requested observation (or observatory system re-configuration).

Discussion: For example, in the case of an instrument change, the ESW will direct the change of the command-and-control hierarchy from the previous to the new instrument.

Discussion: Different hierarchical relationships and sequencer arrangements can be established for different observing modes. For example, 'Figure 5-8: Observation execution system architecture sequencer hierarchy' below shows a logical hierarchical relationship established to execute an IRIS observation using laser guide stars.

[REQ-1-OAD-9340] The ESW OCS shall develop a common sequencer framework to be used by all subsystems that contain sequencers.

Discussion: The sequencer framework is available to component developers for reuse. It can be useful for testing all parts of the software system.

[REQ-1-OAD-9344] ESW shall provide a scripting language that integrates with TIO Common Services and allows development of sequences for operations and testing of software components.

Discussion: A scripting language is the obvious choice. There is a risk that specific technology choices may indicate a different solution. In this case, this requirement will be modified.

[REQ-1-OAD-9803] The ESW OCS sequencer shall allow the execution of more than one independent, non-conflicting sequence in parallel.

Discussion: Non-conflicting means that each sequence uses a different set of resources (examples of resources are the telescope pointing or NFIRAOS Science Calibration Unit). It is assumed that only one sequence has access to the telescope and that other sequences are executing calibrations that do not conflict with the sequence accessing the telescope.

[REQ-1-OAD-9346] The ESW OCS shall integrate with the DMS.SCI infrastructure to ensure information for dataset headers is gathered or made available at the appropriate times.

5.4.2.2 ESW High Level Control and Monitoring System (HCMS)

[REQ-1-OAD-9357] The ESW HCMS shall provide the high-level, operations-focused user interfaces necessary to display, command and operate the system including those of telescope controls, instruments, and adaptive optics controls during daytime and nighttime operations.

Discussion: In the case of the SCMS, user interfaces are read-only for monitoring by staff during operations.

Discussion: This requirement is also applicable for both local and remote operations.

Discussion: OESA user interfaces must be provided to accept user input, generate and submit observation requests and process and display ("monitor") health and status information.

Discussion: ESW delivers the following user interface programs: Telescope Observing Assistant user interface (TCS, AO control), Status monitors for telescope, AO and subsystems, Health/Alarm monitoring user interface, observation browser/selection user interface, instrument observing user interfaces.

Discussion: Engineering user interfaces, which are used to access lower-level system information and diagnose problems, are typically delivered by the teams developing individual subsystems.

[REQ-1-OAD-9360] The ESW HCMS shall provide an operations-based read-only user interface for monitoring of the OSS.

Discussion: The assembly/HCD interface to the OSS is provided by the TCS. The ESW HCMS read-only interface serves two purposes: to present OSS information (i.e. interlock status) to users during observing and to allow the archiving of OSS interlocks in the DMS.

5.4.2.3 User Interface Standards

The ESW provides user interface standards for use by other subsystems based on the use of Graphical User Interface (UI) technology.

The ESW UI standards should include software toolkits and style choices/patterns that optimize the number of windows and control screens.

[REQ-1-OAD-9016] The ESW UI Standards shall allow for the creation of reusable Graphical UI templates, frameworks, libraries, or tools as needed.

[REQ-1-OAD-9018] ESW UIs shall only be able to be executed by authenticated users on trusted machines.

Discussion: CIS provides the Authentication and Authorization (A&A) system that implements access policies and access control, which interfaces with CSW for execution of the A&A policies.

[REQ-1-OAD-9030] ESW user interfaces shall make use of the communication and integration services defined in 'Table 5-8: TIO 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 TIO observing sites configured according to TIO 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 TIO Observation Workflow (RD44).

[REQ-1-OAD-9348] ESW ACQ shall provide support for gathering and logging information for basic observing-oriented metrics including: total amount of science and non-science observing time, open shutter efficiency, target acquisition statistics, Target of Opportunity observations.

Discussion: The implementation should allow for additional related metrics that may be devised during construction and operations.

Discussion: Careful measurement of observing-oriented metrics allows a calculation of observatory downtime needed for [REQ-1-OPSRD-3085].

[REQ-1-OAD-9350] ESW ACQ shall provide support gathering and persisting information needed to monitor the amount of observing time used by each partner.

Discussion: The policy for calculating the amount of time used by a partner will be determined during construction. However, this requirement is expected to support the gathering of the required information.

Discussion: The intention is to state that we need to track telescope usage and tie it to the amount of time allocated to partners in a way that will be determined in the future, but is assumed to depend on statistics similar to those gathered for [REQ-1-OAD-9348].

5.4.3 DATA MANAGEMENT SYSTEM

The Data Management System (DMS) provides the necessary software infrastructure to capture, format (as necessary), store and manage the TIO science data streams.

[REQ-1-OAD-9366] The DMS shall capture and store science metadata during science data acquisition and associate it with an exposure or observation.

Discussion: The metadata to be captured from subsystems is defined in the DMS ICDs.

[REQ-1-OAD-9369] DMS shall provide a service that allows the retrieval of science metadata associated with an exposure or observation.

Discussion: The metadata retrieved should be formatted using commonly used formats such as FITS headers or JSON.

[REQ-1-OAD-9812] The DMS shall follow astronomy standards including FITS and the International Virtual Observatory Alliance (RD60: Astronomy)

5.4.3.1 DATA MOVEMENT

[REQ-1-OAD-9368] The DMS shall provide infrastructure to move or copy science data and metadata from the telescope and instruments to the support facility and on to the archive and partner data centers.

5.4.3.2 DATA STORAGE

[REQ-1-OAD-9370] The DMS shall provide a persistent data store as per [REQ-1-OAD-9600] with the ability to increase its capacity as needed over the lifetime of the observatory.

[REQ-1-OAD-9503] Two copies of all data objects covered by [REQ-1-OAD-9600] shall be kept in physically separate locations where the physical separation is large enough that local catastrophic events do not destroy both data copies.

Discussion: the minimal separation solution is one copy on summit, one copy in support facility. A more desirable solution is a separation of 10s of kilometers or more.

[REQ-1-OAD-9506] The DMS shall regularly check that the two data copies per [REQ-1-OAD-9503] are identical.

[REQ-1-OAD-9376] The DMS shall provide a database or other system that allows association of science datasets and calibrations as well as associations with other files such as Adaptive Optics Point Spread Function files.

5.4.3.3 SCIENCE DATA ACCESS

Science Data Access refers to accessing both the TIO Science Archive and the US-ELTP Science Archive.

[REQ-1-OAD-9372] The DMS shall provide authorized users with access to and retrieval capabilities for data packages associated with observations and science programs.

Discussion: A data package includes all related science, calibration, and ancillary data as well as any associated information such as observing logs. The list of authorized users for each archive is a policy decision and subject to change, and includes:

- *TIO Science Archive: Only TIO staff and on-site observers*
- *US-ELTP Science Archive: All users including TIO staff*

[REQ-1-OAD-9810] The DMS data access functionality shall provide access to TIO science data and other science data products to authorized users according to the TIO proprietary period policies.

Discussion: Science data products include science metadata, proposal metadata, observing logs, and ancillary data. Proprietary policies may only apply to subsets of these products.

The proprietary period policy is expected to change prior to the end of construction so the software must allow for expected changes.

[REQ-1-OAD-9814] The DMS access functionality shall use a Single Sign-on Service to authenticate and authorize user roles and set data access rights.

5.4.3.4 ENGINEERING DATABASE

DMS collects, stores and provides tools for monitoring engineering telemetry. DMS also includes an Engineering Database subsystem for this purpose.

[REQ-1-OAD-9378] The DMS shall capture and store event and non-event engineering/technical data.

Discussion: The two sources of data for the DMS Engineering Database are the events transmitted throughout the system via the CSW Event Service and the engineering files produced by subsystems. Some high-bandwidth engineering data sources write their data products to a local storage device (e.g., AO and ESEN) instead of writing it directly to DMS.

Discussion: The set of events that is persisted in the DMS Engineering Database is selected for operations and it is indicated by a flag in the ICDs generated from the ICD Database, but is assumed to be a subset of all events.

Discussion: The Engineering Database has access to all telemetry items made available by subsystems using the TIO Common Software Event Service.

[REQ-1-OAD-9823] The DMS Engineering subsystem shall be capable of capturing and storing a minimum of 10,000 events/second from the Event Service assuming event size is 128 bytes.

[REQ-1-OAD-9826] The DMS Engineering Database storage system and backup strategy shall use the same strategy as defined for science data.

[REQ-1-OAD-9828] The DMS Engineering Database shall provide an access user interface that allows time-based range queries, user selectable at query time, on a subset of stored telemetry items.

[REQ-1-OAD-9829] The DMS Engineering Database access user interface shall be restricted to authorized users using the CSW Authentication and Authorization Service.

[REQ-1-OAD-9830] The DMS Engineering Database shall include a service with an API that supports the ability to generate daily reports of telemetry trends for the purpose of monitoring technical performance.

5.4.3.5 Catalog Access Service

[REQ-1-OAD-9253] The DMS Catalog Service, for use by all other TIO software subsystems, shall provide access to a defined set of astronomical catalogs stored at the telescope site and support facility using the DMS shared storage system.

Discussion: A typical Catalog Access Service action is to request possible guide stars for adaptive optics wavefront sensors near a specific celestial coordinate. A specialized TIO guide star catalog is required to support guide and wavefront sensor systems.

5.4.4 Science Operations Support Software

Science Operations Support Software (SOSS) is the observatory software subsystem that provides the PESA infrastructure and applications (see Section 5.2.2) that support the operations plan observing workflow that occurs before observations are executed on the telescope. The workflow is described in the Operations Plan (RD43) and duplicated in 'Figure 5-10: The TIO Operations Plan observing workflow. The workflow consists of a number of steps that take the observer from proposing to get time on the telescope to distribution of data after the data has been acquired.

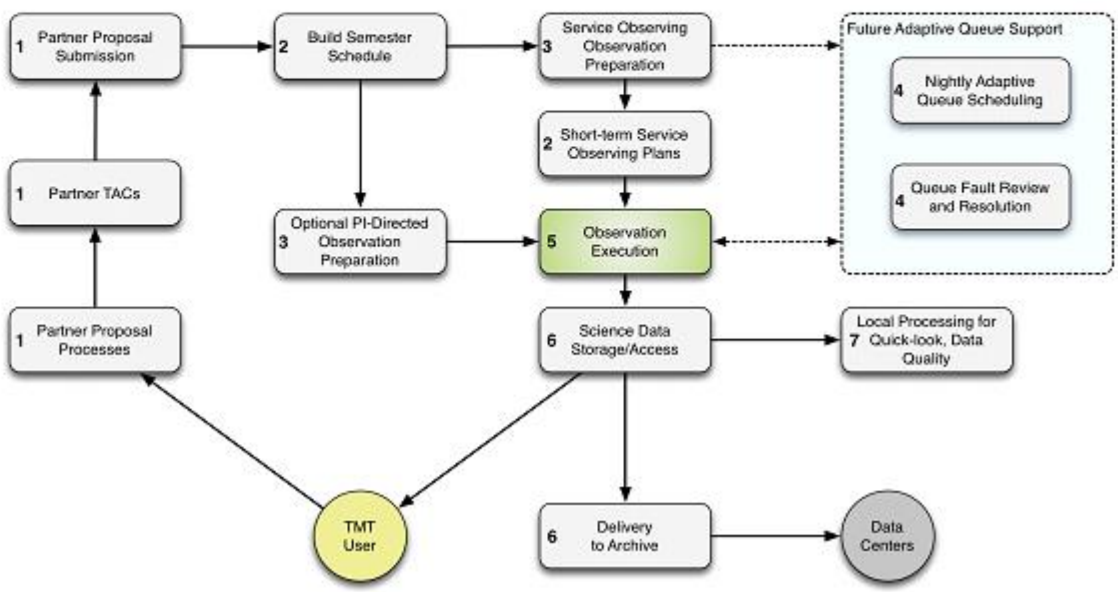

Figure 5-10: The TIO Operations Plan observing workflow

[REQ-1-OAD-9109] Each SOSS subsystem shall support one aspect of the TIO observing workflow (e.g. proposal management, observation preparation, scheduling, data processing, and data access and distribution).

Discussion: Each subsystem may be implemented independently, and they share information through the observatory databases (see 'Figure: Program Execution System Architecture decomposition and relationship to Observation Execution System Architecture' below).

Discussion: At each step of the observing workflow, SOSS tools can augment the observatory databases with additional information as needed. Examples are: allocated time, assigned scientific priority, observation descriptions, system status information, observing condition information, raw data frames, output from data processing systems and others.

[REQ-1-OAD-9426] The SOSS shall provide an Observation Manager with the functionality needed to browse the valid OB collection in the Observatory Databases, select one or more OBs for execution, and send the selected OB(s) to the ESW for execution.

Discussion: The Observation Manager functionality is required, but it may be implemented in some way other than creating an Observation Manager tool.

5.4.4.1 Proposal Submission and Handling (Phase 1)

[REQ-1-OAD-9420] SOSS shall include a Proposal Submission and Handling Subsystem (PSHS, also known as Phase 1) that provides the functionality required to enable users and collaborations to create and submit proposals to TIO.

Discussion: The PSHS provides a user interface program that allows for creation of TIO 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 TIO. The construction Phase 1 system may not be fully integrated with other TIO SOSS tools.

[REQ-1-OAD-9422] The PSHS shall include a Proposer User Interface/Tracking Tool, Partner Proposal Interchange Document Specification, Proposal Ingest Tool, Support Staff Tracking, and Proposal Database.

Discussion: Proposer User Interface/Tracking tool allows the creation, submission, and tracking of proposals for telescope time. The Proposal Ingest Tool ingests proposals from partners in the Proposal Interchange Document Specification format into a Proposal Database. Support Staff Tracking Tool allows for tracking progress of proposals after ingest. The Proposal Database is created to hold the contents of proposals over the lifetime of the observatory.

5.4.4.2 Semester Scheduling

Based on the information gathered during the proposal process, a semester schedule and other scheduling artifacts are created.

[REQ-1-OAD-9425] SOSS shall provide a Semester Scheduling subsystem that uses the information provided by the Proposal Submission and Handling Subsystem and the policies of TIO Observatory to provide an observing semester’s time allocation and long-term schedule products.

Discussion: The Semester Scheduling subsystem is not part of the construction effort. The development of Semester Scheduling is deferred until first light.

[REQ-1-OAD-9427] The integrated Scheduling System shall produce a long-term schedule that includes time allocations for visitor observing programs, service observing programs, engineering time and scheduled down-time.

Discussion: The contents of the schedule and policies for its creation may change with subsequent operations planning work.

[REQ-1-OAD-9428] The Semester Scheduling Subsystem shall include a Proposal Database Ingest or Access, Long-term Scheduling Algorithms/Engine, Scheduler User Interface, Generation of Time Allocation Notifications, Generation of Nightly Schedules for Support Staff, and Schedule Database or other long-term schedule storage.

Discussion: The Proposal Database Ingest or Access allows the Scheduling System to use the Phase 1 information for the development of the schedule. The Scheduling Algorithms/Engine contains the policies of TIO that must be followed in order to properly schedule the telescope. When the schedule has been set, the system shall allow emails to be sent to all proposers notifying them of the results of the scheduling process. The Scheduler User Interface allows a staff member to interactively configure and trigger schedule generation. Generation of Night Schedules for Support staff provides information to support nightly operations. Schedule Database or other long-term schedule storage is used to persist the observatory schedules over the lifetime of the observatory.

[REQ-1-OAD-9832] The Semester Scheduling Subsystem shall provide scheduling support for synoptic or cadence observations during Service Observing periods.

Discussion: Cadence and synoptic observations must be supported in the semester schedule. A cadence constraint might be 8 observations/month for 3 months. A synoptic observing constraint might be 1 observation each night at a specific time for 10 nights.

5.4.4.3 Observation Preparation

[REQ-1-OAD-9423] The SOSS shall provide an integrated Observation Preparation Subsystem (P2S, also known as Phase 2) that provides functionality required to allow users to create, plan, modify and submit information needed to enable the service and Visitor observing modes.

Discussion: The use of the P2S is required for the Visitor and Service Observing mode.

Discussion: The integrated Observation Preparation Subsystem is not part of the construction effort. Its development is deferred until first light.

Discussion: Construction includes development of a first-light Phase 2 tool, based on reuse of an existing tool with modifications for TIO.

[REQ-1-OAD-9834] P2S shall provide an integrated software tool/user interface (P2S Tool) that allows individual observers and multi-partner collaborations to enter Phase 2 observation information and track the progress of their observations. The tool shall act as an Observing Block Generator (see 'Figure 5-7: The ESW sequencing system accepts Observation Blocks (OBs) created by Observation Block Generators' below [REQ-1-OAD-9806] and store information in an observatory database.

Discussion: The P2S Tool will be used by remote users and staff members.

[REQ-1-OAD-9836] P2S Tool and the P2S subsystem shall support the concept of backup programs.

Discussion: All observers are required to prepare a backup program in case weather conditions are not adequate for their observations or their primary instrument is not functional. During Pre-planned Service Queue observing, a queue of possible observations is made available in case the observer has no backup program. Observers will use the same planning tools for creating and planning their backup observations.

[REQ-1-OAD-9438] The Observation Preparation Subsystem shall include a Schedule and Proposal Database Ingest, P2S Tool, Science Program Access and definition of the Science Program Database or other long-term science program storage.

Discussion: Schedule and Proposal Database Ingest creates the set of initial Science Programs for a semester from the Phase 1 and Scheduling Database information. The P2S Tool is defined above. Science Program Access allows remote users to connect using the P2S tool and access *and update the Science Program Database that contains the Observing Blocks and other Science Program information.*

5.4.5 DATA PROCESSING

Most science data requires some amount of data processing in order to do even basic quality during observing. The Data Processing System is planned to support an observatory infrastructure for integrating data processing into the OESA.

The Data Processing System is no longer a part of the construction project, but the system design must allow for possible integration with data processing suites delivered by instrument builders, which are a part of observatory construction.

[REQ-1-OAD-9429] The integrated Data Processing System (DPS) subsystem contains all the functionality necessary to orchestrate automatic data processing for the purposes of quick-look analysis, system performance evaluation, science data quality evaluation and other data-related system performance measurements.

Discussion: This requirement establishes the scope of a future TIO 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 TIO operation management.

[REQ-1-OAD-9430] The DPS acts as a wrapper around instrument-specific data processing modules. The DPS shall deliver a pipeline infrastructure and hardware compute engine (e.g., multi-processor cluster) that can execute software delivered by instrument groups.

Discussion: Instrument builders are delivering data processing modules for the observing modes of their instruments. These packages are standalone, in a sense that they do not depend on other observatory infrastructure.

Discussion: It is advantageous to specify a specific development environment for data processing including programming languages and libraries. (More?)

Discussion: Use of a hardware engine is aligned with common grid computing concepts related to high throughput computing (HTC). For one example, see the Condor project page (RD32).

[REQ-1-OAD-9432] The observatory shall provide disk space and computing capability for data reduction by users at remote facilities.

Discussion: The strategy for supporting remote users of data reduction software is to provide a hardware/software environment for data reduction that is accessible by off site users.

[REQ-1-OAD-9434] The software system design shall include a strategy for integrating data processing and visualization that meets the basic goals of the Data Processing System subsystem.

Discussion: Minimal capabilities are needed to support construction. The software system must determine and address the proper software effort for construction.

5.5 TECHNICAL DATA ACQUISITION, STORAGE, RETRIEVAL AND USAGE

5.5.1 PURPOSE

This section includes requirements for efficient acquisition, storage, and retrieval of technical data, in support of AIV and operations. Efficiency in these processes will reduce the required technical labor, reduce schedule in AIV, and increase observational efficiency during operations. The capabilities as specified will assist in timely debugging and troubleshooting of complex interconnected subsystem processes such as guiding and mirror alignment, that often require on-sky testing time. This functionality will additionally support the automated gathering of technical data for the generation of look-up tables, and verification and monitoring of system technical performance.

5.5.2 DEFINITIONS

Technical Data - Information that is generated and used by the observatory subsystems that are not the science product of the observatory. Included are command and control signals, sensor data, status information in the form of Events (see below), and non-event data for configuration and performance data stored as files.

Event - An event is a data item, including an accurate time of creation and if necessary, time of occurrence, that is published by an observatory component through CSW. Events can be subscribed to by other components, and are therefore a method of passing data. Events can be published at regular time intervals or can be intermittent (e.g. on-change events). Events are used for multiple purposes, including passing control signals between software components, for publishing informational data about system status and performance, and for making available technical data for testing, monitoring, diagnostic purposes and assessing performance. Events that are captured in the DMS engineering database are subscribed to by DMS. An observe event is a special category of an event. It uses the same CSW Event Service infrastructure but it serves a special purpose in the observatory as it is used for metrics and for associating metadata with science data.

Alarm - An alarm is asynchronously generated by a component, notifying other observatory systems of abnormal conditions that require attention and action within a required time frame based on the severity of the alarm. Alarms indicate warning, failure or okay (no alarm) state of a component. A warning could include a current lack of availability (such as a system that is not initialized or indexed), or that a measured parameter is outside its nominal range. A failure indicates that a component of the system is non-functional. The okay state of the alarm indicates that there are no current irregularities in performance.

Alarms are not utilized by the Observatory Safety System as inputs to safety critical functions. For example, an alarm may indicate a system temperature is out of its nominal range, even at a level that may damage a system, but this data would not be used by the OSS. The OSS will have a separate interface to observatory subsystems to monitor critical safety related system states.

Health - Health is a representation of the system's ability to operate properly. Health state can have values GOOD, ILL, BAD, or UNKNOWN. Health with GOOD indicates the component has no problems. Health ILL means that problems exist that are important and should be brought to the attention of the users. A component should be able to continue operating and observations can continue with ILL health, but with possible data degradation. BAD health indicates that a component is in a state that will not allow continued operations. The user or operator must solve a problem before continuing operations. ILL health does not go away until fixed. In this case, health includes a description of the cause. UNKNOWN health indicates that a component is not responding; it may or may not be operating.

As per the requirements below, it is required that system health information be readily available to the telescope operator, in the form of a graphical health tree, and the status and alarms database.

Health status is not utilized by the OSS in safety critical subsystems.

5.5.3 TIO TECHNICAL DATA REQUIREMENTS

The following requirements guide observatory software in support of acquisition, storage and retrieval of system technical data for system performance evaluation and trouble-shooting.

To support technical data requirements, most components will likely have two modes, diagnostic and regular operations. Diagnostic is likely to publish events at a higher bandwidth than is done for regular operations, but for each event it is at a predefined rate. Diagnostic mode data rates for each event will be picked from an agreed number of choices such as 1, 10, 100, 1000 Hz. For some components it may be necessary to have more than one diagnostic mode to support multiple use cases without creating unmanageably large data sets.

> **[REQ-1-OAD-9901]** All TIO OSA subsystems (including instruments) shall publish diagnostic events through the CSW Event Service for the purposes of performance monitoring and failure analysis.

5.5.4 TECHNICAL DATA STORAGE CAPACITY AND PERSISTENCE

> **[REQ-1-OAD-9911]** To reduce storage cost, the DMS shall be capable to delete technical data that is considered not necessary for operations according to observatory policy.

Discussion: The Data Retention Policy will be based on observatory staff experience and possibly informed by the information provided by subsystem teams in an ICD.

[REQ-1-OAD-9903] OSA subsystems shall support regular operations and the standard set of diagnostic modes defined by DMS per [REQ-1-OAD-9916].

Discussion: Rather than requiring real-time configuration of modes, which would be more difficult to implement, DMS defines the standard set of diagnostic modes that support standard observing use cases for monitoring performance, diagnostic testing, and verification.

Discussion: Depending on the system, more than one diagnostic mode may be necessary to support the identified test, problem diagnosis and verification use cases with reasonable data rates and volumes.

[REQ-1-OAD-9902] The DMS engineering database shall allow growth over the lifetime of the observatory according to the data estimates of [REQ-1-OAD-9600].

Discussion: It is assumed that after five years of operations, storage and database performance will allow for an upgrade to increased capacity at a reasonable cost. Maintaining this data for the lifetime of the observatory is needed for supporting technical operations.

5.5.5 Technical Data Acquisition and Retrieval General Requirements

The following requirements enable efficient acquisition, storage, and retrieval of technical data from the system. Further, the use of scripts or data objects enables self-documentation, storage, reuse of test procedures, and coordination of technical data gathering with the sequencing of commands through ESW. This eliminates errors in the execution of tests and ensures that repeated tests use the same data acquisition and retrieval methods.

[REQ-1-OAD-9904] The acquisition of technical data shall be able to be sequenced with an ESW sequencer and synchronized with science data acquisition or other absolute time.

Discussion: To support technical data acquisition requirements, most components will likely have two modes, diagnostic and regular operations. Diagnostic is likely to publish events at a higher bandwidth than is done for regular operations. The technical data acquisition during diagnostic mode would be run from a different script in ESW than the observation. The start of the diagnostic mode technical data acquisition can be triggered on an event, but also could start at a specific time.

Discussion: Therefore, data acquisition can be synchronized in time with the execution of observations.

Discussion: A potential implementation is to create a technical data sequence that runs alongside a science data sequence and listens to Observe Events or others we may define. For instance, when an observation starts, the technical sequence would “turn on” the storage of the specific set of events.

[REQ-1-OAD-9906] ESW shall be able to configure the DMS to collect technical data for any diagnostic mode.

Discussion: This requirement gives ESW the ability to configure the DMS as appropriate for specific diagnostic modes. For example, special engineering database collectors may be started to handle the high bandwidth stream of technical data for the more demanding diagnostic modes.

[REQ-1-OAD-9907] The ESW sequencing system shall support methods to notify users of the status of the execution of scripts, including starting and completion.

Discussion: This is expected to be implemented via e-mail or other messaging methods. When the script is used to trigger diagnostic data, the notification should include information about what subsystems were affected and the time range diagnostic data was acquired, to assist in retrieval.

[REQ-1-OAD-9908] DMS shall be able to retrieve non-event technical data products from the local storage of a subsystem for a specified range of time.

Discussion: Some technical data products will be stored locally on subsystems. An example is the NFIRAOS RTC, that will store many technical data products to a local storage device. This requirement requires DMS to have interfaces to other subsystem data repositories (where specifically called out in ICDs), to enable it to retrieve and supply such data to a technical data user. REQ-1-OAD-9909 and REQ-1-OAD-9524 requires the subsystem to provide an HTTP service and client API to enable this access.

[REQ-1-OAD-9910] DMS shall be able to retrieve the values of all technical data from a subsystem at a specified point in time.

Discussion: Subsystem state includes information about the physical hardware configuration, operating parameters through identification of configuration file versions, and look-up table versions that are available from the configuration service, as well as all published events by that subsystem, and alarms and health information from the alarm service.

Discussion: This is an operations decision, but it is desirable that the system configuration be saved and available from the start of operations throughout the lifetime of the observatory.

[REQ-1-OAD-9912] DMS shall be able to retrieve information stored in the CSW Logging Service for a specified period of time.

5.5.6 Event Data

The following requirements ensure that event data is readily available for system diagnostics, trouble-shooting, verification of system performance, and tracking system performance over time. These requirements make it be possible to define a dataset that is stored when a test is executed. The requirements also ensure that datasets can be readily retrieved for analysis.

5.5.6.1 Event Publishing

[REQ-1-OAD-9914] An ESW sequencer shall have the ability to set the diagnostic mode of a component and return to operations mode after a specified period of time.

Discussion: This requirement requires the ability to set diagnostic mode or operations mode in a sequencer, which allows the sequencing system (i.e. one or more sequencers) to configure subsystems for troubleshooting modes and return them to operations mode when complete. These operations will be performed in a script, which can be written to provide custom functionality according to observing mode and/or the applicable diagnostic use case. REQ-1-OAD-9904 specifies the synchronization requirements.

[REQ-1-OAD-9916] The publishing behavior of OSA subsystem components for each diagnostic mode shall be specified in applicable ICDs as per (RD1).

Discussion: The ICD Database is a configuration controlled database of interfaces that subsystems are required to use to generate ICDs. The event publishing characteristics described in this database are levied as requirements on observatory subsystems.

[REQ-1-OAD-9919] The CSW Event Service shall provide the time of creation of each event using the CSW Time Service, as described in [REQ-1-OAD-9250].

Discussion: Every published event has a creation time stamp, which can be used by the subscriber to make a judgement about whether the latest value is useful or potentially whether the publisher is actually publishing values. (This assumes the subscriber knows the publisher's frequency.)

[REQ-1-OAD-9922] The CIS and CSW shall have the capacity to handle and store, over and above the peak loading during regular observing operations, up to 20 technical data event data streams, synchronized in time at 1 kHz each, of events containing 64 bytes of data each.

5.5.6.2 Event Data Retrieval

[REQ-1-OAD-9924] The DMS shall provide a service that allows time-based queries on one or more engineering events or data products.

[REQ-1-OAD-9928] It shall be possible to extract engineering event data from DMS.ENG in the form of a time series using binning, filling gaps for missing data using either linear interpolation or by carrying forward the most recent value.

Discussion: In this requirement, binning means grouping data values by intervals of time. Using bins smaller than the sampling interval of the original data may result in a gap when no values from the original data exist within the interval.

[REQ-1-OAD-9929] The DMS.ENG shall provide the ability to aggregate values within bins using common operations including at least: mean, median, maximum, minimum, and count.

Discussion: When bins are larger than the sampling interval of the original data, an operation is applied to aggregate the values within the bin.

[REQ-1-OAD-9930] DMS shall be able to save results of requested event data queries to a file in standard machine parse-able ASCII formats.

Discussion: For example, as a CSV file. Date/time formats should be standard (such as RD60: ISO 8601). Engineers often prefer to do data analysis and visualization of telemetry in the tools with which they are familiar (i.e. Excel, Matlab, IDL). For this reason, the system supports extraction of data to formats recognizable by these tools.

[REQ-1-OAD-9932] Requested data products consisting of a query of a single event of less than 1 MB of data shall be delivered by DMS within 5 seconds of the request being submitted.

[REQ-1-OAD-9934] Requested data products consisting of a query of a single event of less than 1 GB of data shall be delivered by DMS within 1 minute of the request being submitted.

5.5.6.3 Real Time Display of Event Data

[REQ-1-OAD-9936] The DMS system shall provide a mechanism to create charts of engineering event data for previous time periods, supporting the display of all event data formats that can be extracted from the system as data files.

[REQ-1-OAD-9938] ESW shall provide a mechanism to display plotting with a common time axis, of the real-time values up to 10 events consisting of a mixture of “analog” traces and logic signals (e.g. telemetry status states).

Discussion: This capability is valuable for debugging complex interactions among subsystems during e.g. acquisition or dithering.

5.5.7 Observatory System Status and Alarms

The guiding requirements on health and alarm status GUI flow to more detailed reporting requirements in the level 2 DRDs.

[REQ-1-OAD-9948] Alarms, including alarm flags, and out of range numeric monitors, shall be assessed by each host subsystem and communicated using the CSW Alarm Service.

Discussion: Conditions for alarms for each subsystem are included in the appropriate ICD documents. An alarm summary document that is applicable to ICDs may also be an efficient method for documentation.

[REQ-1-OAD-9954] DMS shall provide simple statistical information for a range of health and alarm values.

Discussion: Simple statistical information includes, for example: frequency, mean-time between occurrence.

[REQ-1-OAD-9956] DMS shall provide the means to display a history of alarm values for a specified period of time.

5.5.8 Other Technical Data Products

[REQ-1-OAD-9958] Non-event data suitable for evaluating system performance shall be stored by observatory subsystems on either local storage within the subsystem and/or on the DMS system.

Discussion: DMS storage is preferred, but it is recognized that this is not always feasible. This requirement will flow to specific requirements on subsystems, guiding the storage of suitable products for evaluating system performance. ICDs or a reference technical data product document will summarize the data products needed to be stored by subsystems, in support of this flowdown.

6 DEFINITIONS

6.1 COORDINATE SYSTEMS

Discussion: The standard coordinate systems for the TIO are defined in (RD11).

Table 6-1: Coordinate systems for the ideal, undisturbed telescope

Coordinate System	Origin	X axis	Y axis	Z axis	Rotation Angle Definition	Notes
Observatory Floor (OFCRS)	The center of the pier in the plane of the observatory finished floor	Points to the East, in the plane of the observatory finished floor.	Points to the North, in the plane of the observatory finished floor.	Right hand complement to x and y axes. Parallel to local gravity		
Terrestrial (TCRS)	The center of the azimuth journal circle, in the plane of the azimuth journal, 3.5m above the level of the OFCRS	Points to the East, in the plane of the azimuth journal	Points to the North, in the plane of the azimuth journal	Right hand complement to x and y axes. Parallel to local gravity		
Azimuth (ACRS)	Identical to TCRS	Aligned with TCRS X-axis when azimuth angle = 0. Is in the plane of the azimuth journal.	Right hand complement to the X and Z axes	Identical to TCRS	Azimuth angle (a) is defined as angle between TCRS x-axis and ACRS x-axis caused by rotation about the Z axis. By convention this increases in a clockwise direction when viewed from above. (This is the opposite	

Coordinate System	Origin	X axis	Y axis	Z axis	Rotation Angle Definition	Notes
					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 on the Z axis of ACRS with the elevation axis of the telescope	Parallel to the X axis of the ACRS.	Parallel to the Y axis of the ACRS	Identical to TCRS		The RCRS rotates with the azimuth axis but does not rotate with changes of telescope zenith angle. This is plane in which all the instrument optical axes lie
Primary Mirror (M1CRS)	The intersection of the Z axis of the ECRS with the M1 optical surface	Parallel to the X axis of the ECRS	Parallel to the Y axis of the ECRS	Right hand complement to the X and Y axes		The origin of the M1CRS relative to the ECRS is defined in [REQ-1-OAD-1315].
Secondary Mirror (M2CRS)	The intersection of the Z axis of the ECRS with the M2 optical surface	Parallel to the X axis of the ECRS	Right hand complement to the X and Z axes	Points to the origin of the ECRS, in the line of the Z axis of the ECRS		The origin of the M2CRS relative to the M1CRS is defined in [REQ-1-OAD-1056].

Coordinate System	Origin	X axis	Y axis	Z axis	Rotation Angle Definition	Notes
Tertiary Mirror (M3CRS)	Identical to ECRS origin	Aligned with ECRS + Y axis when M3 rotation angle (θ) = 0. Collinear with M3 tilt axis.	Right hand complement to the X and Z axes	Normal to M3 surface; points away from the reflective surface.	θ is the rotation angle of M3 about the ECRS z-axis, defined as the angle between the ECRS Y axis and the M3 X axis. F is the M3 tilt is rotation angle of M3 about the M3 x-axis defined as the angle between the M3CRS z axis and the ECRS z axis.	M3 position is described by the polar coordinates□ θ and F of the M3CRS Z axis in the ECRS.
Focal Surface (FCRS)	Right hand complement to the Y and Z axes	Projection of the ACRS Z axis on the plane perpendicular to the FCRS Z axis	Normal to the focal surface at the origin; points towards the tertiary mirror			The location of the focal surface for different instruments is defined by the instrument bearing angle. This is the angle between the ECRS X axis and the FCRS Z-axis. The distance between the origin of the FCRS and the origin of

Coordinate System	Origin	X axis	Y axis	Z axis	Rotation Angle Definition	Notes
						the ECRS is given by [REQ-1-OAD-1020]
Segment (SCRS)	The midpoint of the segment optical surface, midpoint is the center of the hexagon transformed as defined in Section 4.1.52	Perpendicular to the Z axis; its projection on the X-Y plane of M1CRS is a line passing through the M1CRS Z axis; the positive SCRSj X axis points in the radial direction away from the M1CRS Z axis	Right hand complement to the X and Z axes	Normal to the segment optical surface at the origin		
Primary Segment Assembly (PSACRS)	Center of scaled flat pattern hex projected parallel to M1CRS z-axis onto optical surface. Coincident with origin of SCRS for corresponding mirror segment. (AD2) defines the co-ordinates of the origin of the PSACRS for each primary segment assembly.	Points towards projection of vertex 1 of best fit regular hexagon onto PSACRS XY plane.	Right hand complement to the X and Z axes	Optical surface normal at the origin.		
M1CS Actuator (ACTCRS)	Intersection of actuator line of action with	Normal to actuator/SSA interface plane, points	U-V-Z is right handed for primary mirror sector	Along actuator output shaft		

Coordinate System	Origin	X axis	Y axis	Z axis	Rotation Angle Definition	Notes
	PSACRS-XY plane. (AD2) defines the coordinates of the origin of the ACTCRS. Normal to actuator/SSA interface plane, points inboard towards SSA.	inboard towards SSA (Note denoted as U Axis)	A, C and E. U-V-Z is left handed for sectors B, D, F. (Note denoted as V Axis)	(parallel to PSACRS-Z).		
Edge Sensor (ESCRS)	On the optical surface, centered between edge sensor halves.	Generally, points towards the midpoint of the segment edge.	Generally, points inboard for sense halves and outboard for drive halves.	Optical surface normal at the origin.		
Edge Sensor Pocket (ESPCRS)	On the edge sensor pocket mounting surface. Co-ordinates of the origin are defined in AD16 (TIO 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	The highest point of the cap base interface plane is defined as being coincident with a line parallel to the EBCRS +ve Y axis.

Coordinate System	Origin	X axis	Y axis	Z axis	Rotation Angle Definition	Notes
					ECCRS z-axis. Angle increases in a clockwise direction when viewed from above.	
Enclosure Cap (ECCRS)	Coincident with ECRS origin	Parallel to EBCRS x-axis when e = 0	Right Hand complement to X and Z axes	Lies in the plane of the EBCRS Y and Z axes. Inclined at an angle of 32.5 degrees from the EBCRS Y axis	Enclosure Cap Rotation Angle e is defined as clockwise rotation (when viewed from above) of the enclosure cap about the ECCRS z axis, e = 0 when ECCRS x axis is parallel to EBCRS x-axis.	The enclosure shutter is zenith pointing when e = 0.

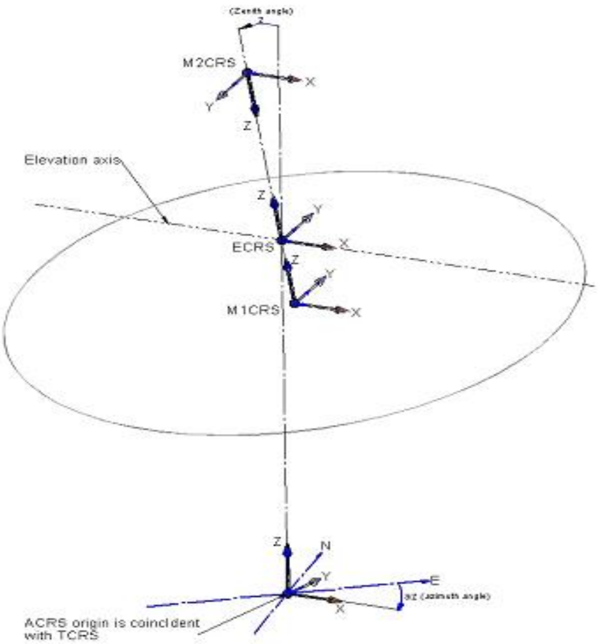

Figure 6-1: The basic coordinate systems of the telescope

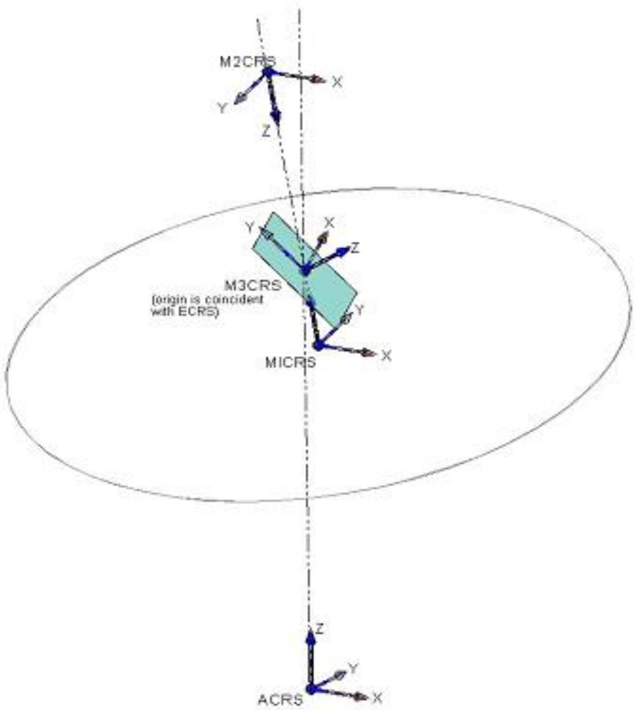

Figure 6-2: Tertiary mirror coordinate system (M3CRS) shown in context of M1CRS and M2CRS

6.2 Image Quality Error Definitions

Table 6-2: Telescope Image Quality Error Budget Notes Definitions

Acronym	Definition
TS	**Thermal Seeing** includes dome and mirror seeing. Dome seeing is defined as the optical effect of non-isothermal air turbulence inside the enclosure and in front of the observing opening. While it is thought of as the adverse effect of the enclosure, for a well-designed enclosure dome seeing can be smaller than the atmospheric ground layer seeing it replaces. Mirror seeing is defined as the adverse optical effect of the air-glass boundary layer at the front surface of the primary mirror due to thermal gradients and heat transfer between the air and the mirror.
SRFE	**Segment Residual Figure Error** Segment Residual Figure Error is quasi-static image degradation due to the non-perfect shape of the M1 segments after correction by the segment warping harnesses. Prior to warping harness correction, the segment surface errors include the (i) residual polishing errors, (ii) uncertainty in the optics shop acceptance testing, (iii) low order passive support errors due to SSA manufacturing and installation errors, (iv) effects of the temperature change between optics shop testing and observatory operating temperature, (v) effects of segment warping from coating stress, (vi) virtual segment shape errors due to segment installation and alignment errors (in-plane translation and rotation). All of these figure errors are partially compensated by the warping harnesses, with the following residuals: (i) fitting errors of the warping harness, including introduced higher order deformations (ii) warping harness noise (repeatability), and (iii) other potential control loop errors. APS measurement errors of the warping harness settings are separately accounted under wavefront sensing This error term is the static residual figure error at the telescope calibration zenith angle and temperature, except the low order passive support errors that are changing with telescope zenith angle.
STD	**Segment Thermal Distortion** accounts for changing segment shape errors due to differences in temperature and temperature distribution between the time of the segment shape measurement used to set the warping harnesses and the actual observation. It includes the combined temperature-induced interaction between the glass and Segment Support System (SSA). Segment-to-segment variations in the mean glass coefficient of thermal expansion (CTE), and CTE gradients are also included.
SSPT	**Segment Support Print Through** includes high order surface distortions associated with the axial and lateral segment support structure. (At a given telescope zenith angle, the segment distortions are in relation to the local segment zenith angles and vary throughout the array due to the curvature of M1.) These errors change with telescope zenith angle and account for (i) fabrication and installation tolerances and (ii) the effect of glass weight. An allowance is also included for M1CS equipment effects that are not polished out during IBF.
SDE	**Segment Drift Errors** capture all the errors associated with (i) uncertainties of the system state at segment shape measurements (LUT generation), (ii) system state drift between those measurements and observation, and (iii) potential numerical (fitting) issues. An example for the first type is our insufficient knowledge of the actual static wind pressure distribution above M1. An example for the second type is M1 edge sensor drift. An example for the third type is extrapolation error between LUTs. It does not include errors separately addressed in SRFE STD, SIPD, and SOPD.
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

Acronym	Definition
	correction. These displacements can be the results of, (i) gravitational effects that change with zenith angle, and (ii) thermal deformations of the mirror cell and SSA.
SOPD	**Segment Out-of-Plane Displacement** accounts for the optical effects of quasi-static segment rigid body misalignment perpendicular to the theoretical primary mirror surface, (in other words segment tip/tilt/piston). , (i) edge sensor calibration and linearity errors, (ii) quasi-static wind pressure, (iii) edge sensor contamination and (v) other potential control loop errors. It's worth to note that this error category may contain global M1 shape errors, besides the local segment to segment displacements. The errors in correcting M2 and M3 shapes, as well as telescope collimation by M1 are accounted for in M2RFE, M3RFE, and COLL, respectively. The APS measurement and estimation errors are separately accounted under wavefront sensing.
SDDR	**Segment Dynamic Displacement Residuals** account for the optical effects of segment rigid body misalignment (segment tip/tilt/piston) due to (i) the control residuals of wind buffeting, equipment and microseismic vibrations, as well as (ii) edge sensor and segment actuator dynamic noise, and (iii) other potential control loop errors, like A matrix uncertainty.
M2RFE	**M2 Residual Figure Error** accounts for image degradation due to the non-perfect shape of M2, including (i) residual polishing errors, (ii) uncertainty in the optics shop acceptance testing, (iii) effects of the temperature change between optics shop testing and observatory operation, and (iv) effects of mirror warping from coating stress. These figure errors are partially compensated by M1 shape, based on a Look-Up-Table (LUT) derived from measurements made by the APS as well as on Telescope Optical Feedback System (TOFS) measurements, with the following residuals: (i) fitting errors, and (ii) increased APS wavefront measurement and estimation errors (delta above the APS measurement and estimation errors if the M2 shape were perfect). For the low (2nd and 3rd) 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 (2nd and 3rd) order components of the surface errors, the measurement and estimation errors are determined by TOFS, instead of APS. Non-repeatable support system errors are covered in M2SDE. The effect of imperfect polishing out of print through bumps at the calibration zenith angle is included in M2RFE.

Acronym	Definition
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. 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) 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

Acronym	Definition
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.

6.3 VIGNETTING AND OBSCURATION

Vignetting: When one of the apertures in a system (such as a lens clear aperture) limits part or all of the bundle of rays determined by the stop.

Obscuration: Anything other than a mirror aperture that gets in the way of the beam (e.g. the top end shape, M2 size, segment gaps, parts of the telescope structure including SHS). Depending on where the obscuration is, the effects can include diffraction, stray light, and thermal background as well as loss of throughput or can also lead to completely blocking part of the field of view (e.g. handrails on the ISS or the edge of M1 at high zenith angles).

6.4 OTHER DEFINITIONS

Nighttime: 12 hours centered around midnight.

Daytime: 12 hours centered around noon.

Steady-State (Science) Operations: the period that starts 36 months after TIO First Light. The intervening time is considered sufficient for tuning the performance and operational procedures to the level necessary to meet requirements.

7 APPENDIX

7.1 ASTRONOMICAL FILTERS

Table 7-1: Astronomical Filters

Band	Center Wavelength (μm)	Bandwidth (μm)
U	0.3663	0.065
B	0.4361	0.089
V	0.5448	0.084
R	0.6407	0.158
I	0.798	0.154
J	1.25	0.16
H	1.635	0.29
K'	2.12	0.34
K_s	2.15	0.32
K	2.2	0.34
L	3.77	0.7
M	4.68	0.22
N	10.47	5.2
Q	20.13	7.8

Data in the table is from (RD6).

7.2 ATMOSPHERIC PARAMETERS

7.2.1 ATMOSPHERIC TRANSMISSION WINDOWS

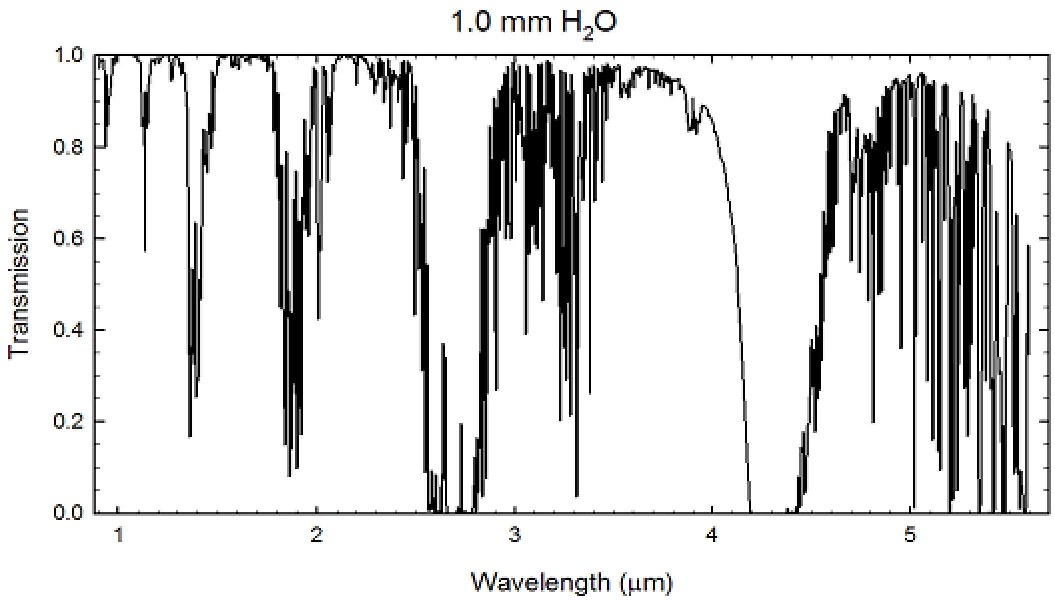

Figure 7-1: Near, mid infrared atmospheric transmission windows for 1 mm precipitable water vapor (RD7)

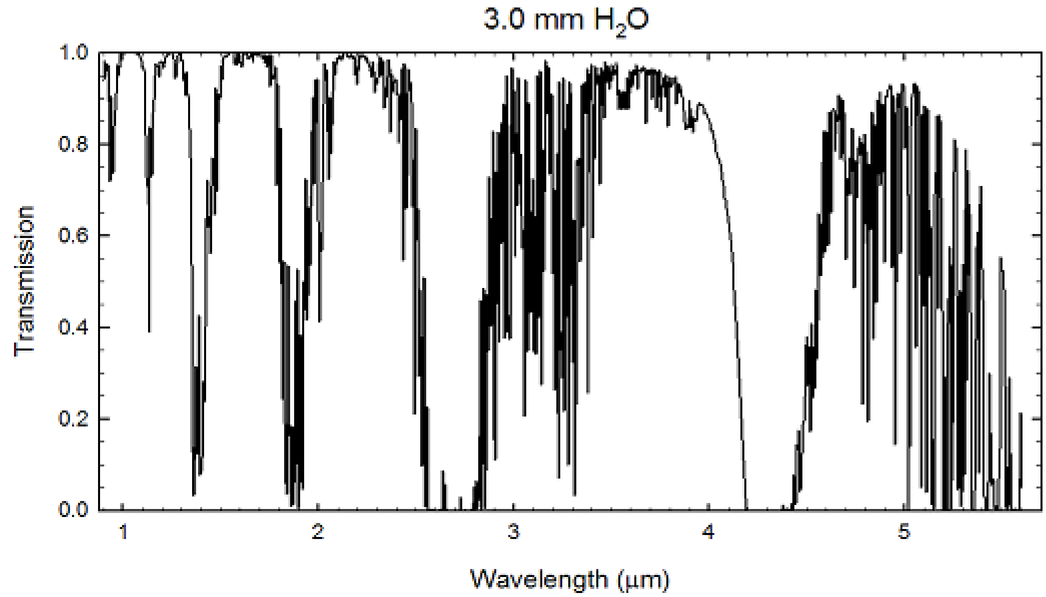

Figure 7-2: Near, mid infrared atmospheric transmission windows for 3 mm precipitable water vapor (RD7)

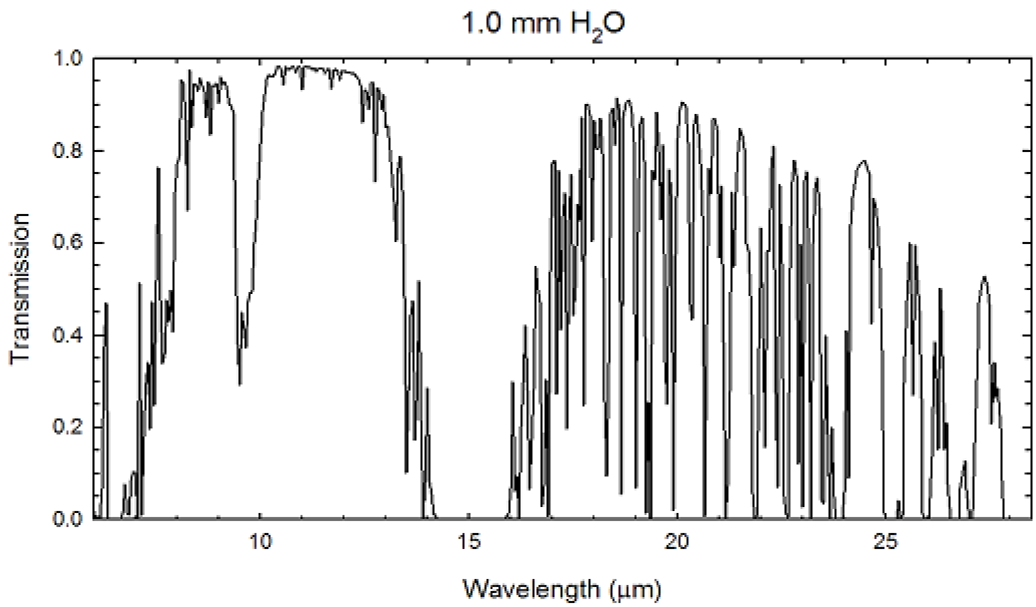

Figure 7-3: Infrared atmospheric transmission windows for 1 mm precipitable water vapor (RD7)

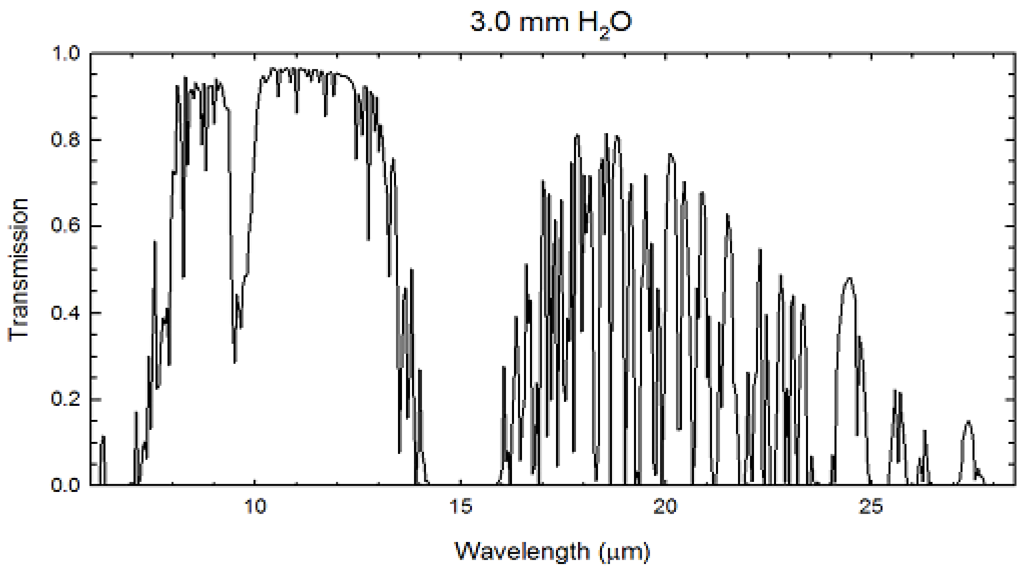

Figure 7-4: Infrared atmospheric transmission windows for 3 mm water vapor (RD7)

7.2.2 Meteorological Parameters

Precipitable H2O = 1.9 mm

7.2.3 Mesospheric Sodium Layer

The following parameters for the mesospheric sodium layer shall be used in the design of LGS AO systems for TIO:

- Centroid sodium layer altitude: 89 to 93 km above sea level (instantaneously)
- Sodium layer thickness: 7- 25 km, but with all atomic sodium >80.5 km ASL
- Column density: 3e13 ions/m2
- Sodium ion cross section: 130 photons-m2/s/W/ion
- Sodium D2 line width: 3 GHz

Based upon temporal PSDs in (RD49) [Pfrommer & Hickson A&A 2014] it is believed that focus measurements from a natural guide star must be obtained at rates of about 100 Hz to track the variations in the range to the sodium layer to the level of accuracy required for the NFIRAOS error budget. Furthermore, higher order wavefront measurements from a natural guidestar must be obtained at rates of 0.01 to 0.1 Hz to calibrate for wavefront reconstruction errors associated with changes in the shape of the sodium layer profile.

7.2.4 Turbulence Parameters

In order to define AO performance requirements, we specify "Standard Conditions" under which the requirements should be met. These conditions are based upon the TIO site testing results taken at Mauna Kea 13N from 29th June 2005 to 1st June 2008. Three sets of standard conditions are given, identified as the 25th and 75th percentile and median conditions. These three sets were established from the 3 years of recorded profiles as follows, using a 'NFIRAOS like' AO system to compute residual DM fitting and servo lag errors:

- Compute the residual DM fitting error and servo lag for each profile
- Sort the profiles based on the results of step 1
- Compute the mean value of the 10% range around each profile (i.e. for 25% profile, calculate mean of the profiles between 20th and 30th percentile)

'Table 7-2: Atmospheric Turbulence Parameters' summarizes the standard values for 4 fundamental atmospheric turbulence parameters for each condition, specified at a wavelength of 0.5 µm and a zenith angle of 0 degrees. We have no measurements of L_0 so we use a generally accepted median value of 30m.

Table 7-2: Atmospheric Turbulence Parameters

Parameter	25th Percentile Conditions	Median	75th Percentile Conditions
Effective coherence diameter (r_0), m	0.27	0.2	0.13
Integrated C_n^2, $m^{1/3}$	1.30E-13	2.21E-13	4.64E-13
Isoplanatic angle (?0), arc sec	2.7	2.23	1.71
Greenwood frequency (f_g), Hz	15.9	21.7	32.2
Outer scale (L_0), m	30	30	30

The values for θ_0 and f_g have been derived using the 7-layer turbulence and wind profiles from 'Table 7-3: Standard Atmospheric Cn^2dh and Windspeed Profiles'. These are also the standard profiles to be used for more detailed AO analysis and simulation.

Table 7-3: Standard Atmospheric Cn^2dh and Windspeed Profiles

h, km	Cn^2dh ($m^{1/3}$)			Median windspeed, m/s
	25th Percentile Conditions	Median	75th Percentile Conditions	
0	4.20E-14	6.39E-14	1.07E-13	5.6
0.5	1.93E-14	3.94E-14	1.11E-13	5.8
1	6.07E-15	1.46E-14	5.72E-14	6.3
2	5.32E-15	1.73E-14	4.45E-14	7.6
4	2.03E-14	3.11E-14	5.09E-14	13.3
8	1.38E-14	2.69E-14	5.49E-14	19.1
16	2.29E-14	2.81E-14	3.83E-14	12.1

Note: The above Cn2 values are based on results taken at a height of 7m above the ground, but have been adjusted to remove turbulence between 7m and 60m to account for the height of the enclosure. 'Table 7-3: Standard atmospheric Cn^2dh and windspeed profiles' consequently does not include conditions inside the enclosure.

7.2.5 TEMPORAL TEMPERATURE GRADIENTS

'Table 7-4: Nighttime temporal temperature gradients' summarizes the night time temporal temperature gradients measured during the TIO site testing at Mauna Kea 13N from 29th June 2005 to 1st June 2008. The temperature gradients quoted are based on temperature values measured at 2 m above ground level.

Table 7-4: Night time temporal temperature gradients

Integration Time (minutes)	Min (°C/h)	2.5% (°C/h)	97.5% (°C/h)	Max (°C/h)
1	-54.1	-9.4	9.4	57.0
4	-32.0	-5.5	5.3	30.9
8	-16.9	-3.4	3.2	13.5
16	-9.8	-2.2	2.0	7.2
32	-5.8	-1.5	1.2	3.7
60	-3.7	-1.1	0.7	2.1

7.3 ACQUISITION

Discussion: The Preset and Acquisition Sequences for Seeing-Limited, NGSAO and LGS MCAO observing modes are defined in (RD48). Section 5.1.5 describes their subsystem time allocations.

7.4 OBSERVATORY CONTROL ARCHITECTURE

Table 7-5: Mount and active optics actuators and corresponding sensors with control bandwidths

		Inner Control Loops Local Encoder Feedback						Middle Control Loop LUT Feedback		Outer Control Loop TOF S		
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.

[11] Coma will be corrected on M2 via tip/tilt, de-center, or rotation about the neutral point. The architecture will easily support any of these three possibilities.

[12] Focus will be corrected via M2 piston.

[13] The instruments and the APS will have the ability to slowly control pupil position via M3 tilt.

7.5 EXAMPLE MIRROR COATING REFLECTANCE CURVES

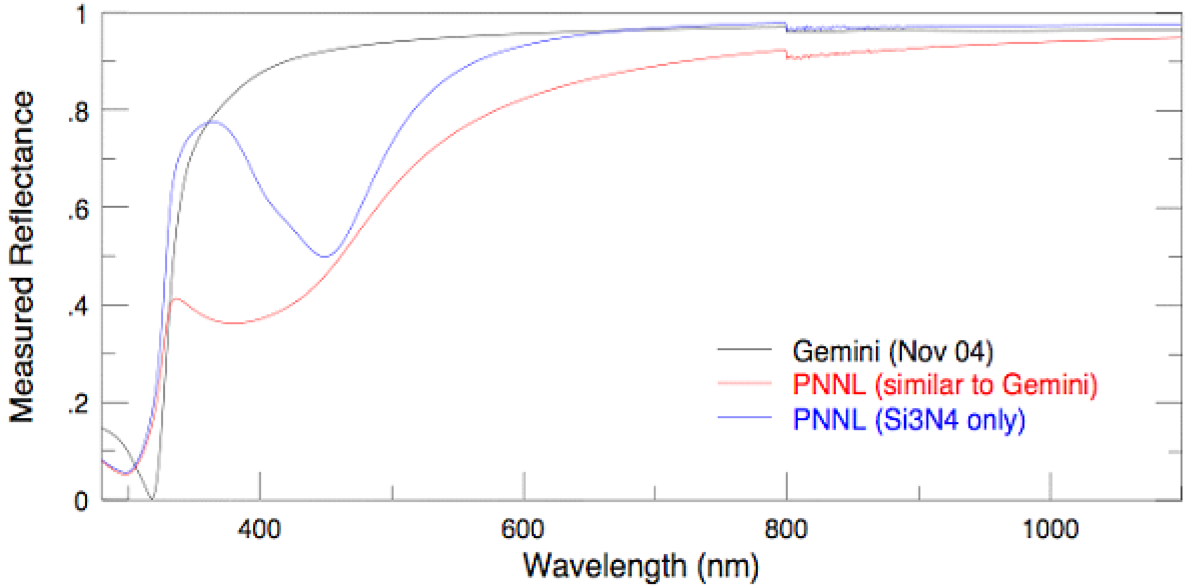

Figure 7-5: Gemini coating plus other coatings in development. Dip in reflectivity other coatings is caused by surface Plasmon resonances.

7.6 MEAN AVAILABLE SCIENCE TIME (MAST)

Under a set of assumptions, the estimated net Mean Available Science Time (MAST) is:

Table 7-6: Mean Available Science Time (MAST)

Time	Hours Per Semester	Hours Per Year	Comments
Possible Observing per Semester	1,734	3,468	365 days per year, average 9.5 hours per night
Engineering Time	-120	-240	On-sky engineering tests
General Instrument Calibrations performed by TIO	-17	-34	SRD requirement <1% available time.
New Instrument Commissioning Time	-48	-96	Estimate 20 nights required every 2 years.
Director Discretionary Time	-30	-60	For unexpected events & adjustments to schedule
Observatory Shutdown	-24	-48	5 nights per year, average 9.5 hours per night
TOTAL AVAILABLE HOURS	1,495	2,990	
Dark Time	498	997	1/3rd of total available hours
Grey Time	498	997	1/3rd of total available hours
Bright Time	498	997	1/3rd of total available hours

TIO is required to maximize the number of net scheduled MAST hours. The table above lists six items that are under direct TIO control, while weather is not (except in the limit that one parameter in TIO site selection is minimizing potential weather downtime). A TIO Observatory designed for robust, efficient operations and low maintenance will pay back in hours available for science observations.