THIRTY METER TELESCOPE

OBSERVATORY ARCHITECTURE DOCUMENT

TMT.SEN.DRD.05.002.CCR25

6 June 2012

TABLE OF CONTENTS

1. INTRODUCTION 10
1.1 Introduction 10
1.2 Purpose 10
1.3 Scope 10
1.4 Applicable Documents 11
1.5 Reference Documents 12
1.6 Change Record 13
1.7 Abbreviations 15
2. SYSTEM DEFINITION 16
2.1 General 16
2.2 Observatory System Decomposition 16
2.2.1 System Decomposition 16
2.2.2 System decomposition element descriptions 17
2.2.2.1 Enclosure (ENC) 17
2.2.2.2 Summit Facilities (SUM) 18
2.2.2.3 Road (ROAD) 18
2.2.2.4 Observatory Headquarters (HQ) 19
2.2.2.5 Telescope Structure (STR) 19
2.2.2.6 M1 Optics System (M1) 20
2.2.2.7 M2 System (M2) 20
2.2.2.8 M3 System (M3) 20
2.2.2.9 Optical Cleaning Systems (CLN) 20
2.2.2.10 Optical Coating System (COAT) 20
2.2.2.11 Test Instruments (TINS) 21
2.2.2.12 Optics Handling Equipment (HNDL) 21
2.2.2.13 Alignment and Phasing System (APS) 21
2.2.2.14 Telescope Control System (TCS) 22
2.2.2.15 M1 Control System (M1CS) 22
2.2.2.16 Test Instrument Control (TINC) 23
2.2.2.17 Observatory Safety System (OSS) 23
2.2.2.18 Engineering Sensors (ESEN) 24
2.2.2.19 Power, Lighting, and Grounding (PL&G) 24
2.2.2.20 Narrow Field Near Infrared On-Axis AO System (NFIRAOS) 24
2.2.2.21 NFIRAOS Science Calibration Unit (NSCU) 25
2.2.2.22 Laser Guide Star Facility (LGSF) 25
2.2.2.23 Adaptive Optics Executive Software (AOESW) 26
2.2.2.24 Instrumentation Cooling Systems (COOL) 26
2.2.2.25 InfraRed Imaging Spectrometer (IRIS) 26
2.2.2.26 Wide Field Optical Spectrometer (WFOS) 27
2.2.2.27 Infrared Multiple Object Spectrograph (IRMS) 27
2.2.2.28 Common Software 27
2.2.2.29 Communications and Information Systems (CIS) 27
2.2.2.30 Data Management System (DMS) 28
2.2.2.31 Executive Software (ESW) 28

2.2.2.32 Science Operations Support Systems (SOSS) 28
2.2.2.33 Data Processing System (DPS) 28
2.2.2.34 Site Conditions Monitoring System (SCMS) 29

3. PERFORMANCE ALLOCATION AND SYSTEM BUDGETS 30
3.1 Reliability and Availability Budgets 30
3.2 Heat dissipation and Power Consumption budgets 32
3.3 Image Size Error Budget for Seeing Limited Operations 35
3.3.1 On-Axis Budget 35
3.3.2 Off-Axis Budget 41
3.3.3 Elevation Angle Dependence of the Budget 41
3.4 Wavefront Error Budget for Adaptive Optics Operations 41
3.4.1 Facility AO System (NFIRAOS) Error Budget 41
3.4.2 Elevation Angle Dependence of the Budget 46
3.4.3 Wavefront Corrector Stroke Allocation 46
3.5 Pointing Error Budget 47
3.6 Pupil Shift Budget 49
3.7 Plate Scale Stability Budget 49
3.8 Mass Budget 50
3.9 Other Performance Budgets 51
3.9.1 M1CS Actuator Range of Travel Budget 51

4. SYSTEM SPECIFICATION 52
4.1 Telescope 52
4.1.1 Optical Design 52
4.1.2 Aerothermal Considerations 54
4.1.3 Telescope Structure 55
4.1.3.1 General 55
4.1.3.2 Telescope Azimuth Structure 58
4.1.3.3 Telescope Elevation Structure 58
4.1.3.4 Telescope Pier 59
4.1.3.5 Cable Wraps 59
4.1.3.6 Mount Control System and Drives 60
4.1.3.7 Nasmyth Platforms and Instrumentation Support 62
4.1.3.8 Segment Handling Crane 70
4.1.4 Telescope Mirror Optical Coating Requirements 72
4.1.5 M1 Optics System 72
4.1.5.1 General 72
4.1.5.2 Segmentation 73
4.1.5.3 Positioning 75
4.1.6 M2 System 76
4.1.6.1 General 76
4.1.6.2 Removal, Cleaning and Coating 76
4.1.6.3 Control 76
4.1.6.4 Optical Quality 77
4.1.7 M3 System 77
4.1.7.1 General 77
4.1.7.2 Removal, Cleaning and Coating 77
4.1.7.3 Control 77

4.1.7.4 Optical Quality 79
4.1.8 Primary Mirror Control System (M1CS) 79
4.1.9 Alignment and Phasing System (APS) 80
4.1.10 Servicing and Maintenance 82
4.1.10.1 Telescope Structure 82
4.1.10.2 Telescope Optics 82
4.1.10.3 Telescope Controls 83
4.2 Instrumentation 84
4.2.1 General 84
4.2.2 Facility AO System 84
4.2.3 NFIRAOS 86
4.2.3.1 General 86
4.2.3.2 Servicing and Maintenance 86
4.2.4 LGSF 87
4.2.4.1 Servicing and Maintenance 88
4.2.5 Adaptive Optics Executive Software (AOESW) 89
4.2.5.1 General 89
4.2.5.2 Servicing and Maintenance 89
4.2.6 IRIS 90
4.2.6.1 General 90
4.2.6.2 Servicing and Maintenance 90
4.2.7 IRMS 90
4.2.7.1 General 90
4.2.7.2 Servicing and Maintenance 90
4.2.8 WFOS 90
4.2.8.1 General 90
4.2.8.2 Servicing and Maintenance 90
4.3 Services 91
4.3.1 Power, Lighting and Grounding 91
4.3.1.1 General 91
4.3.1.2 Lighting Requirements 93
4.3.1.3 Grounding Requirements 93
4.3.2 Coolant 93
4.3.2.1 General 93
4.3.3 Communications and Information Services (CIS) 94
4.3.3.1 Local Area Network (LAN) 94
4.4 Facilities 96
4.4.1 Enclosure 96
4.4.1.1 General 96
4.4.1.2 Enclosure Geometry 97
4.4.1.3 Slewing 97
4.4.1.4 Wind, Thermal and Environmental Management 98
4.4.1.5 Summit Facility Fixed Base 100
4.4.1.6 Top End Servicing Platform 101
4.4.1.7 Survival Loads 102
4.4.1.8 Enclosure Servicing and Maintenance 103
4.4.2 Summit Facilities 104
4.4.2.1 General 104
4.4.2.2 Mirror Maintenance 104

4.4.2.3 Operations Spaces 104
4.4.2.4 Lab & Shop Spaces 105
4.4.2.5 Personnel Spaces 105
4.4.2.6 Shipping & Receiving 105
4.4.2.7 Mechanical Plant 105
4.4.2.8 Electrical Plant 106
4.4.2.9 Roads & Parking 106
4.4.2.10 Grounding and Lightning Protection 107
4.4.2.11 Fire Protection and Safety 107
4.4.2.12 Summit Facility Servicing and Maintenance 108
4.4.3 Headquarters 108
4.4.3.1 General 108
4.4.3.2 Administration 108
4.4.3.3 Remote Control Room 108
4.4.3.4 Lab & Shop Spaces 108
4.4.3.5 Storage 109
4.4.3.6 Shipping & Receiving 109
4.4.3.7 Mechanical Plant 109
4.4.3.8 Electrical Plant 109
4.4.3.9 Roads & Parking 109
4.5 Servicing and Maintenance 110
4.5.1 Crane Systems 110
4.6 Safety 113
4.6.1 General Requirements on Subsystems 113
4.6.2 Observatory Safety System 113
4.6.2.1 General 113
4.6.2.2 Interlocks 115
4.6.2.3 Emergency Stop (E-Stop) 116
4.6.3 Telescope Safety 117
4.6.3.1 General 117
4.6.4 Enclosure Safety 118
4.6.4.1 General 118
4.6.4.2 Enclosure Safety System 118
4.6.5 Laser Guide Star Facility 118
5. SYSTEM ARCHITECTURE 120
5.1 Observatory Control Architecture 120
5.1.1 Pointing, Offsetting, Tracking, Guiding and Dithering 120
5.1.2 Field De-rotation 122
5.1.3 Atmospheric Dispersion Compensation 123
5.1.4 Active and Adaptive Optics Control Architecture 123
5.1.4.1 General 123
5.1.4.2 Active Optics Actuators 123
5.1.4.3 Active Optics Sensors 124
5.1.4.4 Compensation Strategy 124
5.1.5 Acquisition 126
5.1.5.1 Acquisition Process 126
5.1.5.2 Acquisition Sequences for Different System Configurations 126
5.2 Observatory Software Architecture 127
5.2.1 High-level software system definition 127

5.2.1.1 Observation Execution System (OES) 127
5.2.1.2 Program Execution System (PES) 130
5.2.2 Software system communications backbone 131
5.2.2.1 General communications backbone requirements 131
5.2.2.2 General common services requirements 131
5.2.2.3 Specific common service definitions 132
5.2.3 High-level OES subsystem definition 133
5.2.3.1 General 133
5.2.3.2 Sequencer framework definition 134
5.2.3.3 Defined OES software subsystems 134
5.2.4 High-level PES subsystem definition 136
5.2.4.1 General 136
5.2.4.2 Defined PES software subsystems 136
5.2.5 Local observatory database 137
5.2.6 Data structures 138
5.2.6.1 General 138
5.2.6.2 Science operations business objects 138
5.2.6.3 Observation description 140
5.2.7 Software development framework definition 141

6. DEFINITIONS 143

6.1 Coordinate Systems 143
6.2 Wavelength Bands 148
6.2.1 Astronomical Filters 148
6.2.2 Atmospheric Transmission Windows 149
6.3 Acquisition 151
6.4 Observatory Control Architecture 154
6.5 First Decade Instrument Layout 155
6.6 Enclosure Geometry 156
6.7 Example Mirror Coating Reflectance Curves 157

TABLE OF FIGURES

Figure 1 Optical Configuration of the telescope 52
Figure 2 Pupil obscuration pattern 53
Figure 3. Bound on mount control torque rejection with respect to open-loop. The mount control rejection achieved with the current design is shown for comparison. 61
Figure 4 Allowable image jitter as seen by an instrument mounted on the Nasmyth Platform 62
Figure 5 Nasmyth Platform Reference Instrument Layout (NFIRAOS, IRIS, IRMS and APS at left, WFOS at right) 67
Figure 6 Layout of the segmented primary mirror, as projected on the X-Y plane of the Elevation Coordinate System (ECRS). The capital letters denote identical sectors rotated by 60 degrees relative to each other. 74
Figure 7 Nasmyth positions addressed by the M3 mirror (ECRS axes shown with telescope zenith pointing) 78
Figure 8 Maximum allowable PSD of M1 Segment Motion driven by vibration disturbances 79
Figure 9 LGSF asterisms supporting different AO modes: **NFIRAOS** (black) 1 on-axis, 5 on a 35 arcsec radius; **MIRAO** (red) 3 on a 70 arcsec radius; **MOAO** (blue) 3 on a 70 arcsec radius, 5 on a 150 arcsec radius; **GLAO** (green) 1 on-axis, 4 on a 510 arcsec radius 87
Figure 10 Allowable enclosure vibration PSD 96
Figure 11- Observatory Safety System Architecture, equipment within dotted line indicates scope of OSS 115
Figure 12 Control architecture for seeing limited observations 121
Figure 13 Control architecture for adaptive optics observations 122
Figure 14: Observation execution system (OES) architecture (communication) 128
Figure 15: Observation execution system (OES) architecture (workflow) 128
Figure 16: PES decomposition 130
Figure 17: OES subsystem architecture templates 136
Figure 18: Observatory database architecture 138
Figure 19: Science operations business objects 139
Figure 20: Simple observation block (OB) example 141
Figure 21 The basic coordinate systems of the telescope 147
Figure 22 Tertiary mirror coordinate system (M3CRS) shown in the context of the M1CRS and M2CRSAppendix 147
Figure 23 Near and mid infrared atmospheric transmission windows for 1 mm precipitable water vapor [RD5] 149
Figure 24 Near and mid infrared atmospheric transmission windows for 3 mm precipitable water vapor [RD7] 149
Figure 25 Infrared atmospheric transmission windows for 1 mm precipitable water vapor [RD7] 150
Figure 26 Infrared atmospheric transmission windows for 3 mm water vapor [RD7] 150
Figure 27 Example acquisition scheme for a GLAO system configuration (WFOS). FOV of guide (TT) WFS is large enough to acquire guide star in one step. 151
Figure 28 Example acquisition scheme for a NGS MCAO system configuration (IRIS). FOV of guide (TT) WFS is not enough for blind pointing the telescope on the WFS; Instrument acquisition camera is needed. 152
Figure 29 Example acquisition scheme for a LGS MCAO system configuration (IRIS). Procedure is similar to Figure 28, but for faint guide stars. The faint natural guide stars are enhanced by higher order, LGS based AO correction. 153
Figure 30 Full SAC Instrument Layout 155
Figure 31TMT Enclosure Geometry 156
Figure 32 Gemini coating plus other coatings in development. Dip in reflectivity other coatings is caused by surface Plasmon resonances. 157

LIST OF TABLES

Table 1 TMT System Decomposition 16
Table 2 Observatory Downtime Allocation 31
Table 3 Heat dissipation and power consumption budget for equipment located within enclosure 33
Table 4 Heat dissipation and power consumption budget for equipment located within summit facilities building 34
Table 5 Telescope Image Quality Error Budget 40
Table 6 NFIRAOS RMS wavefront error budget (60 x 60 actuators, on axis) in nm 45
Table 7 OPD budget for the correction of Observatory wavefront error source 47
Table 8 Pointing Error Budget 48
Table 9 Pupil Shift Budget in RMS, assuming a Gaussian distribution with RMS = 1 sigma. 49
Table 10 Telescope budget for stability of plate scale, specified in terms of maximum image motion of any point in the full 20 arcmin diameter field relative to the center of the field. 49
Table 11 Telescope Mass Budget – Requirement is for not to exceed mass, CG and mass moment of inertia are estimates for information only 50
Table 12 M1CS Actuator Range of Travel Budget 51
Table 13 Summary of the optical design 54
Table 14 Maximum Allowable Cross Sectional Area of Telescope Top End 54
Table 15 – Sub-system equipment mounted to telescope structure (excluding instruments) 57
Table 16 Maximum allowable deflection of the telescope top end 59
Table 17 Instrument Volumes (not including electronics cabinets and other support equipment) 64
Table 18 Requirements for M1, M2 and M3 Optical Coatings 72
Table 19 Alignment maintenance mode capture range 81
Table 20 Post-segment exchange mode capture range 82
Table 21 Telescope structure Servicing Requirements 82
Table 22 Telescope Optics Servicing Requirements 83
Table 23 Telescope Controls Servicing Requirements 83
Table 24: Non-common path slope error allocation 85
Table 25 NFIRAOS Servicing Requirements 86
Table 26 LGSF Servicing Requirements 88
Table 27 AOESW Servicing Requirements 89
Table 28 IRIS Servicing Requirements 90
Table 29 IRMS Servicing Requirements 90
Table 30 WFOS Servicing Requirements 90
Table 31 – Power types delivered to enclosure, telescope and telescope mounted equipment and sub-systems 91
Table 32 Observatory coolant supply 93
Table 33 Enclosure Servicing Requirements 103
Table 34 Summit Facility Servicing Requirements 108
Table 35 Telescope azimuth stopping deceleration, time and distance 117
Table 36 Telescope elevation stopping deceleration, time and distance 117
Table 37 Software system user types 129
Table 38: Communications protocol stack 132
Table 39: Common services definition 132
Table 40: Principal TMT software subsystems 135
Table 41: Science operations business objects 139
Table 42 Coordinate systems for the ideal, undisturbed telescope 143

Table 43 Astronomical Filters 148
Table 44 Mount and active optics actuators and corresponding sensors with control bandwidths 154

1. INTRODUCTION

1.1 INTRODUCTION

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

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

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

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

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

1.2 PURPOSE

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

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

1.3 SCOPE

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

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

- Observatory Control Architecture
- Observatory Software Architecture
- Coordinate Systems

1.4 APPLICABLE DOCUMENTS

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

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

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

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

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

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

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

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

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

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

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

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

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

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

AD15 - TMT Interface N^2 Diagram

AD16 - TMT M1 Segmentation Database TMT.OPT.TEC.07.044

AD17 - Ritchey – Chretien Baseline Design TMT.TEL.SEN.SPE.006.001

AD18 - Title 49, Code of Federal Regulations, Transportation: 49 CFR

AD19 - U.S. Department of Energy Handbook on Electrical Safety, draft for R&D: DOE-HDBK-1092-2009

AD20 - Functional Safety – Safety-Related Systems: IEC 61508

AD21 - Metallic Materials and Elements for Aerospace Vehicle Structures: metallic material definitions, formulas, principles, failures, properties, metallurgical joints, and analysis procedures: MIL-HDBK-5J

AD22 - Design Criteria for Controlling Stress Corrosion Cracking: MSFC-SPEC-522B

AD23 - Handbook for Corrosion Prevention and Deterioration Control in Electronic Components and Assemblies: MIL-STD-1250A

AD24 - Fasteners – General Requirements for bolts, screws, studs, and nuts: ISO 8992:1986

AD25 - Standard Specification for Annular Ball Bearings for Instruments and Precision Rotation Components: ASTM F2332-06

AD26 - Lift Sling Design: 540-PG-8719.1.1-A

AD27 - Standard Practice for Performance Testing of Shipping Containers and Systems: ASTM D 4169

AD28 - Standard General Requirements for Safe Design and Operation of Pressurized Missile and Space Systems: MIL-STD-1522A

AD29 - NFPA-75 – Fire Protection for Essential Electronic Equipment

AD30 - National Fire Protection Association (NFPA) – Fire Codes and Handbook of Fire Protection

AD31 - ANSI Z136.1 – Safe Use of Lasers

AD32 - Accident Prevention Manual for Industrial Operations

AD33 - Toxic Substances Control Act (TSCA)

AD34 - TMT Seismic Hazard Analysis (TMT.STR.TEC.10.001.REL01)

1.5 REFERENCE DOCUMENTS

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

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

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

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

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

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

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

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

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

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

RD11 – TMT Co-ordinate Systems and Transforms, TMT.SEN.TEC.07.031

RD12 - **Image Distortion Budget Spreadsheet** TMT.TEL.TEC.09.001.

RD13 - TMT Telescope Structure Cable Wrap Requirements TMT.STR.TEC.08.039

RD14 - TMT Power and Cooling Budget TMT.SEN.TEC.08.054

RD15 - B-J Seo *et al*., "Normalized Point Source Sensitivity for Off-Axis Optical Performance Evaluation of the Thirty Meter Telescope" Proc. SPIE **7738** 77380G, 2010. TMT.SEN.TEC.09.041.DRF01

1.6 CHANGE RECORD

Revision	Date	Section	Modifications
CCR25	June 6th 2012		• Incorporated Change Request 106. Updates as per Level 1 DRD Change History Document, TMT.SEN.TEC.07.038.REL10
CCR24	October 12th 2011		• Incorporated Change Request2 50, 87, 90 and 93. Updates as per Level 1 DRD Change History Document, TMT.SEN.TEC.07.038.REL09
CCR23	Dec 1st 2010		• Incorporated Change Request 80. Updates as per Level 1 DRD Change History Document, TMT.SEN.TEC.07.038.REL08
CCR22	April 27th 2010		• Incorporated Change Requests 062, 070, 071 and 072. Updates as per Level 1 DRD Change History Document, TMT.SEN.TEC.07.038.REL07
CCR21	December 17th 2009		• Incorporated Change Requests 31, 42, 57 and 60. Updates as per Level 1 DRD Change History Document, TMT.SEN.TEC.07.038.REL06
CCR20	March 27 2009		• Updates as per Level 1 DRD Change History Document, TMT.SEN.TEC.07.038.REL05
CCR19	January 28' 2009		• Updates as per Level 1 DRD Change History Document, TMT.SEN.TEC.07.038.REL04
CCR18	September 4, 2008		• Updates as per Level 1 DRD Change History Document, TMT.SEN.TEC.07.038.REL03
CCR 17	March 19, 2008		• Updates as per Level 1 DRD Change History Document, TMT.SEN.TEC.07.038.REL02

CCR 16	November 14, 2007		• Updates as per Level 1 DRD Change History Document, TMT.SEN.TEC.07.038.REL01
CCR 15	October 19, 2007		• Updates as per systems engineering watch list document TMT.SEN.TEC.07.025.REL14
CCR 14	August 14, 2007	3.4.3 4.1.2 4.1.3.3 4.1.3.7.1 4.1.3.7.5 4.1.3.7.7 4.1.3.7.12 4.1.5.1 4.1.5.2 4.1.6.1 4.2.2 4.2.4 4.3.2.1 4.4.1.4 4.5.1 4.6.4.1	• Change to REQ-1-OAD-0595 • Added REQ-1-OAD-1080, 1085 • Change to REQ-1-OAD-1310 • Modification to discussion point after REQ-1-OAD-1385. • Update to REQ-1-OAD-1460 • Added REQ-1-OAD-1461, 1467, 1472, 1473, 1482 • Addition of REQ-1-OAD-1492 • Added REQ-1-OAD-1580, 1585, 1590 • Added REQ-1-OAD-1692, 1694 • Updated Figure 6 (Primary Mirror Layout) • Deleted REQ-1-OAD-1810, 1815 • Change to REQ-1-OAD-2760 • Change to REQ-1-OAD-2940 • Added REQ-1-OAD-4705, 4710 • Added REQ-1-OAD-5257, 5258 • Update of Crane System requirements, Requirements REQ-1-OAD-6200 through 6275. • Added REQ-1-OAD-7230, 7235
CCR13	May 25, 2007	4.1.2.5 4.1.2.7.2 4.1.2.7.2 4.1.2.7.1	• *Updates as per proposed errata and updates as documented in TMT.SEN.TEC.07.025.DRF05, including:* ▪ Add Cable Wrap requirements. ▪ Update Table 8 to include WIRC and planned 1st decade instrument positions on NFIRAOS. ▪ Update OAD requirement [REQ-1-OAD-1415] to include WIRC ▪ Update of equation in [REQ-1-OAD-1385]

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

1.7 ABBREVIATIONS

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

2. SYSTEM DEFINITION

2.1 GENERAL

[REQ-1-OAD-0010] All dimensions contained within this document apply when the sub-systems are at their expected steady state operating temperature during observing and the ambient temperature is equal to the median nighttime temperature for the site (T=275.3K).

2.2 OBSERVATORY SYSTEM DECOMPOSITION

2.2.1 System Decomposition

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

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

[REQ-1-OAD-0110] The interfaces between the subsystems shall be as defined in [AD15] TMT Interface N^2 Diagram

Table 1 TMT System Decomposition

System	**Related WBS Element(s)**
Enclosure (ENC)	TMT.FAC.ENC
Summit Facilities (SUM)	TMT.FAC.INF.SUM
Road (ROAD)	TMT.FAC.INF.ROAD
Observatory Headquarters (HQ)	TMT.FAC.INF.HQ
Telescope Structure (STR)	TMT.TEL.STR
M1 Optics System (M1)	TMT.TEL.OPT.M1
M2 System (M2)	TMT.TEL.OPT.M2
M3 System (M3)	TMT.TEL.OPT.M3
Optical Cleaning Systems (CLN)	TMT.TEL.OPT.CLN
Optical Coating System (COAT)	TMT.TEL.OPT.COAT
Test Instruments (TINS)	TMT.TEL.OPT.TINS
Optics Handling Equipment (HNDL)	TMT.TEL.OPT.HNDL
Alignment and Phasing System (APS)	TMT.TEL.CONT.APS
Telescope Control System (TCS)	TMT.TEL.CONT.TCS
Mount Control System (MCS)	TMT.TEL.CONT.MCS
M1 Control System (M1CS)	TMT.TEL.CONT.M1CS
Test Instrument Control (TINC)	TMT.TEL.CONT.TINC
Observatory Safety System (OSS)	TMT.TEL.CONT.OSS
Engineering Sensors (ESEN)	TMT.TEL.CONT.ESEN
Power, Lighting, and Grounding (PL&G)	TMT.TEL.CONT.POWR

Narrow Field Near Infrared On-Axis AO System (NFIRAOS)	TMT.INS.AO.NFIRAOS TMT.INS.AO.COMP.PCVWFS.NFIRAOS, TMT.INS.AO.COMP.RTC.NFIRAOS, TMT.INS.AO.COMP.WC.NFIRAOS
NFIRAOS Science Calibration Unit (NSCU)	TMT.INS.INST.NSCU
Laser Guide Star Facility (LGSF)	TMT.INS.AO.LGSF, TMT.INS.AO.COMP.SLASR
Adaptive Optics Executive Software (AOESW)	TMT.INS.AO.AOESW
Instrumentation Cooling System (COOL)	TMT.INS.COOL
InfraRed Imaging Spectrometer (IRIS)	TMT.INS.INST.IRIS TMT.INS.AO.COMP.IRWFS.IRIS
Wide Field Optical Spectrometer (WFOS)	TMT.INS.INST.WFOS
IRMS/MOSFIRE (IRMS)	TMT.INS.INST.IRMS TMT.INS.AO.COMP.IRWFS.IRMS
Communications and Information Systems (CIS)	TMT.DEOPS.CIS
Common Software (CSW)	TMT.DEOPS.OSW.CSW
Data Management System (DMS)	TMT.DEOPS.OSW.DMS
Executive Software (ESW)	TMT.DEOPS.OSW.ESW
Science Operations Support Systems (SOSS)	TMT.DEOPS.OSW.SOSS
Data Processing System (DPS)	TMT.DEOPS.OSW.DPS
Site Conditions Monitoring System (SCMS)	TMT.DEOPS.SCMS

2.2.2 System decomposition element descriptions

2.2.2.1 Enclosure (ENC)

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

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

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

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

Enclosure mounted cranes and hoists enable service and handling of large components inside the enclosure. The enclosure incorporates components to provide adequate safety for the observatory personnel and visitors including local and global e-stops, sensors and wiring that interface with the observatory safety system. The enclosure also includes the M2 servicing platform and lighting.

2.2.2.2 Summit Facilities (SUM)

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

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

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

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

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

2.2.2.3 Road (ROAD)

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

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

This is the access road between an existing public road and the TMT observatory. This road will be an improved gravel road with a width that allows two vehicles to meet or pass without either vehicle having to pull off the road, has a surface and alignment to permit reasonable driving speeds, allows for future paving of the surface, and has curves with sufficiently large radii so that large trucks may easily negotiate the curves. The road will be unpaved except where necessary to prevent generating dust around existing observatories.

2.2.2.4 Observatory Headquarters (HQ)

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

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

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

2.2.2.5 Telescope Structure (STR)

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

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

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

The Stationary Structures include the azimuth track, pintle bearing assembly, a raised service walkway inside the pier, elements of the seismic restraint, a raised azimuth walkway outside the pier and stationary elevator(s) from the observing floor to the level of the azimuth walkway. The Azimuth Structure includes the central structure, Nasmyth platforms, instrument support structures, aerial service platform, elements of the seismic restraint, telescope elevator(s), access walkways, stairways and safety barriers. The Elevation Structure includes the lower tube structure, elevation journals, mirror cell, segment handling system, upper tube structure and walkways to access the LGSF components and mirror cell.

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

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

The Telescope Utility Services include the azimuth and elevation cable wraps, cable trays and pipe racks throughout the telescope, and the utility lines to supply electrical power, chilled water and compressed air to the main portions of the telescope at dedicated connection panel locations. Not included in the utility services are lines supplying cryogenic and refrigerant coolant to the science instruments (these are part of the instrument cooling system)

2.2.2.6 M1 Optics System (M1)

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

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

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

2.2.2.7 M2 System (M2)

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

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

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

2.2.2.8 M3 System (M3)

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

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

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

2.2.2.9 Optical Cleaning Systems (CLN)

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

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

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

2.2.2.10 Optical Coating System (COAT)

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

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

The Optical Coating system includes the coating chamber with its associated equipment (vacuum pumps, magnetrons, etc.), the equipment used to remove the old reflective coating and wash and dry the mirror, coating laboratory instruments, and fixtures used to support the mirrors during washing and in the coating chamber. It does not include the mirror handling equipment, which is included in Optics Handling Equipment. It also does not include the coating laboratory facility equipment (air compressors, cranes, sinks, drains & sumps or fume hoods) or the utilities for the coating chamber, which are included in Summit Facilities. Safety equipment including local and global e-stops and any sensors and wiring that interface with the Observatory Safety System will be provided.

2.2.2.11 Test Instruments (TINS)

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

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

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

2.2.2.12 Optics Handling Equipment (HNDL)

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

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

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

2.2.2.13 Alignment and Phasing System (APS)

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

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

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

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

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

APS will have an acquisition camera with a 1 to 2 arcminute field of view which can be used for telescope pointing, acquisition, and tracking tests. APS will also provide an optical port where a guider camera and a low order wavefront sensor can be placed in order to test its performance and to validate the active optics control algorithms.

APS will provide an expert user GUI.

2.2.2.14 Telescope Control System (TCS)

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

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

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

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

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

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

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

The TCS includes an expert user GUI.

2.2.2.15 M1 Control System (M1CS)

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

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

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

The M1CS is a distributed control system that includes actuators for 492 segments, sensors for 574 segments (includes sensors for spare segments), electronics mounted and distributed on the telescope mirror cell, telescope and segment mounted cabling, telescope mounted power supplies, a communications bus, control software, and associated computer processing hardware. The M1CS also controls the M1 warping harness actuators and reads the warping harness strain gauges.

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

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

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

2.2.2.16 Test Instrument Control (TINC)

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

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

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

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

The GMS will include an expert user GUI.

2.2.2.17 Observatory Safety System (OSS)

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

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

The Observatory Safety System (OSS) contributes to the enforcement of safe conditions throughout the summit facility by continuously monitoring the state of connected equipment, systems and sensors and taking appropriate action as soon as an unsafe condition is detected. It is independent from and supplementary to any safety systems and functionality that is contained within individual subsystems. Based on one or more

Programmable Logic Controllers (PLCs), it will interface with connected subsystems via dedicated fail-safe signals; monitor interlock requests and possibly a defined subset of additional signals from all connected subsystems; monitor the emergency stop switches located throughout the summit facility; generate interlock demands to observatory subsystems; provide a user interface enabling fault and interlock visualization and reset: communicate the state of all connected subsystems to, at a minimum, the Data Management System (DMS) & Executive Software (ESW).

The OSS includes one or more centralized PLCs, remote I/O (RIO) modules necessary for interfacing to connected subsystems, a user interface and any independent sensors and warning devices that do not fall directly under a defined subsystem. It does not include fire suppression systems, emergency lighting or the individual emergency stop buttons and wiring. These are the responsibility of the individual subsystems.

2.2.2.18 Engineering Sensors (ESEN)

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

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

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

The ESEN system will include an expert user GUI.

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

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

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

The PL&G system will provide electrical panels and distribution boxes at the following locations on the telescope structure: +X and –X Nasmyth platforms, +X and –X elevation journals, M3 support tower and telescope top end. . Both clean and dirty power will be distributed. Dedicated primary power will be made available, at a minimum for the following systems; Instruments and AO systems, Telescope Drives, Laser System, Cable Wraps, Laser Launch Telescope, M1, M2, and the M3 systems; and the Beam Transfer Optics. General utility power will be made available via industry standard keyed and color coded power outlets. Single and Three Phase power will be available The wiring from the summit facility tunnel to these distribution locations is not part of the PL&G system but is provided by the telescope structure.

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

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

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

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

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

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

2.2.2.21 NFIRAOS Science Calibration Unit (NSCU)

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

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

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

2.2.2.22 Laser Guide Star Facility (LGSF)

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

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

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

2.2.2.23 Adaptive Optics Executive Software (AOESW)

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

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

2.2.2.24 Instrumentation Cooling Systems (COOL)

[REQ-1-OAD-0201] The Instrumentation Cooling System decomposition element is defined as follows:

The Instrumentation Cooling Systems includes the refrigerant and cryogenic cooling systems provided for TMT science instruments and AO systems (WFOS, IRIS, IRMS and NFIRAOS). The instrumentation refrigerant cooling system includes all compressors, condensors, heat exchangers and other components in the summit facilities building; the distribution systems located between these components and the instruments/AO systems on the Nasmyth platforms; the purging and filling apparatus for servicing and re-charging instrumentation prior to connection with the refrigerant system. The instrumentation cryogenic cooling system includes all compressors, heat exchangers, pumps and other components in the summit facilities building and the distribution system located between these components and the instruments on the Nasmyth platforms. It does not include the cold heads in the instruments themselves; these are included as part of the individual science instruments.

The Instrumentation Cooling System does not include water/glycol coolant systems. Water/glycol coolant systems required for the instruments and guidestar lasers are part of the Observatory chilled water/glycol cooling systems.

2.2.2.25 InfraRed Imaging Spectrometer (IRIS)

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

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

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

2.2.2.26 Wide Field Optical Spectrometer (WFOS)

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

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

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

2.2.2.27 Infrared Multiple Object Spectrograph (IRMS)

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

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

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

2.2.2.28 Common Software

[REQ-1-OAD-0210] The CSW system decomposition element is defined as follows:

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

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

2.2.2.29 Communications and Information Systems (CIS)

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

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

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

2.2.2.30 Data Management System (DMS)

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

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

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

2.2.2.31 Executive Software (ESW)

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

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

The Executive Software (ESW) subsystem includes the software tools necessary for efficient TMT operations. Specifically, the ESW contains the master system sequencer, which enables synchronized operation of all TMT subsystems. ESW includes user interfaces for control and monitoring of TMT subsystems and overall environmental conditions. This subsystem enables the execution of observations (both classical and queue) for on-site and remote observers.

2.2.2.32 Science Operations Support Systems (SOSS)

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

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

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

2.2.2.33 Data Processing System (DPS)

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

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

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

2.2.2.34 Site Conditions Monitoring System (SCMS)

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

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

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

3. PERFORMANCE ALLOCATION AND SYSTEM BUDGETS

3.1 RELIABILITY AND AVAILABILITY BUDGETS

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

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

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

Table 2 Observatory Downtime Allocation

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

3.2 HEAT DISSIPATION AND POWER CONSUMPTION BUDGETS

Discussion: The peak loads listed within Table 3 and Table 4 are the sum of the individual peak loads of all subcomponents within a subsystem. This total is higher than the total allowed contribution to demand load for some subsystems, in particular, the ENC and SUM which each consist of many subcomponents whose loads are not all coincident.

Discussion: The definition of the power types used is contained in Table 31

Requirement Number	Item name	Peak Load (kW)	Contribution to system Demand Load (kW)	Backup Generator Connected Load (kW)	UPS Connected Load (kW)	Nighttime power dissipated to building air (kW)	Nighttime power dissipated to water-glycol (kW)	Daytime power dissipated to building air (kW)	Daytime power dissipated to water-glycol (kW)	Expected annualized average power consumption (kW)	Subcomponents connected to UPS	Additional subcomponents connected to backup generator	Power types used
[REQ-1-OAD-0900]	Enclosure (ENC)	1473.2	830.5	998.6	23.4	0.8	0.0	9.0	0.0	71.6	I/O panels	Cap drives, Shutter, Outer vent doors, aperture flaps, shutter locks and seals, cranes, dome plug, some general lighting	L1CUG H3D H3DG
[REQ-1-OAD-0901]	Summit Facilities (SUM)	164.1	126.1	3.0	0.0	0.0	0.0	1.3	105.7	39.5	None	Segment storage crane	L1C L3D L3DG H3D
[REQ-1-OAD-0902]	Observatory Safety System (OSS)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0			
[REQ-1-OAD-0903]	Telescope structure (STR)	289.5	246.4	63.5	3.0	0.8	11.4	2.7	6.4	12.3	Some computing	Segment handling cranes, nasmyth platform cranes, elevator.	L1CUG L3D L3DG H3D H3DG
[REQ-1-OAD-0904]	M1 Optics System (M1)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	None	None	
[REQ-1-OAD-0905]	M2 System (M2)	2.6	1.8	0.0	0.0	0.6	1.2	0.0	0.0	0.9	None	None	L1C
[REQ-1-OAD-0906]	M3 System (M3)	2.4	1.7	0.0	0.0	0.4	1.3	0.0	0.0	0.8	None	None	L1C
[REQ-1-OAD-0907]	Optical Cleaning Systems (CLN)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	None	None	
[REQ-1-OAD-0908]	Optical Coating System (COAT)	35.0	0.0	2.0	2.0	4.0	16.0	4.0	16.0	0.8	Controls equipment	None	L1C L1CUG L3D H3D
[REQ-1-OAD-0909]	Test Instruments (TINS)	0.8	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	None	None	L1C
[REQ-1-OAD-0910]	Optics Handling Equipment (HNDL)	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	None	None	L3D
[REQ-1-OAD-0911]	Alignment and Phasing System (APS)	4.9	0.0	2.8	2.8	0.0	0.8	0.0	0.4	0.2	Computers on telescope	None	L1C L1CUG L3D
[REQ-1-OAD-0912]	Telescope Control System (TCS)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	None	None	
[REQ-1-OAD-0914]	M1 Control System (M1CS)	12.5	12.5	15.0	15.0	10.0	2.5	10.0	2.5	12.5	Entire subsystem		L3CUG
[REQ-1-OAD-0915]	Test Instrument Control (TINC)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	None	None	
[REQ-1-OAD-0916]	Engineering Sensors (ESEN)	1.1	1.0	0.7	0.7	0.6	0.0	0.6	0.0	1.1	Sensors and computer	None	L1C L1CUG
[REQ-1-OAD-0917]	Power, Lighting, and Grounding (PL&G)	129.0	57.6	10.0	0.0	2.7	0.0	20.4	0.0	7.2	None	Telescope lighting	L3C L3D L3DG
[REQ-1-OAD-0918]	Narrow Field Near Infrared On-Axis AO System (NFIRAOS)	33.1	22.6	1.5	1.5	0.2	6.6	0.1	3.2	4.6	A subset of the electronics cabinet	None	L1C L3C L3CUG H3D
[REQ-1-OAD-0919]	NFIRAOS Science Calibration Unit (NSCU)	1.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	None	None	L1C
[REQ-1-OAD-0920]	Laser Guide Star Facility (LGSF)	74.0	71.5	0.0	0.0	0.9	35.2	0.1	0.0	14.9	None	None	L1C L3C L3D H3D
[REQ-1-OAD-0921]	Adaptive Optics Executive Software (AOESW)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	None	None	
[REQ-1-OAD-0922]	Instrumentation Cooling (COOL)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	None	None	
[REQ-1-OAD-0923]	Infrared Imaging Spectrometer (IRIS)	6.0	6.0	3.0	3.0	0.2	3.4	0.2	2.2	2.5	Electronics	None	L1C L1CUG
[REQ-1-OAD-0924]	Wide Field Optical Spectrometer (WFOS)	3.0	3.0	3.0	3.0	0.2	2.1	0.2	1.3	1.9	Electronics	None	L1CUG
[REQ-1-OAD-0925]	IRMS/MOSFIRE (IRMS)	1.9	1.9	1.9	1.9	0.1	1.4	0.1	1.2	1.2	Electronics	None	L1CUG
[REQ-1-OAD-0926]	High Resolution Optical Spectrometer (HROS)	20.0	15.0	7.0	2.0	0.3	14.8	0.3	9.8	10.3	Electronics	TBD	L1CUG L3C L3D L3DG
[REQ-1-OAD-0927]	Near-Infrared Multi-Object Sectrometer (IRMOS)	7.0	7.0	2.0	2.0	0.0	4.0	0.0	2.6	2.9	Electronics	None	L1C L1CUG
[REQ-1-OAD-0928]	Planet Formation Instrument (PFI)	8.0	0.0	2.0	2.0	0.3	2.1	0.3	2.1	2.0	Electronics	None	L1C L1CUG
[REQ-1-OAD-0929]	Mid-Infrared AO System (MIRAO)	1.5	1.5	1.5	1.5	0.1	0.7	0.1	0.4	0.5	Electronics	None	L1CUG
[REQ-1-OAD-0930]	Mid-Infrared Echelle Spectrometer (MIRES)	2.0	2.0	2.0	2.0	0.1	0.7	0.1	0.5	0.6	Electronics	None	L1CUG
[REQ-1-OAD-0931]	Near Infrared Echelle Spectrometer (NIRES-B)	1.5	1.5	1.5	1.5	0.1	0.8	0.1	0.5	0.6	Electronics	None	L1CUG
[REQ-1-OAD-0932]	Near Infrared Echelle Spectrometer (NIRES-R)	1.5	1.5	1.5	1.5	0.1	0.5	0.1	0.5	0.5	Electronics	None	L1CUG
[REQ-1-OAD-0933]	Wide-field Infrared Camera (WIRC)	1.9	1.9	1.9	1.9	0.1	1.4	0.1	1.2	0.0	Electronics	None	L1CUG
[REQ-1-OAD-0934]	Communications and Information Systems (CIS)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	None	None	
[REQ-1-OAD-0935]	Common Software (CSW)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	None	None	
[REQ-1-OAD-0936]	Data Management System (DMS)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	None	None	
[REQ-1-OAD-0937]	Executive Software (ESW)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	None	None	
[REQ-1-OAD-0938]	Science Operations Support Systems (SOSS)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	None	None	
[REQ-1-OAD-0939]	Data Processing System (DPS)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	None	None	
[REQ-1-OAD-0940]	Site Conditions Monitoring System (SCMS)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	None	None	

Table 3 Heat dissipation and power consumption budget for equipment located within enclosure

Requirement Number	Item name	Peak Load (kW)	Contribution to system Demand Load (kW)	Backup Generator Connected Load (kW)	UPS Connected Load (kW)	Nighttime power dissipated to building air (kW)	Nighttime power dissipated to water-glycol (kW)	Daytime power dissipated to building air (kW)	Daytime power dissipated to water-glycol (kW)	Expected annualized average power consumption (kW)	Subcomponents connected to UPS	Additional subcomponents connected to backup generator	Power types used
[REQ-1-OAD-0941]	Enclosure (ENC)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	None	None	
[REQ-1-OAD-0942]	Summit Facilities (SUM)	805.6	620.4	526.6	2.0	22.9	35.1	69.0	29.1	299.2	Selected wall outlets in the Engineering lab	Selected pumps, chillers, air handlers, fans, cranes	L1C L1CUG L3D L3DG H3D H3DG
[REQ-1-OAD-0943]	Observatory Safety System (OSS)	1.5	1.2	1.5	1.5	1.2	0.0	0.8	0.0	1.0	All computing	None	L1CUG
[REQ-1-OAD-0944]	Telescope structure (STR)	36.8	25.9	0.0	0.0	0.6	33.8	0.1	3.4	20.2	None	None	H3D
[REQ-1-OAD-0945]	M1 Optics System (M1)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	None	None	
[REQ-1-OAD-0946]	M2 System (M2)	1.5	1.2	1.5	1.5	1.2	0.0	0.6	0.0	0.9	All computing	None	L1CUG
[REQ-1-OAD-0947]	M3 System (M3)	1.5	1.2	1.5	1.5	1.2	0.0	0.6	0.0	0.9	All computing	None	L1CUG
[REQ-1-OAD-0948]	Optical Cleaning Systems (CLN)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	None	None	
[REQ-1-OAD-0949]	Optical Coating System (COAT)	88.4	88.4	1.0	1.0	8.7	26.4	14.3	30.8	36.4	Monitoring and controls	None	L1C L1CUG L3D H3D
[REQ-1-OAD-0950]	Test Instruments (TINS)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	None	None	
[REQ-1-OAD-0951]	Optics Handling Equipment (HNDL)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	None	None	
[REQ-1-OAD-0952]	Alignment and Phasing System (APS)	6.0	0.6	6.0	6.0	1.0	0.0	0.5	0.0	0.8	All computing	None	L1CUG
[REQ-1-OAD-0953]	Telescope Control System (TCS)	1.5	1.2	1.5	1.5	1.2	0.0	1.2	0.0	1.2	All computing	None	L1CUG
[REQ-1-OAD-0955]	M1 Control System (M1CS)	1.5	1.2	1.5	1.5	1.2	0.0	0.8	0.0	1.0	All computing	None	L1CUG
[REQ-1-OAD-0956]	Test Instrument Control (TINC)	1.5	1.2	1.5	1.5	1.2	0.0	0.8	0.0	1.0	All computing	None	L1CUG
[REQ-1-OAD-0957]	Engineering Sensors (ESEN)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	None	None	
[REQ-1-OAD-0958]	Power, Lighting, and Grounding (PL&G)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	None	None	
[REQ-1-OAD-0959]	Narrow Field Near Infrared On-Axis AO System (NFIRAOS)	4.9	3.9	4.9	4.9	2.5	0.0	1.5	0.0	2.0	All computing	None	L1CUG
[REQ-1-OAD-0960]	NFIRAOS Science Calibration Unit (NSCU)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	None	None	
[REQ-1-OAD-0961]	Laser Guide Star Facility (LGSF)	6.8	5.0	2.8	2.8	3.4	0.0	0.8	0.0	1.9	Computing	None	L1CUG H3D
[REQ-1-OAD-0962]	Adaptive Optics Executive Software (AOESW)	1.4	1.1	1.4	1.4	0.7	0.0	0.4	0.0	0.6	All computing	None	L1CUG
[REQ-1-OAD-0963]	Instrumentation Cooling (COOL)	90.0	75.0	60.0	0.0	6.8	61.8	6.7	61.8	65.9	None	Helium compressors	H3D H3DG
[REQ-1-OAD-0964]	Infrared Imaging Spectrometer (IRIS)	1.5	1.2	1.5	1.5	0.8	0.0	0.5	0.0	0.6	All computing	None	L1CUG
[REQ-1-OAD-0965]	Wide Field Optical Spectrometer (WFOS)	1.5	1.2	1.5	1.5	0.8	0.0	0.5	0.0	0.6	All computing	None	L1CUG
[REQ-1-OAD-0966]	IRMS/MOSFIRE (IRMS)	1.5	1.2	1.5	1.5	0.8	0.0	0.5	0.0	0.6	All computing	None	L1CUG
[REQ-1-OAD-0967]	High Resolution Optical Spectrometer (HROS)	1.5	1.2	1.5	1.5	0.8	0.0	0.5	0.0	0.6	All computing	None	L1CUG
[REQ-1-OAD-0968]	Near-Infrared Multi-Object Sectrometer (IRMOS)	3.0	2.4	3.0	3.0	1.5	0.0	0.9	0.0	1.2	All computing	None	L1CUG
[REQ-1-OAD-0969]	Planet Formation Instrument (PFI)	3.0	2.4	3.0	3.0	1.5	0.0	0.9	0.0	1.2	All computing	None	L1CUG
[REQ-1-OAD-0970]	Mid-Infrared AO System (MIRAO)	1.5	1.2	1.5	1.5	0.8	0.0	0.5	0.0	0.6	All computing	None	L1CUG
[REQ-1-OAD-0971]	Mid-Infrared Echelle Spectrometer (MIRES)	1.5	1.2	1.5	1.5	0.8	0.0	0.5	0.0	0.6	All computing	None	L1CUG
[REQ-1-OAD-0972]	Near Infrared Echelle Spectrometer (NIRES-B)	1.5	1.2	1.5	1.5	0.8	0.0	0.5	0.0	0.6	All computing	None	L1CUG
[REQ-1-OAD-0973]	Near Infrared Echelle Spectrometer (NIRES-R)	1.5	1.2	1.5	1.5	0.8	0.0	0.5	0.0	0.6	All computing	None	L1CUG
[REQ-1-OAD-0974]	Wide-field Infrared Camera (WIRC)	1.5	1.2	1.5	1.5	0.8	0.0	0.5	0.0	0.0	All computing	None	L1CUG
[REQ-1-OAD-0975]	Communications and Information Systems (CIS)	4.0	3.2	4.0	4.0	3.2	0.0	3.2	0.0	3.2	All computing	None	L1CUG
[REQ-1-OAD-0976]	Common Software (CSW)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	None	None	
[REQ-1-OAD-0977]	Data Management System (DMS)	4.0	3.2	4.0	4.0	3.2	0.0	2.4	0.0	2.8	All computing	None	L1CUG
[REQ-1-OAD-0978]	Executive Software (ESW)	6.4	5.1	6.4	6.4	4.4	0.0	4.2	0.0	4.2	Operations control room computers	None	L1CUG
[REQ-1-OAD-0979]	Science Operations Support Systems (SOSS)	1.5	1.2	1.5	1.5	1.2	0.0	0.8	0.0	1.0	All computing	None	L1CUG
[REQ-1-OAD-0980]	Data Processing System (DPS)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	None	None	
[REQ-1-OAD-0981]	Site Conditions Monitoring System (SCMS)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	None	None	

Table 4 Heat dissipation and power consumption budget for equipment located within summit facilities building

3.3 IMAGE SIZE ERROR BUDGET FOR SEEING LIMITED OPERATIONS

3.3.1 On-Axis Budget

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

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

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

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

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

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

A more detailed discussion of PSS_N is in [RD4]

Discussion: The error categories of the budget are explained below as Notes to Table 5.

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

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

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

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

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

This error term is the static residual figure error at the telescope calibration zenith angle and temperature, except for the low order passive support errors that change with telescope zenith angle.

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

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

Non-repeatable support system errors are covered in M1-D. Low order, gravity dependent support system fabrication and installation errors are covered in M1-A. The effect of imperfect polishing out of print through bumps at the calibration zenith angle is included in M2-A (residual polishing error).M1-D ***Segment Drift Errors*** *capture all the errors associated with (i) uncertainties of the system state at segment shape measurements (LUT generation), (ii) system state drift between 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 M1-A, M1-B, M1-E, and M1-F.*

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

M1-F ***Segment Out-of-Plane Displacement*** *accounts for the optical effects of quasi-static segment rigid body misalignment perpendicular to the theoretical primary mirror surface, in other words segment tip/tilt/piston. These errors are the results of (i) APS measurement and estimation errors, both correlated (atmospheric residual) and uncorrelated (optical sensor noise), (ii) edge sensor calibration and linearity errors, (iii) quasi static wind pressure, and (iv) other potential control loop errors. It's worth to note that this error category may contain global M1 shape errors, besides the local segment to segment displacements. The errors in correcting M2 and M3 shapes and telescope collimation by M1 are accounted for in M2-A, M3-A, and COLL, respectively. M1-G* ***Segment Dynamic***

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

M2-A ***M2 Residual Figure Error** accounts for image degradation due to the non-perfect shape of M2, including (i) residual polishing errors, (ii) uncertainty in the optics shop acceptance testing, (iii) effects of the temperature change between optics shop testing and observatory operation, and (iv) effects of mirror warping from coating stress.*

These figure errors are partially compensated by M1 shape, based on a Look-Up-Table (LUT) derived from measurements made by the APS as well as on Telescope Optical Feedback System (TOFS) measurements, with the following residuals : (i) fitting errors, and (ii) increased APS wavefront measurement and estimation errors (delta above the APS measurement and estimation errors if the M2 shape were perfect). For the low (2^{nd} and 3^{rd}) order components of the surface errors, the measurement and estimation errors are determined by TOFS, instead of APS.

This error term is the static residual figure error at the telescope calibration zenith angle and temperature.

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

M2-C ***M2 Shape Drift Errors** capture all the errors associated with (i) uncertainties of the 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 M2-B, M2-D, and M2-E.*

M2-D ***M2 Support Print Through** accounts for surface distortions associated with the axial and lateral support structure, including (i) fabrication and installation tolerances, and (ii) the effect of glass weight.*

These figure errors are partially compensated by M1 shape, based on a Look-Up-Table (LUT) derived from measurements made by the APS at multiple zenith angles as well as on TOFS measurements, with the following residuals: (i) fitting errors, and (ii) increased APS wavefront measurement and estimation errors (delta above the APS measurement and estimation errors if the M2 shape were perfect). For the low (2^{nd} and 3^{rd}) order components of the surface errors, the measurement and estimation errors are determined by TOFS, instead of APS.

Non-repeatable support system errors are covered in M2-C. The effect of imperfect polishing out of print through bumps at the calibration zenith angle is included in M2-A.

M2-E ***M2 Dynamic Shape Residual** includes residuals caused by (i) wind buffeting reacted at the support system, and (ii) equipment and microseismic vibrations.*

M3-A ***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.

M3-B ***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.*

M3-C ***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 M3-B, M3-D, and M3-E.*

M3-D ***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 M3-C. The effect of imperfect polishing out of print through bumps at the calibration zenith angle is included in M3-A.

M3-E ***M3 Dynamic Shape Residual*** *includes residuals caused by (i) wind buffeting reacted at the support system, and (ii) equipment and microseismic vibrations.*

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, and (ii) TOFS wavefront measurement and estimation errors.

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 (i) tip/tilt noise of the guide sensor, and (ii) local sensor and actuator dynamic noise. The budget breaks down the errors into the degrees of freedom having noticeable effect on image jitter. While the position of M1 (as a whole) is defined against the sky (pointing), M2, M3, and the instruments are positioned relative to M1.*

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

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

DBLUR ***Dynamic Blur Residual*** *accounts for all optical surface rigid body motions due to wind, vibration, and control noise that result in image blur. The effect of segment rigid body motion is not contained here, only the motion of M1 as a whole. As both the mount control system and the guiding system reduce this blur, this error category includes the dynamic residuals only.*

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

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

Table 5 Telescope Image Quality Error Budget

Requirement #	Description	Error allocation				Wavefront Error Allocation after AO (NFIRAOS) Correction [nm_{RMS}]				Notes
[REQ-1-OAD-0400]	System (up to the Nasmyth Focus)	0.8500				50.0				
[REQ-1-OAD-0402]	Thermal (mirror and dome) seeing		0.9750				18.4			T-A
[REQ-1-OAD-0404]	Optical surface shapes		0.8986				38.5			
[REQ-1-OAD-0406]	M1 shape			0.9214				36.0		
[REQ-1-OAD-0408]	Segment residual figure error				0.9650				26.3	M1-A
[REQ-1-OAD-0410]	Segment thermal distortion				0.9980				3.5	M1-B
[REQ-1-OAD-0412]	Segment support print through				0.9762				18.2	M1-C
[REQ-1-OAD-0414]	Segment drift errors				0.9999				0.5	M1-D
[REQ-1-OAD-0416]	Segment in-plane displacement				0.9998				1.4	M1-E
[REQ-1-OAD-0418]	Segment out-of-plane residual				0.9910				10.2	M1-F
[REQ-1-OAD-0420]	Segment dynamic displacement residual				0.9894				12.3	M1-G
[REQ-1-OAD-0422]	M2 shape			0.9872				10.7		
[REQ-1-OAD-0424]	M2 residual figure error				0.9900				10.5	M2-A
[REQ-1-OAD-0426]	M2 thermal distortion				0.9984				0.9	M2-B
[REQ-1-OAD-0428]	M2 shape drift errors				0.9999				0.5	M2-C
[REQ-1-OAD-0430]	M2 support print through				0.9991				1.5	M2-D
[REQ-1-OAD-0432]	M2 dynamic shape residual				0.9998				0.6	M2-E
[REQ-1-OAD-0434]	M3 shape			0.9879				8.3		
[REQ-1-OAD-0436]	M3 residual figure error				0.9900				8.2	M3-A
[REQ-1-OAD-0438]	M3 thermal distortion				0.9991				0.9	M3-B
[REQ-1-OAD-0440]	M3 shape drift errors				0.9999				0.5	M3-C
[REQ-1-OAD-0442]	M3 support print through				0.9991				0.8	M3-D
[REQ-1-OAD-0444]	M3 dynamic shape residual				0.9998				0.7	M3-E
[REQ-1-OAD-0446]	Optical alignment		0.9849				25.9			
[REQ-1-OAD-0448]	Telescope collimation errors			0.9949				0.5		COLL
[REQ-1-OAD-0454]	Image jitter (control noise)			0.9947				17.0		CN
[REQ-1-OAD-0480]	Wind jitter residual			0.9986				17.0		WIND
[REQ-1-OAD-0486]	Vibration jitter residual			0.9979				10.0		VIB
[REQ-1-OAD-0488]	Dynamic blur residual			0.9987				5.2		DBLUR
[REQ-1-OAD-0492]	Contingency		0.985				2.8			

3.3.2 Off-Axis Budget

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

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

When the optical design error is combined with the on-axis error allocation, the resultant error at the edge of the FOV is a PSS_N of 0.5620 normalized to the on-axis image. An additional 5% decrease is budgeted in the form of field dependent errors that are due to both the linear functions of the field angle, and field rotation image motion. This additional allowance leads to a total PSS_N of 0.5339 at 10 arcmin normalized to the on-axis image. This on-axis normalized PSS_N allocation is – by definition – the product of the on-axis normalized PSS_N corresponding to the design aberration (0.6612) and the off-axis normalized allocation (0.8075).

3.3.3 Elevation Angle Dependence of the Budget

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

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

3.4 WAVEFRONT ERROR BUDGET FOR ADAPTIVE OPTICS OPERATIONS

3.4.1 Facility AO System (NFIRAOS) Error Budget

Discussion: The RMS wavefront error budgets define the allocations at the center of the corrected field and over a 17" x 17" FoV. The higher order wavefront error requirements specified for the telescope, instrument, dome, and mirror seeing are to be computed as the fitting and servo lag errors for an idealized (linear, noise free, well calibrated) AO system with a -3dB error rejection bandwidth of 30 Hz and order 60 x 60 wavefront compensation. Any additional wavefront errors due to AO component imperfections should be treated as part of the "Implementation" error term. Table 4 therefore imposes requirements upon both the Facility AO system and the other observatory subsystems introducing these disturbances.

The error terms are defined as follows:

***DM fitting error**: RMS difference between a wavefront and its least squares best fit (projection) onto the span of the influnce functions of all DMs. The least-squares projection is restricted to a single-direction (on-axis fitting field), and performance is evaluated in that direction (on-axis performance evaluation field). This error is driven by the inter-actuator spacing and actuator geometry on the DMs. The result obtained is smaller than would be expected using standard scaling laws because the actuator geometries on the two*

NFIRAOS DMs are interlaced. This serves to reduce the fitting error for the case of an on-axis fitting field.

***DM projection error**: The quadrature difference between a generalized, or wide-field fitting error computed for DM actuators commanded to minimize the field-averaged RMS WFE for wavefronts across an extended FoV, and the on-axis DM fitting error defined above. This error is driven by the number and ranges of the DMs.*

***LGS WFS aliasing error:** Defined as the quadrature difference between the reconstruction and fitting errors in an open-loop, noise-free, single-conjugate AO simulation using a minimum variance wavefront reconstructor, with turbulence phase screens sampled several orders of magnitude more finely than the WFS subaperture spacing and the above DM fitting error. This error is driven by the WFS subaperture spacing.*

***Tomography error:** The quadrature difference between the residual error in an open-loop, noise-free, multi-conjugate simulation using minimum variance wavefront reconstruction, and the RSS of all the above errors. This error is driven by the guide star asterism geometry.*

***Servo lag:** Defined as the quadrature difference between the residual errors in closed- and open-loop, noise-free, multi-conjugate simulations. This error is driven by the temporal sampling frequency and processing latency.*

***LGS WFS non-linearity:** The LGS WFS nonlinearity error is defined as the incremental WFE for a physical optics WFS with finite linear dynamic range. The error is driven by the spot position estimation algorithm.*

***LGS WFS noise:** The LGS WFS measurement noise error is defined as the quadrature difference between the residual errors in noisy and noise-free, closed-loop multi-conjugate simulations. The error includes guide star signal level, spot size on subapertures, WFS CCD parameters and the spot position estimation algorithm*

***TMT pupil function:** This term accounts for the pupil obscuration due to M2 support struts and the gap between and the irregular shape of the primary mirror segments when compared to a annular pupil of the same inner and outer diameter of 3.6 and 30 meters*

***Telescope pupil mis-registration:** The telescope pupil misregistration is governed by [REQ-1-ORD-2875] which requires exit pupil to be within 0.3% peak to valley of pupil diameter. The misregistration is applied to the LGS WFS and DM*

***M1 static shape:** The M1 contributions to this term are described in the discussion point to the Telescope Image Quality Error Budget (Table 5): Segment Residual Figure Error (M1-A), Segment Thermal Distortion (M1-B), Segment Support Print Through (M1-C), Segment Drift Errors (M1-D), Segment In-Plane Displacement (M1-E), and Segment Out-of-Plane Displacement (M1-F).*

***M2 & M3 static shape:** The M2 and M3 contributions to this term are described in the discussion point to the Telescope Image Quality Error Budget (Table 5): M2 Residual Figure Error (M2-A), M2 Thermal Distortion (M2-B), M2 Shape Drift Errors (M2-C), M2 Support Print Through (M2-D), M3 Residual Figure Error (M3-A), M3 Thermal Distortion (M3-B), M3 Shape Drift Errors (M3-C), and M3 Support Print Through (M3-D).*

***Telescope collimation errors:** The telescope contribution to this term is described in the discussion point to the Telescope Image Quality Error Budget (Table 5): Telescope Collimation Errors (COLL).*

Segment dynamic mis-alignment: *The M1 contribution to this term is described in the discussion point to the Telescope Image Quality Error Budget (Table 5): Segment Dynamic Displacement Residuals (M1-G).*

Thermal seeing: *This is the optical effect described in the discussion point to the Telescope Image Quality Error Budget (Table 5): Thermal Seeing (T-A).*

NFIRAOS: *This includes the NFIRAOS opto-mechanical error terms, mirror polishing, gravitational and thermal print through errors uncorrectable by the DMs, DM/wavefront sensor pupil distortion error, DM wavefront sensor pupil misregistration and the non-common path errors between the LGS WFS and the science path*

Residual instrument: *The residual instrument errors include all errors within the science instrument that are uncorrectable by NFIRAOS. It is assumed that NFIRAOS will correct all instrument aberrations with a spatial frequency of <1 cycle/m*

DM effects: *The DM effects include DM saturation, hysteresis, failed actuators, DM dynamics, influence function and flattening*

LGS WFS & Na layer: *This comprises WFS stale matched filter, LGS overall altitude tracking, sodium layer differential range variability, tomography point source approximation, Rayleigh backscattering, signal level variations, atmospheric refractive index dispersion and chromatic anisoplanatism****Control algorithm:*** *This accounts for; algorithm precision; numerical precision induced by finite precision arithmetic; turbulence profile mismatch*

Control algorithm: *This accounts for; algorithm precision; numerical precision induced by finite precision arithmetic; turbulence profile mismatch*

Simulation undersampling: *Term included in error budget to compensate for the discrete turbulence phase screens used in the simulation*

Residual tip/tilt jitter due to windshake: *This term accounts for effects described in the discussion point to the Telescope Image Quality Error Budget (Table 5): Wind Jitter Residual (Wind).*

Residual telescope vibration: *This term accounts for effects described in the discussion point to the Telescope Image Quality Error Budget (Table 5): Vibration Jitter Residual (VIB).*

Residual telescope tracking jitter: *This term accounts for effects described in the discussion point to the Telescope Image Quality Error Budget (Table 5): Image Jitter (Control Noise) (CN), but does not include wavefront sensor error (see below).*

Residual tip/tilt jitter due to turbulence: *Global image jitter resulting from atmospheric turbulence over 17" field after correction. This term includes wavefront sensor errors contributing to this effect.*

Residual plate scale mode due to turbulence: *Plate scale errors (image magnification, differential magnification in x versus y and differential magnification at 45 degrees) due to atmospheric turbulence. This term includes wavefront sensor errors contributing to this effect.*

Residual plate scale mode due to telescope misalignment: *This term accounts for the image smear due to dynamic plate scale changes resulting from Dynamic Blur Residual (DBLUR), described in the discussion point to the Telescope Image Quality Error Budget (Table 5).*

Telescope misalignment: *This term accounts for the direct wavefront error residual due to effects described in the discussion point to the Telescope Image Quality Error Budget (Table 5): Dynamic Blur Residual (DBLUR).*

Field dependent wavefront error*: Field-dependent implementation wavefront errors in NFIRAOS and the telescope degrade the NGS image sharpening by the AO system and increase both tip-tilt and plate-scale errors due to increased wavefront-sensor measurement noise.*

Table 6 NFIRAOS RMS wavefront error budget (60 x 60 actuators, on axis) in nm

		On Axis WFE				17" x 17" FoV WFE			
REQ-1-OAD-0550	Delivered Wavefront	187				191			
REQ-1-OAD-0552	First-order turbulence compensation		117				122		
REQ-1-OAD-0530	LGS control loop			117				122	
REQ-1-OAD-0531	DM fitting error				75				75
REQ-1-OAD-0532	DM projection error				46				62
REQ-1-OAD-0533	LGS WFS aliasing error				42				42
REQ-1-OAD-0534	Tomography error				30				22
REQ-1-OAD-0535	Servo lag				4				9
REQ-1-OAD-0549	LGS WFS non-linearity				19				21
REQ-1-OAD-0536	LGS WFS noise				46				45
REQ-1-OAD-0562	TMT Pupil Function				27				24
REQ-1-OAD-0554	Opto-mechanical implementation		77				77		
REQ-1-OAD-0538	Telescope pupil misregistration			12				12	
REQ-1-OAD-0556	Telescope and observatory OPD			45				45	
REQ-1-OAD-0558	M1 static shape				36				36
REQ-1-OAD-0560	M2 & M3 static shape				14				14
REQ-1-OAD-0582	Telescope Collimation Errors				1				1
REQ-1-OAD-0584	Telescope Misalignment				1				1
REQ-1-OAD-0540	Segment dynamic misalignment				14				14
REQ-1-OAD-0566	Thermal seeing				18				18
REQ-1-OAD-0580	Field dependent astigmatism				0				0
REQ-1-OAD-0541	NFIRAOS			53				53	
REQ-1-OAD-0564	Residual Instrument			30				30	
REQ-1-OAD-0542	AO component errors & higher order effects		60				60		
REQ-1-OAD-0543	DM effects			45				45	
REQ-1-OAD-0544	LGS WFS & Na layer			34				34	
REQ-1-OAD-0545	Control algorithm			21				21	
REQ-1-OAD-0569	Simulation undersampling		48				48		
REQ-1-OAD-0570	NGS Mode WFE at 50% sky coverage		58				58		
REQ-1-OAD-0546	Residual tip/tilt jitter due to windshake			17				17	
REQ-1-OAD-0572	Residual telescope			10				10	

		On Axis WFE				17” x 17” FoV WFE			
	vibration								
REQ-1-OAD-0573	† Residual telescope tracking jitter			17				17	
REQ-1-OAD-0574	Residual tip/tilt jitter due to turbulence			32				31	
REQ-1-OAD-0547	Residual plate scale mode due to turbulence			35				36	
REQ-1-OAD-0580	Residual plate scale mode due to windshake			5				5	
REQ-1-OAD-0581	Field dependent wavefront error			20				20	
REQ-1-OAD-0548	Contingency		81				80		

*† Discussion: This is 0.4 mas on the sky after correction by the NFIRAOS tip/tilt rejection transfer function modeled as a second-order high-pass filter with damping ζ = 0.7 and natural frequency ω0 = 15 Hz*2*π. The intent is 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. It also does not include OIWFS noise because this noise is specified in [REQ-1-OAD-0578]. This latter exclusion is different from the seeing limited case.

3.4.2 Elevation Angle Dependence of the Budget

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

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

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

3.4.3 Wavefront Corrector Stroke Allocation

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

Table 7 OPD budget for the correction of Observatory wavefront error source

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

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

3.5 POINTING ERROR BUDGET

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

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

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

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

Telescope pointing error budget in arcsec:

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

Table 8 Pointing Error Budget

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

3.6 PUPIL SHIFT BUDGET

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

Table 9 Pupil Shift Budget in RMS, assuming a Gaussian distribution with RMS = 1 sigma.

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

3.7 PLATE SCALE STABILITY BUDGET

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

Table 10 Telescope budget for stability of plate scale, specified in terms of maximum image motion of any point in the full 20 arcmin diameter field relative to the center of the field.

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

3.8 MASS BUDGET

Table 11 Telescope Mass Budget – Requirement is for not to exceed mass, CG and mass moment of inertia are estimates for information only

Requirement	Subsystem Decompostion		Mass (not to exceed)				Estimated Center of Gravity (Information only)				Estimated Mass moment of Inertia about CofG (Information only)				Reference
	Abbreviation	Description	Elevation (tonnes)	Azimuth (tonnes)	Sub-total (tonnes)	Subsystem Total (tonnes)	Coordinate System	Location X (m)	Location Y (m)	Location Z (m)	Alignment of axes	Ix (kg x m^2)	Iy (kg x m^2)	Iz (kg x m^2)	
[REQ-1-OAD-0740]	STR	Telescope Structure				1859.3									TMT.STR.TEC.07.010.REL01
		Elev. Structure	887.0		887.0		ECRS	TBD	TBD	TBD	ECRS	TBD	TBD	TBD	
		Az. Structure		909.4	909.4		ACRS	TBD	TBD	TBD	ACRS	TBD	TBD	TBD	
		Inst. Support Structures (1st Light)		28.0	28.0		ACRS	TBD	TBD	TBD	ACRS	TBD	TBD	TBD	
		Utility Service Lines	5.6	22.4	28.0		ACRS/ECRS	TBD	TBD	TBD	ACRS/ECRS	TBD	TBD	TBD	
		Mount Control System	0.4	6.4	6.8		ACRS/ECRS	TBD	TBD	TBD	ACRS/ECRS	TBD	TBD	TBD	
[REQ-1-OAD-0742]	M1S	M1 System	144.1		144.1	144.1	ECRS	0.0	0.0	-2.8	ECRS	8191982	8191982	16292743	TMT.OPT.TEC.07.031.DRF01
[REQ-1-OAD-0744]	M2S	M2 System	6.5		6.5	6.5	ECRS	0.0	0.0	24.1	M2CRS	7691	7649	12910	TMT.OPT.TEC.07.034.DRF01
[REQ-1-OAD-0746]	M3S	M3 System	11.2		11.2	11.2	ECRS	0.0	0.0	-1.1	ECRS	20802	19567	9808	TMT.OPT.TEC.07.035.DRF01
[REQ-1-OAD-0748]	TINS	Test Instruments	0.3		0.3	0.3	ECRS	0.0	0.1	12.5	ECRS	TBD	TBD	TBD	TMT.OPT.TEC.07.032.DRF01
[REQ-1-OAD-0750]	APS	Alignment and Phasing System			6.0	6.0									TMT.INS.TEC.07.004.DRF01
		Instrument (early light)		5.6	5.6		ACRS	-21.0	-1.0	19.5	FCRS	7083	10417	4167	
		Instrument (first decade)		5.6	5.6		ACRS	-20.5	-5.1	19.5	FCRS	7083	10417	4167	
		Electronics + misc Nasmyth (early light)		0.4	0.4		ACRS	-21.0	-1.0	13.0	FCRS	84	108	84	
		Electronics + misc Nasmyth (first decade)		0.4	0.4		ACRS	-20.5	-5.1	19.5	FCRS	84	108	84	
[REQ-1-OAD-0754]	M1CS	M1 Control System	29.1		29.1	29.1	ECRS	0.0	0.0	-4.7	ECRS	2355383	2355383	3421493	TMT.CTR.TEC.07.024.REL01
[REQ-1-OAD-0756]	TINC	Test Instrument Controls				0.1	ACRS/ECRS	TBD	TBD	TBD	ACRS/ECRS	TBD	TBD	TBD	TMT.CTR.TEC.07.024.REL01
[REQ-1-OAD-0758]	OSS	Telescope Safety System		0.1	0.1	0.1	ACRS	TBD	TBD	TBD	ACRS	TBD	TBD	TBD	TMT.CTR.TEC.07.024.REL01
[REQ-1-OAD-0760]	ESEN	Engineering Sensors	0.8	0.8	1.6	1.6	ACRS	TBD	TBD	TBD	ACRS	TBD	TBD	TBD	TMT.CTR.TEC.07.024.REL01
[REQ-1-OAD-0762]	PL&G	Power, Lighting and Grounding			11.6	11.6					ACRS	TBD	TBD	TBD	
		Sub Nasmyth (-X) Breaker boxes		0.7	0.7		ACRS	-16.2	0.3	9.8	ACRS	1095	146	982	
		Sub Nasmyth (+X) Breakers		0.5	0.5		ACRS	16.2	0.3	9.7	ACRS	887	85	825	
		EL Journal (-X) Breaker boxes	0.4		0.4		ECRS	-14.8	1.1	-3.3	ECRS	151	60	107	
		EL Journal (-X) Breaker boxes	0.3		0.3		ECRS	14.8	1.0	-3.4	ECRS	128	47	95	
		Mirror Cell Breaker Boxes	0.1		0.1		ECRS	-0.8	0.0	-4.4	ECRS	26	17	14	
		Top End Breaker Boxes	0.1		0.1		ECRS	0.0	-1.2	25.6	ECRS	15	28	14	
		Miscellaneous elevation (lighting, cabling etc)	2.2		2.2		ECRS	0.0	0.0	9.9	ECRS	TBD	TBD	TBD	
		Miscellaneous azimuth (lighting, cabling etc)		7.3	7.3		ACRS	0.0	0.0	15.3	ACRS	TBD	TBD	TBD	
[REQ-1-OAD-0764]	NFIRAOS	NFIRAOS			49.5	49.5									TMT.AOS.TEC.07.039.DRF01
		Instrument		46.8			ACRS	-21.7	5.1	18.7	FCRS	1189753	1834957	988240	
		Electronics + misc Nasmyth		2.7			ACRS	-21.7	5.1	13.8	FCRS	5078	4212	3335	
[REQ-1-OAD-0766]	LGSF	Laser guide star facility			11.6	11.6									TMT.AOS.CDD.06.035.REL03
		LGSF laser system	8.3				ECRS	-12.6	1.3	-6.1	ECRS	210963	14580	220303	
		LGSF BTO Optical Path	1.8				ECRS	-5.0	11.6	11.1	ECRS	222653	241387	94587	
		LGSF Top End	1.5				ECRS	0.0	-0.2	26.2	ECRS	410	388	582	TMT.AOS.CDD.08.001.REL09
[REQ-1-OAD-0768]	IRIS	IRIS				7.7									TMT.INS.TEC.07.004.DRF01
		Instrument		6.8	6.8		ACRS	-19.8	6.0	16.0	FCRS	8500	8500	11492	
		Electronics + misc Nasmyth		0.9	0.9		ACRS	-19.8	6.0	13.0	ACRS	361	732	493	
[REQ-1-OAD-0770]	IRMS	IRMS				2.6									TMT.INS.TEC.07.004.DRF01
		Instrument + elec		2.6	2.6		ACRS	-19.8	6.0	23.0	FCRS	3649	3649	1420	
[REQ-1-OAD-0772]	MIRES	MIRES + MIRAO				7.2									TMT.INS.TEC.07.004.DRF01
		Instrument (MIRAO)		2.6	2.6		ACRS	-19.7	-8.4	20.0	FCRS	2809	2126	1415	
		Instrument (MIRES)		3.6	3.6		ACRS	-19.0	-8.1	17.0	FCRS MIRAO	4835	1012	4835	
		Electronics + misc Nasmyth		1.0	1.0		ACRS	-19.0	-8.1	17.0	FCRS MIRAO	167	167	167	
[REQ-1-OAD-0774]	PFI	PFI				5.7									TMT.INS.TEC.07.004.DRF01
		Instrument		4.5	4.5		ACRS	-22.0	-1.2	19.5	FCRS	21750	21750	6750	
		Electronics + misc Nasmyth		1.3	1.3		ACRS	-22.0	-1.2	13.0	FCRS	213	213	213	
[REQ-1-OAD-0776]	NIRES-B	NIRES				7.4									TMT.INS.TEC.07.004.DRF01
		Instrument		6.4	6.4		ACRS	20.0	-9.5	19.5	FCRS	1597	1597	799	
		Electronics + misc Nasmyth		1.0	1.0		ACRS	20.0	-9.5	13.0	FCRS	171	171	171	
[REQ-1-OAD-0777]	NIRES-R	NIRES				7.4									
		Instrument		6.4	6.4		ACRS	-18.3	-8.1	22.2	FCRS	1597	1597	799	
		Electronics + misc Nasmyth		1.0	1.0		ACRS	-18.3	-8.1	13.0		171	171	171	
[REQ-1-OAD-0778]	WIRC	WIRC				6.1									TMT.INS.TEC.07.004.DRF01
		Instrument		5.1	5.1		ACRS	-19.8	6.0	23.0	FCRS	7121	7121	2560	
		Electronics + misc Nasmyth		1.0	1.0		ACRS	-19.8	6.0	13.0	FCRS	171	171	171	
[REQ-1-OAD-0780]	WFOS	WFOS				42.0									TMT.INS.TEC.07.004.DRF01
		Instrument		41.0	41.0		ACRS	22.5	0.0	18.7	FCRS	633992	594666	342131	
		Electronics + misc Nasmyth		1.0	1.0			22.5	0.0	13.0	FCRS	171	171	171	
[REQ-1-OAD-0782]	HROS	HROS				49.7									TMT.INS.TEC.07.004.DRF01
		Instrument		47.4	47.4		ACRS	20.8	8.9	16.2	ACRS	516088	429652	819340	
		Electronics + misc Nasmyth		2.3	2.3		ACRS	20.8	8.9	13.0	ACRS	167	167	167	
[REQ-1-OAD-0784]	IRMOS	IRMOS				19.3									TMT.INS.TEC.07.004.DRF01
		Instrument		16.6	16.6		ACRS	17.9	-6.5	17.5	FCRS	64755	64755	33201	
		Electronics + misc Nasmyth		2.7	2.7		ACRS	17.9	-6.5	13.0	FCRS	448	448	448	
[REQ-1-OAD-0785]	NSCU			2.6	2.6	2.6	ACRS	-17.7	1.7	19.5	ACRS	-17.6	1.4	19.3	
[REQ-1-OAD-0786]	Misc. Nasmyth	Misc. Nasmyth				20.0									TMT.INS.TEC.07.004.DRF01
		+X Side		10.0	10.0		ACRS	TBD	TBD	TBD	ACRS	TBD	TBD	TBD	
		-X Side		10.0	10.0		ACRS	TBD	TBD	TBD	ACRS	TBD	TBD	TBD	
		Mass Sums	**1099.7**	**1208.9**	**2308.7**										

3.9 OTHER PERFORMANCE BUDGETS

3.9.1 M1CS Actuator Range of Travel Budget

Discussion: The range of travel of the M1CS position actuators is budgeted to accommodate the factors listed in Table 12.

Table 12 M1CS Actuator Range of Travel Budget

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

4. SYSTEM SPECIFICATION

4.1 TELESCOPE

4.1.1 Optical Design

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

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

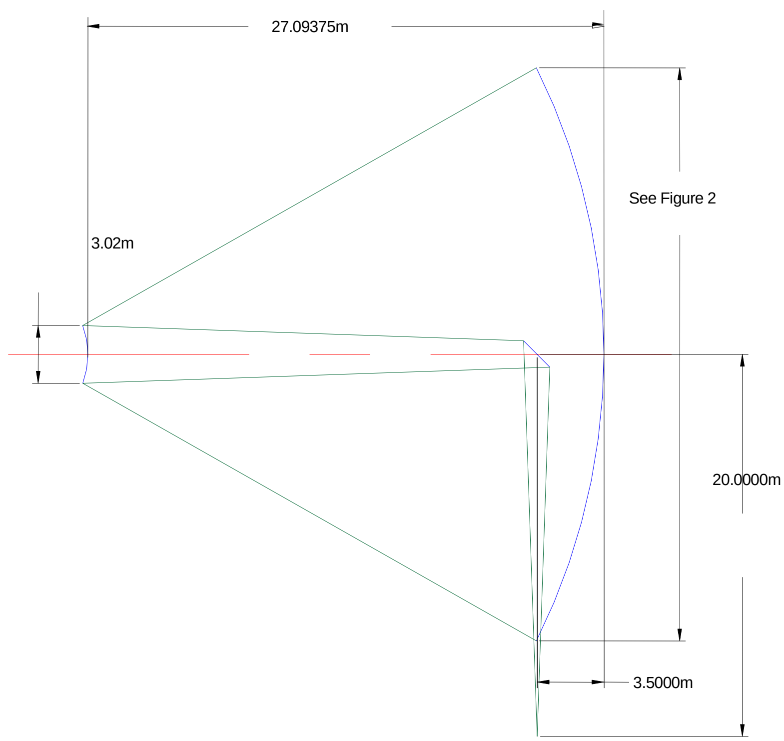


Figure 1 Optical Configuration of the telescope

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

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

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

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

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

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

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

[REQ-1-OAD-1025] Stray light control shall be provided by a baffle around the M3 and in the instrument designs. The size of the M3 baffle shall, at minimum, equal the size of a beam from the telescope exit pupil to a 20 arcmin diameter field-of-view.

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

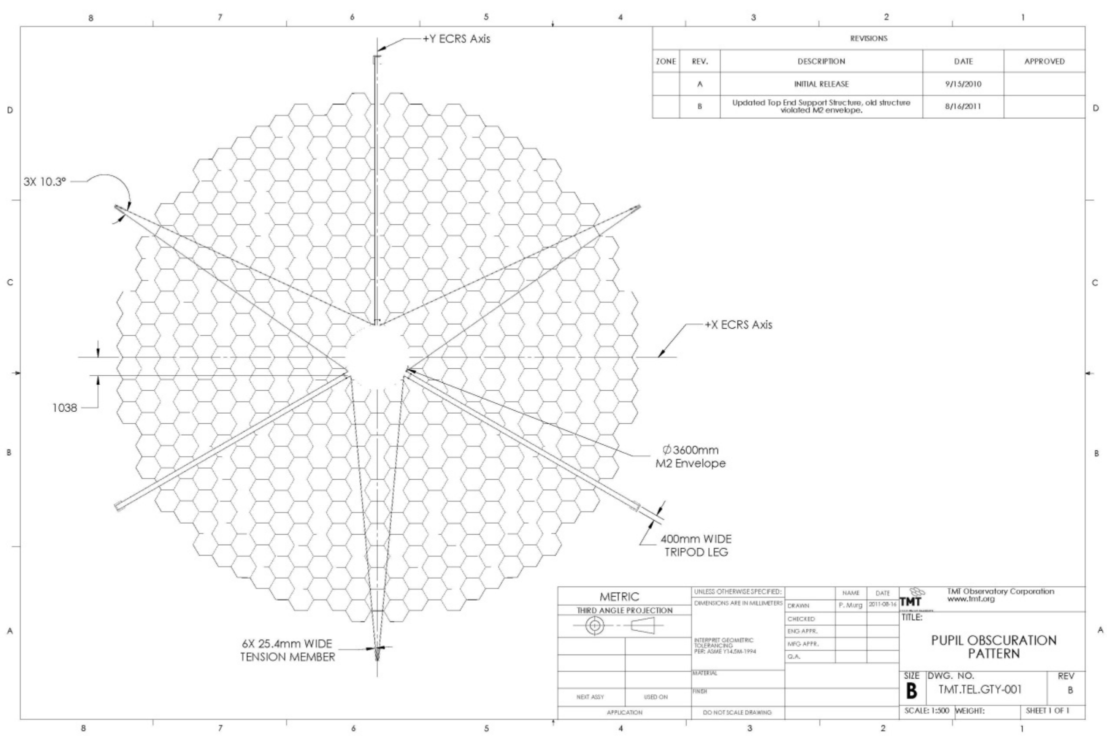


Figure 2 Pupil obscuration pattern

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

Table 13 Summary of the optical design

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

4.1.2 Aerothermal Considerations

[REQ-1-OAD-1080] The maximum transverse cross sectional area of the telescope, when considered from any direction perpendicular to the telescope optical axis and above a plane perpendicular to the optical axis and 14.4m above the telescope elevation axis, shall be less than 44 m^2. The allocation to LGSF, M2S and Telescope Structure is shown in Table 14 below:

Table 14 Maximum Allowable Cross Sectional Area of Telescope Top End

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

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

4.1.3 Telescope Structure

4.1.3.1 General

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

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

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

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

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

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

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

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

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

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

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

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

Discussion: The above requirement in conjunction with REQ-1-OAD-5150 ensures a 0.5m gap between the telescope and enclosure.

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

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

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

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

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

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

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

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

[REQ-1-OAD-1285] The telescope structure shall provide space, structural support and access/servicing provisions for the equipment listed in Table 15 and instruments listed in Table 17.

Sub-System	Equipment	Location (see space envelope drawing for details)	Space Envelope Reference	Services Required*	Notes
M2 System	M2 Mirror and Positioner	Elevation Structure, top end	TMT.TEL.OPT.M2-ENV	L1C Variable temperature water/ glycol	
M3 System	M3 Mirror and Positioner	Elevation Structure, M3 Support Tower	TMT.TEL.OPT.M3-ENV	L1C	
	M3 Electronics	Elevation Structure, Mirror Cell	TMT.TEL.OPT.M3.EL-ENV	L1C Variable temperature water/ glycol	
Test Instruments	Global Metrology System	Elevation Structure	Not available	L1C	
M1 Control System	Node Boxes	Elevation Structure, Mirror Cell	TMT.TEL.CONT.M1CS.SCC-ENV	L3CUG Compressed air	Compressed air distributed to sensors. Compressed air supply is responsibility of M1CS and is separate from supply to LGSF, NFIRAOS. Telescope to provide provision for routing only.
Laser Guide Start Facility	Laser System	Elevation Structure, -X Laser Platform	TMT.INS.AO.LGSF.LAS-ENV	L3C, H3D Fixed temperature water/glycol	Fixed temperature water/glycol supply is the responsibility of LGSF and is separate from general variable temperature water/glycol system. Telescope to provide provision for routing only.
	Beam Transfer Optical Path	Elevation Structure,	TMT.INS.AO.LGSF.ELOP-ENV	L1C Compressed Air	
	Beam Transfer Optical Path Electronics	Elevation Structure	TMT.INS.AO.LGSF.BTOCC-ENV	L1C Variable temperature water/glycol	
	Laser Launch Telescope and top end	Elevation Structure, Top End	TMT.INS.AO.LGSF.TE-ENV	L1C Variable temperature water/glycol	

Table 15 – Sub-system equipment mounted to telescope structure (excluding instruments)

4.1.3.2 Telescope Azimuth Structure

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

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

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

[REQ-1-OAD-1297] A man lift shall be mounted on the azimuth structure to enable personnel to access to M3 mirror during removal installation (with the telescope horizon pointing).

4.1.3.3 Telescope Elevation Structure

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

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

[REQ-1-OAD-1310] The telescope shall support a laser system mounted on the inside of the –X ECRS elevation journal.

Discussion: The space required for the laser system is defined in TMT drawing TMT.INS.AO.LGSF.LAS-ENV

[REQ-1-OAD-1312] The telescope structure shall provide appropriate walkways for access and servicing of the LGSF Laser Systems and the part of the LGSF Beam Transfer Optics Optical Path located at the outputs of the Laser Systems.

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

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

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

[REQ-1-OAD-1321] The maximum deflections of the interface planes between the telescope and the M2S and LGSF laser launch telescope shall not exceed the values given in Table 16. These limits apply at any observing temperature combined with any elevation angle between 0 and 65º.

Table 16 Maximum allowable deflection of the telescope top end

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

4.1.3.4 Telescope Pier

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

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

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

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

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

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

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

4.1.3.5 Cable Wraps

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

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

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

[REQ-1-OAD-1345] The cable wraps will accommodate the distribution of all utilities, coolants, high pressure oil, power, data and control lines to the telescope structure as defined in RD13 (TMT Telescope Structure Cable Wrap Requirements).

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

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

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

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

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

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

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

4.1.3.6 Mount Control System and Drives

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

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

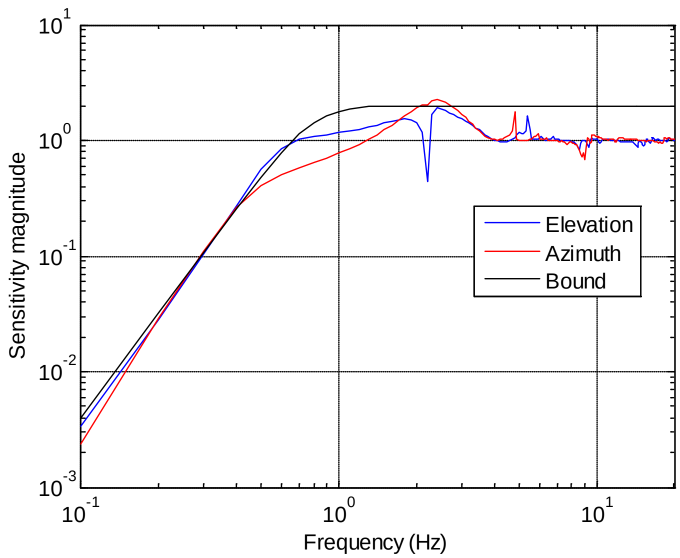


Figure 3. Bound on mount control torque rejection with respect to open-loop. The mount control rejection achieved with the current design is shown for comparison.

4.1.3.6.1 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.

4.1.3.6.2 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 0.07 degrees/s^2 and a maximum velocity of 2.0 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.

4.1.3.7 Nasmyth Platforms and Instrumentation Support

4.1.3.7.1 Performance

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

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

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

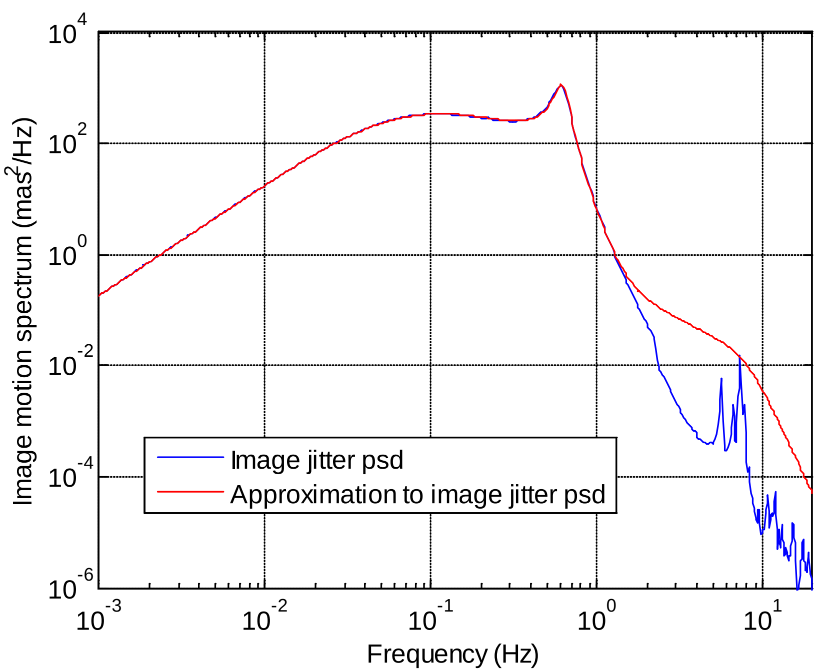


Figure 4 Allowable image jitter as seen by an instrument mounted on the Nasmyth Platform

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

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

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

4.1.3.7.2 Configuration

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

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

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

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

[REQ-1-OAD-1410] At early light, the Nasmyth Platforms shall provide support for the following instruments as defined in the ORD, each at their own foci: NFIRAOS with the NSCU, feeding IRIS and IRMS, at the 174.5 degree position on the -X platform, WFOS at the 0 degree position on the +X platform, and APS at the 180 degree position on-axis and beside NFIRAOS. The location of these instruments is shown in **Error! Reference source not found.**.

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

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

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

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

Discussion: The instrument locations for the full SAC instrument suite (early light plus future instrumentation) on the Nasmyth Platforms shall be as shown in Figure 30 in the Appendix.

[REQ-1-OAD-1425] Instruments shall not exceed the volumes, and shall meet the focal plane position requirements listed in Table 17.

Discussion: These volumes and focal plane positions are required to meet the instrument arrangement as shown in Figure 30***Error! Reference source not found.***

Table 17 Instrument Volumes (not including electronics cabinets and other support equipment)

Instrument	Shape	Width or Dia (m)	Height (m)	Depth (m)	Focal Plane Position	Notes
APS	See drawing TMT.TEL.CONT.APS-ENV					
HROS	See drawing TMT.INS.HROS-ENV					UC Envelope
IRIS	See drawing TMT.INS.INST.IRIS-ENV					Mounted on NFIRAOS bottom port
IRMOS	See drawing TMT.INS.INST.IRMOS-ENV					Florida envelope
IRMS	See drawing TMT.INS.INST.IRMS-ENV					Mounted on NFIRAOS top port. Dimensions based on Keck Mosfire requirements
MIRAO	See drawing TMT.INS.INST.MIRAO-ENV					
MIRES	See drawing TMT.INS.INST.MIRES-ENV					
NFIRAOS	See drawing TMT.INS.NFIRAOS-ENV					
NIRES-B	See drawing TMT.INS.INST.NIRESB-ENV					Mounted on NFIRAOS side port
NIRES-R	Cylinder	1	1.5		0.5m inside, on axis	Fed by MIRAO
NSCU	See drawing TMT.INS.NSCU-ENV					
PFI	See drawing TMT.INS.INST.PFI-ENV					
WIRC	Cylinder	2		3.7	Focal plane position as per that defined for IRIS	Mounted on NFIRAOS top port. Volume doesn't include protrusion into NFIRAOS
WFOS	See drawing TMT.INS.INST.WFOS-ENV					

4.1.3.7.3 Instrument Mounting Points

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

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

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

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

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

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

4.1.3.7.4 Services

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

4.1.3.7.5 Access to Platforms and Instrument Locations

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

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

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

[REQ-1-OAD-1465] One or more elevators shall be provided to lift personnel and pieces of equipment up to 1.5 x 1.5 x 1.5 m and 500 kg to the Nasmyth platforms.

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

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

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

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

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

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

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

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

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

Discussion: Crane and hoist working volumes are defined in Section 4.5.1 of the OAD.

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

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

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

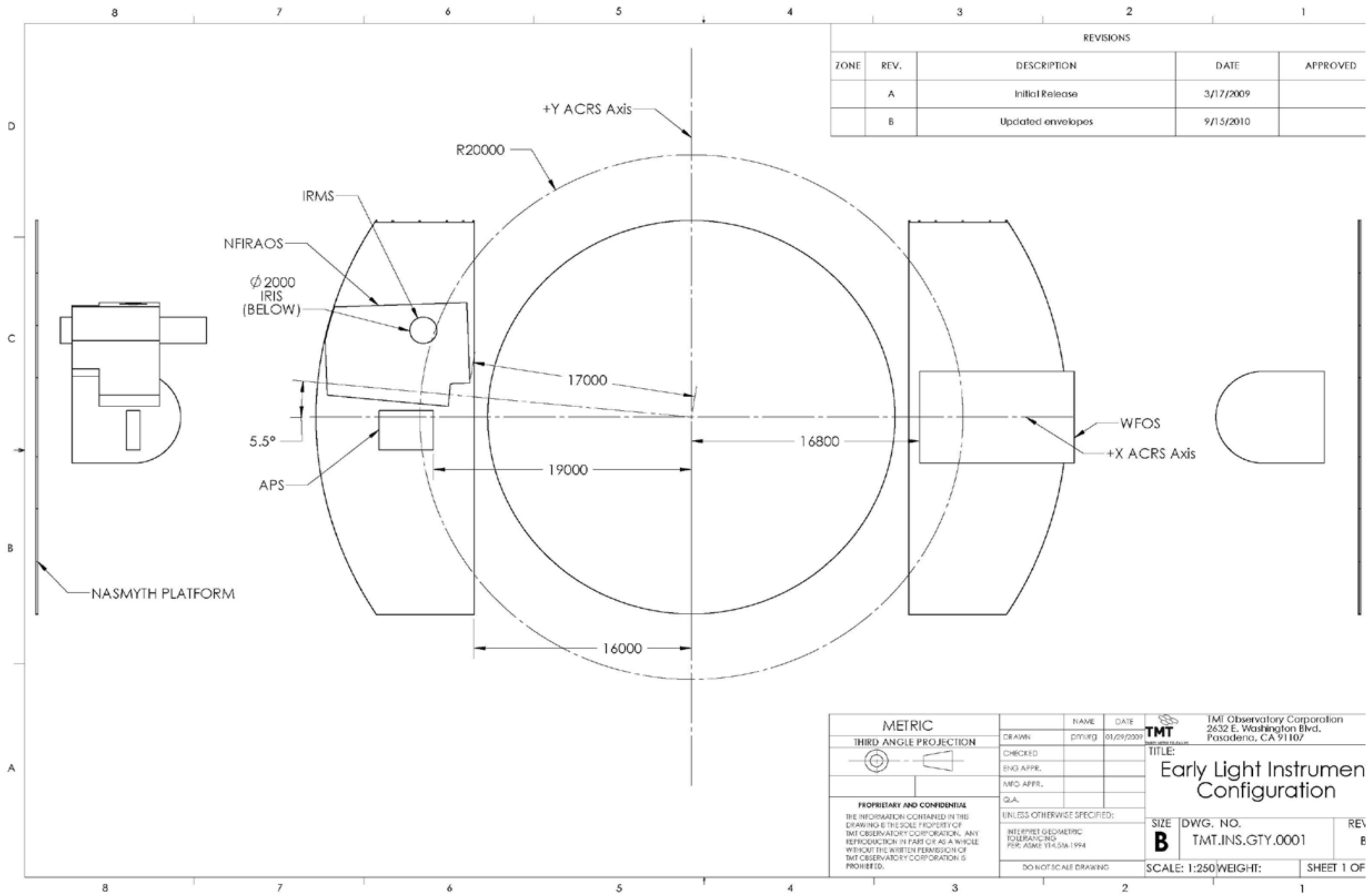


Figure 5 Nasmyth Platform Reference Instrument Layout (NFIRAOS, IRIS, IRMS and APS at left, WFOS at right)

4.1.3.7.6 Access to Instruments

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

4.1.3.7.7 Access between Platforms

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

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

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

4.1.3.7.8 Instrument Handling, Installation and Removal

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

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

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

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

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

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

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

4.1.3.7.9 Requirements for Regular Maintenance and Servicing of Instruments

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

4.1.3.7.10 Floor Space and Storage Requirements

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

[REQ-1-OAD-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.

4.1.3.7.11 Safety and Personnel Considerations

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

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

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

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

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

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

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

[REQ-1-OAD-1600] 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

4.1.3.8 Segment Handling Crane

[REQ-1-OAD-1610] The M1 segment handling system (M1 SHS) is an integrated system that consists of: (1) a Segment Lifting Fixture (SLF) that interfaces to the Mounted Segment Assembly (MSA); (2) a positioning system that moves the SLF to install or remove the segments in the primary mirror array; and (3) a crane or other means to raise segments from the observing floor to the mirror cell and lower them back to the observing floor.

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

[REQ-1-OAD-1612] The M1 SHS shall be mounted on the telescope structure.

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

[REQ-1-OAD-1616] The M1 SHS shall enable the installation and removal of any 10 primary mirror segments per 10-hour day

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

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

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

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

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

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

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

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

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

[REQ-1-OAD-1632] The M1 SHS shall have six motorized degrees of freedom (Tx, Ty, Tz, Rx, Ry, Rz, defined in a convenient orthogonal coordinate system)

[REQ-1-OAD-1634] The M1 SHS shall level the segment (Tip = Tilt = 0) prior to installing/removing the segment onto the handling cart.

Discussion: To minimize risk to the segments, the number of transfers of the MSA from one piece of handling equipment to another should be minimized.

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

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

[REQ-1-OAD-1639] If the M1 SHS is raising or lowering a segment from/to the observing floor when an earthquake up to the level of a frequent earthquake occurs, the M1 SHS shall not allow damage to the MSA being moved.

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

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

[REQ-1-OAD-1641] In its stowed position, the M1 SHS shall not significantly interfere with the free flow of air across the surface of the primary mirror.

[REQ-1-OAD-1642] No elements of the M1 segment handling system (including any payload) shall be able to contact the primary mirror under any combination of environmental, seismic and operational conditions or during loss of power. The SHS should minimize the potential damage to the segment which is in the process of being engaged during a seismic condition or operational failure.

4.1.4 Telescope Mirror Optical Coating Requirements

Discussion: Table 18 lists the requirements for the optical coatings on each of the M1, M2 and M3 mirror surfaces. These requirements are based on what is achievable with existing coatings (see example coating plots in the Appendix 1.1).

Table 18 Requirements for M1, M2 and M3 Optical Coatings

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

4.1.5 M1 Optics System

4.1.5.1 General

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

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

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

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

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

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

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

[REQ-1-OAD-1665] The M1 system shall be designed to allow in situ CO_2 cleaning of the mirror.

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

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

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

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

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

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

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

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

4.1.5.2 Segmentation

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

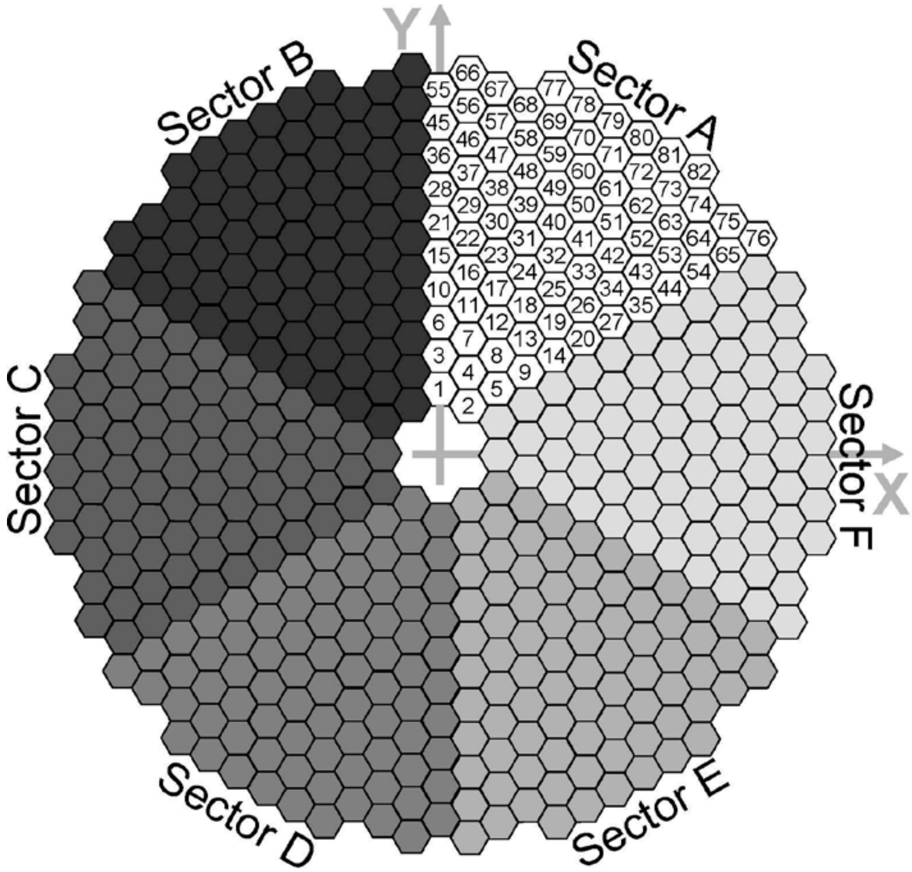


Figure 6 Layout of the segmented primary mirror, as projected on the X-Y plane of the Elevation Coordinate System (ECRS). The capital letters denote identical sectors rotated by 60 degrees relative to each other.

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

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

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

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

[REQ-1-OAD-1720] The primary segment assembly shall be compatible with an actuator stroke range as specified in Section 3.9.1 of this document.

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

*Discussion: This range is easily achieved by the actuator stroke spe*cified in Section 3.9.1 of this document.

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

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

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

Discussion: Segment to segment contact will cause damage.

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

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

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

$\alpha =$ radial scaling coefficient

$R_{max} =$ Primary mirror nominal radius

$R_1 =$ Primary mirror radius of curvature

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

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

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

4.1.5.3 Positioning

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

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

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

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

4.1.6 M2 System

4.1.6.1 General

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

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

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

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

4.1.6.2 Removal, Cleaning and Coating

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

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

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

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

4.1.6.3 Control

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

[REQ-1-OAD-1860] In addition to any other motion requirements, the mechanical range of motion of the M2 system shall be sufficient to accommodate any combination of the telescope top end deflections as specified in Table 16.

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

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

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

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

4.1.6.4 Optical Quality

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

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

4.1.7 M3 System

4.1.7.1 General

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

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

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

4.1.7.2 Removal, Cleaning and Coating

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

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

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

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

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

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

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

4.1.7.3 Control

[REQ-1-OAD-2000] The M3 System shall provide two degree of freedom motion of the tertiary mirror relative to the telescope structure. The required mechanical range of motion shall be sufficient to redirect a beam of light from the secondary mirror towards the Nasmyth platform instrument locations as shown in Figure 7. The motion shall be achieved over a telescope zenith angle range of 0 to 65 degrees. All instrument optical axes are located in a plane perpendicular to the ACRS z-axis and coincident with the ECRS origin.

Discussion: The location of the HROS focal plane and optical feed is currently under study (ref. TMT.SEN.COR.09.011*). The resulting position may lie above the plane described above.*

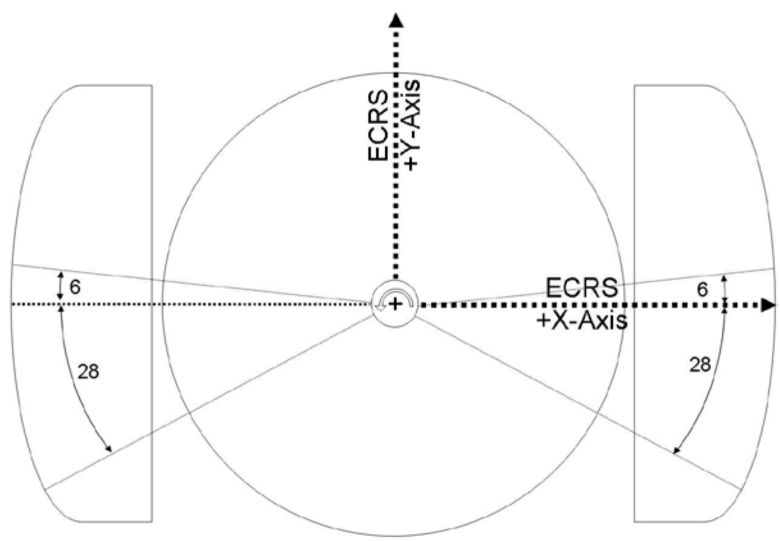


Figure 7 Nasmyth positions addressed by the M3 mirror (ECRS axes shown with telescope zenith pointing)

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

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

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

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

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

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

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

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

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

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

4.1.7.4 Optical Quality

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

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

4.1.8 Primary Mirror Control System (M1CS)

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

Discussion: The "combined segment support" is intended to include all in-situ segment support structure elements; this includes the Primary Mirror Assembly, the Subcell, three actuators, and the mirror cell. The static stiffness of the "combined segment support" is defined by the slope of the force versus displacement curve for forces applied normal to, and at the center of, the front surface of a segment properly installed in the telescope and displacement of the segment relative to its neighbours.

[REQ-1-OAD-2101]. The M1CS bandwidth (3dB) shall be no less than 0.5 Hz.

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

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

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

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

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

FIGURE TBD

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

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

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

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

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

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

[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.

4.1.9 Alignment and Phasing System (APS)

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

[REQ-1-OAD-2255] In alignment maintenance mode the initial M1, M2 and M3 optics shall not exceed the error shown in Table 19.

Table 19 Alignment maintenance mode capture range

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

[REQ-1-OAD-2257] In the absence of segment exchanges the Observatory System shall meet all performance requirements for periods of no less than four weeks without calibration by the APS.

[REQ-1-OAD-2285] In post-segment exchange mode the initial M1, M2 and M3 optics shall not exceed the error shown in Table 20.

Table 20 Post-segment exchange mode capture range

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

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

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

[REQ-1-OAD-2330] The APS shall be able to perform on-axis alignment in less than 120 minutes when all optics are within the post-segment exchange specifications.

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

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

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

4.1.10 Servicing and Maintenance

4.1.10.1 Telescope Structure

[REQ-1-OAD-2400] The telescope structure shall be designed to be consistent with the servicing and replacement intervals and scenarios shown in Table 21.

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

Table 21 Telescope structure Servicing Requirements

TBD

4.1.10.2 Telescope Optics

[REQ-1-OAD-2500] The telescope optics shall be designed to be consistent with the servicing and replacement intervals and scenarios shown in Table 22.

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

Table 22 Telescope Optics Servicing Requirements

TBD

4.1.10.3 Telescope Controls

[REQ-1-OAD-2600] The telescope controls shall be designed to be consistent with the servicing and replacement intervals and scenarios shown in Table 23.

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

Table 23 Telescope Controls Servicing Requirements

TBD

4.2 INSTRUMENTATION

4.2.1 General

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

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

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

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

[REQ-1-OAD-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

4.2.2 Facility AO System

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

[REQ-1-OAD-2766] The worst case defined in REQ-1-OAD-2765 for slope errors in the non-common path wavefront between the LGS WFS and the Science Instrument shall be as defined in Table 24.

Table 24: Non-common path slope error allocation

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

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

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

4.2.3 NFIRAOS

4.2.3.1 General

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

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

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

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

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

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

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

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

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

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

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

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

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

4.2.3.2 Servicing and Maintenance

[REQ-1-OAD-2845] NFIRAOS shall be designed to be consistent with the servicing and replacement intervals and scenarios shown in Table 25.

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

Table 25 NFIRAOS Servicing Requirements

TBD

4.2.4 LGSF

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

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

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

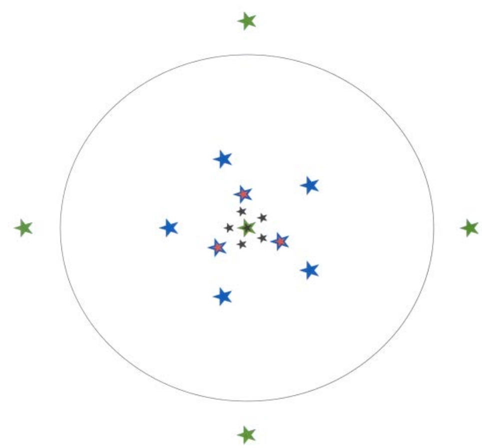


*Figure 9 LGSF asterisms supporting different AO modes: **NFIRAOS** (black) 1 on-axis, 5 on a 35 arcsec radius; **MIRAO** (red) 3 on a 70 arcsec radius; **MOAO** (blue) 3 on a 70 arcsec radius, 5 on a 150 arcsec radius; **GLAO** (green) 1 on-axis, 4 on a 510 arcsec radius*

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

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

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

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

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

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

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

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

[REQ-1-OAD-2937] In addition to any other motion requirements, the LGSF shall be capable of correcting for any combination of the deflections at the telescope top end as specified in Table 16.

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

[REQ-1-OAD-2942] The LGSF Beam Transfer Optics shall transport the laser beams from the laser system up to the LGSF Laser Launch Telescope via the Beam Transfer Optics Elevation Optical Path. This is routed from the –X ECRS telescope elevation journal up to the laser launch telescope via the –X, +Y ECRS diagonal column of the telescope elevation structure and the connecting tripod leg (+Y ECRS tripod leg).

Discussion: The routing of the beam transfer optics elevation optical path is defined in drawing TMT.INS.AO.LGSF.ELOP-ENV

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

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

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

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

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

4.2.4.1 Servicing and Maintenance

[REQ-1-OAD-2960] The LGSF shall be designed to be consistent with the servicing and replacement intervals and scenarios shown in Table 26.

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

Table 26 LGSF Servicing Requirements

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

[REQ-1-OAD-2992] Access shall be provided to those components of the LGSF Beam Transfer Optics Elevation Optical Path which are located along the –X,+Y ECRS diagonal column when the telescope is zenith pointing.

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

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

4.2.5 Adaptive Optics Executive Software (AOESW)

4.2.5.1 General

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

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

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

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

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

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

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

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

4.2.5.2 Servicing and Maintenance

[REQ-1-OAD-3050] The AOESW shall be designed to be consistent with the servicing and replacement intervals and scenarios shown in Table 27.

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

Table 27 AOESW Servicing Requirements

TBD

4.2.6 IRIS

4.2.6.1 General

4.2.6.2 Servicing and Maintenance

[REQ-1-OAD-3150] IRIS shall be designed to be consistent with the servicing and replacement intervals and scenarios shown in Table 28.

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

Table 28 IRIS Servicing Requirements

TBD

4.2.7 IRMS

4.2.7.1 General

4.2.7.2 Servicing and Maintenance

[REQ-1-OAD-3250] IRMS shall be designed to be consistent with the servicing and replacement intervals and scenarios shown in Table 29.

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

Table 29 IRMS Servicing Requirements

TBD

4.2.8 WFOS

4.2.8.1 General

4.2.8.2 Servicing and Maintenance

[REQ-1-OAD-3350] WFOS shall be designed to be consistent with the servicing and replacement intervals and scenarios shown in Table 30.

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

Table 30 WFOS Servicing Requirements

TBD

4.3 SERVICES

4.3.1 Power, Lighting and Grounding

4.3.1.1 General

[REQ-1-OAD-4400] Electrical power shall be distributed to the summit facilities, enclosure, telescope and sub-systems as defined in Table 31 – Power types delivered to enclosure, telescope and telescope mounted equipment and sub-systems.

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

*See discussion for explanation

Table 31 – Power types delivered to enclosure, telescope and telescope mounted equipment and sub-systems

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

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

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

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

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

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

[REQ-1-OAD-4425] The backup generator shall be sized to support the following loads:

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

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

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

Discussion: The purpose of the UPS is to maintain power to systems and equipment that cannot tolerate the expected 30 second delay between loss of normal power and the availability of the backup generator. All UPS loads will be transferred to the back up generator when its operation allows load transfer. This approach is taken in preference to the alternative of maintaining power to equipment until it can be manually shut down in a predictable manner. The list of equipment that is connected to the UPS is defined in RD14 (TMT Power and Cooling Budget).

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

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

[REQ-1-OAD-4500] The power, lighting and grounding system shall distribute the electrical power types on the telescope structure as described in Table 31.

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

4.3.1.2 Lighting Requirements

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

Illumination of floor at 100 lux

Illumination of Nasmyth platforms at 100 lux

Illumination of walkways at 300 lux

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

4.3.1.3 Grounding Requirements

TBD

4.3.2 Coolant

4.3.2.1 General

[REQ-1-OAD-4660] Coolant shall be supplied to the observatory at the temperatures defined in Table 32:

Description	Temperature	Comments	Anticipated Uses
Fixed temperature facility coolant	+7 +/-ºC	Chosen at operating temperature for standard chiller equipment	Majority of facility cooling including computer room, mirror coating equipment
Variable temperature coolant	See comments	Temperature approximately 5 degrees C below the desired enclosure temperature for the next night's observing. The offset below the enclosure temperature set point may vary depending on the set point.	Majority of electronic equipment located on telescope
Air handler fixed low temperature coolant	-15 +/-ºC		Enclosure air handlers and hydrostatic bearing system (tbc)

Table 32 Observatory coolant supply

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

Discussion: The choice of coolant is still TBD. Both ethylene glycol/water solutions and Dynalene are being considered as the primary coolant used throughout the observatory.

[REQ-1-OAD-4670] The normal operating pressure of the coolant supplies listed in table 2 will be 5 bar.

[REQ-1-OAD-4675] The maximum pressure drop through any single equipment heat exchanger shall be less than 1 bar.

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

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

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

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

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

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

[REQ-1-OAD-4725] Chilled glycol coolant shall be provided to the different locations of the LGSF Beam Transfer Optics Optical Path and LGSF Top End.

[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
- All cryogenic cooling
- 'Variable temperature coolant' as per Table 31

Discussion: It is expected that the variable coolant will be maintained at an elevated temperature, possibly by using the enclosure air handlers to cool it.

4.3.3 Communications and Information Services (CIS)

4.3.3.1 Local Area Network (LAN)

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

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

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

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

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

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

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

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

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

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

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

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

4.4 FACILITIES

4.4.1 Enclosure

4.4.1.1 General

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

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

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

[REQ-1-OAD-5065] The enclosure shall be capable of pointing the aperture opening to a target on the sky over the required range of motion within a peak error of 10 arcmin in each axis on the sky.

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

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

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

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

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

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

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

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

TBD

Figure 10 Allowable enclosure vibration PSD

[REQ-1-OAD-5105] Except when observing or when necessary in servicing and maintenance mode, the enclosure shall be parked such that the top end servicing platform is aligned with the telescope top end and the shutter is pointing north.

Discussion: REQ-1-OAD-1270 defines the telescope parked position.

4.4.1.2 Enclosure Geometry

[REQ-1-OAD-5150] No part of the inner enclosure shall be within the volume defined in drawing TMT.FAC.ENC-ENV.

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

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

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

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

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

[REQ-1-OAD-5161] The size of the clear aperture opening shall be 31.25 m diameter at the external radius as shown in the TMT Enclosure Geometry Drawing TMT.ENC.GTY-0001 (see section 1.1)

Discussion: The 30 m primary mirror aperture as defined by the perimeter of the mirror is located 3.5 - 1.875 = 1.625 m below the elevation axis. The height of the aperture opening defined by the flaps is 32.5 m above the primary aperture. A 31.25 m opening gives an oversize in radius of tan-1{0.625/32.5} = 66 arcmin.

We need 10 arcmin for the science FOV radius, and about 10 arcmin for pointing and tracking, which leaves slightly less than 50 arcmin of radius or 100 arcmin of diameter for telescope tracking with the enclosure held fixed. At a sidereal rate of 15 degrees/hour, 100 arcmin of diameter oversize represents about 400 seconds of tracking with a strategy of fixing the enclosure 50 arcmin ahead of the telescope then letting the telescope track until the enclosure is 50 arcmin behind.

4.4.1.3 Slewing

4.4.1.3.1 Enclosure Base Axis Slewing

[REQ-1-OAD-5162] In observing mode the enclosure shall be capable of making all base axis moves rapidly, such that they can be completed, including smooth ramping profiles and settling time, faster than an equivalent move with a trapezoidal velocity profile with acceleration and deceleration rate of 0.25 degrees/s^2 and a maximum velocity of 1.25 degrees/sec.

Discussion: "Observing mode" for the enclosure indicates that the wind speed is within the observing performance conditions and that there are no snow and ice accumulations on the enclosure.

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

[REQ-1-OAD-5164] The maximum slewing rate of the enclosure base axis shall not exceed 1.25 degrees/sec.

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

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

4.4.1.3.2 Enclosure Cap Axis Slewing

[REQ-1-OAD-5168] In observing mode the enclosure shall be capable of making all cap axis moves rapidly, such that they can be completed, including smooth ramping profiles and settling time, faster than an equivalent move with a trapezoidal velocity profile with acceleration and deceleration rate of 0.15 degrees/s^2 and a maximum velocity of 1.75 degrees/sec.

Discussion: "Observing mode" for the enclosure indicates that the wind speed is within the observing performance conditions and that there are no snow and ice accumulations on the enclosure.

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

[REQ-1-OAD-5170] The maximum slewing rate of the enclosure cap axis shall not exceed 1.75 degrees/sec.

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

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

4.4.1.4 Wind, Thermal and Environmental Management

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

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

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

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

[REQ-1-OAD-5190] The enclosure design shall include vent openings with a minimum total vent area of 1500m2. The shape and location of the vent openings is defined in the TMT Enclosure Geometry Drawing TMT.ENC.GTY-0001 (see section 1.1)

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 then the maximum *defined by the vent openings to account for bracing, vent door frames and other obstructions (conservative estimate, 1,500 m²).*

[REQ-1-OAD-5195] The area averaged RSI insulation value of the enclosure including the fixed base shall be at least 6 m2K/W. This insulation value shall be provided between the enclosure interior and the interstitial space.

Discussion: This insulation value is averaged over the entire enclosure interior surface including the vent doors, shutter rail and other areas which may have lower insulation values than the bulk areas of insulation covering the interior walls.

[REQ-1-OAD-5197] Vent doors (including door seal conductance but not infiltration) shall provide an averaged RSI insulation value of at least 4 m^2K/W.

[REQ-1-OAD-5198] Any heat loads related to operation of the enclosure shall be dissipated to the enclosure interstitial space.

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

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

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

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

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

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

[REQ-1-OAD-5208] The enclosure shall incorporate aperture flaps with geometry as per the TMT Enclosure Geometry Drawing TMT.ENC.GTY-0001 (see section 1.1).

[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^2/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).

4.4.1.5 Summit Facility Fixed Base

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

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

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

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

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

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

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

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

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

- Sector extending 22.5º counterclockwise from main enclosure door
- Sector extending 60º clockwise from main enclosure door (excluding air handler and protrusion of M2/M3 coating chamber into fixed enclosure)
- Sector extending TBDº counterclockwise from entrance from summit facilities building to fixed base (excluding air handlers and stairways)

Discussion: The sector extending clockwise and counterclockwise from the main entrance into the enclosure is to be kept clear for vehicular access, M2 and M3 operations and transferring large components into the enclosure.

[REQ-1-OAD-5259] The inner radius of the fixed enclosure walkway shall be greater than 26.8m.

[REQ-1-OAD-5260] The summit facility fixed base shall provide an access door to the exterior of the facility at grade with an opening of at least 4.88m wide by 5.03 m high for equipment and component movement.

Discussion: The size restrictions for components that can be transferred into the enclosure via these doors is defined in TMT.SEN.TEC.11.014

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

[REQ-1-OAD-5267] Two entrances 1m wide by 2m high shall be provided in the pier wall to allow personnel access to the area enclosed by the pier.

Discussion: At least one of these doorways may need to be an 'emergency exit' only to prevent personnel using the area within the pier as a throughway from one side of the telescope to the other.

[REQ-1-OAD-5270] The summit facility fixed base shall provide a tunnel from the facilities mechanical and electrical plant to the pintle bearing area housing the telescope cable wrap for delivery of utility services to the telescope and telescope mounted sub-systems

[REQ-1-OAD-5272] An emergency egress route shall be provided from the pintle bearing/cable wrap area that allows personnel to exit to the observing floor outside the telescope pier in the event of a fire or other hazard occurring in the service tunnel.

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

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

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

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

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

[REQ-1-OAD-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.

4.4.1.6 Top End Servicing Platform

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

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

Discussion: To prevent possible collisions between the top end servicing platform and the telescope, the Observatory Safety System will provide interlock signals as required to prevent deployment of the top end platform unless the telescope and enclosure are aligned and stationary. It will also prevent motion of either the telescope or enclosure if the platform is not stowed.

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

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

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

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

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

4.4.1.7 Survival Loads

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

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

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

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

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

1) rotation of the enclosure cap or base.

2) operation of the aperture flaps.

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

4) operation of the vents.

5) the ability to safely observe.

6) Opening of the shutter

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

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

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

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

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

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

4.4.1.8 Enclosure Servicing and Maintenance

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

[REQ-1-OAD-5355] The enclosure shall be designed to be consistent with the servicing and replacement intervals and scenarios shown in Table 33.

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

Table 33 Enclosure Servicing Requirements

TBD

4.4.2 Summit Facilities

4.4.2.1 General

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

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

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

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

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

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

4.4.2.2 Mirror Maintenance

[REQ-1-OAD-5505] A mirror stripping and coating facility sufficient to process the M1 mirror segments shall be located adjacent to the enclosure to minimize mirror transportation

[REQ-1-OAD-5507] A mirror stripping and coating facility sufficient to process the M2 and M3 mirrors shall be located either adjacent to or within the enclosure to minimize mirror transportation

[REQ-1-OAD-5510] The M1 mirror coating and stripping facility shall be equipped with an overhead crane.

Discussion: It is anticipated that the M2 and M3 coating chamber will be located in an area accessible by the enclosure mounted crane or hoist.

[REQ-1-OAD-5515] The M1 mirror coating area shall be built and equipped to be capable of providing a class 10,000 clean room environment.

[REQ-1-OAD-5517] The M2 and M3 mirror coating chamber shall be located in an area that will allow a temporary clean environment to be constructed during mirror stripping and coating activities.

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

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

4.4.2.3 Operations Spaces

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

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

4.4.2.4 Lab & Shop Spaces

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

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

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

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

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

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

4.4.2.5 Personnel Spaces

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

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

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

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

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

4.4.2.6 Shipping & Receiving

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

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

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

4.4.2.7 Mechanical Plant

[REQ-1-OAD-5620] A mechanical plant will be provided to house the mechanical equipment required at the summit facilities.

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

[REQ-1-OAD-5630] The summit facility mechanical plant shall incorporate chillers, to be used in the daytime with the air conditioning system in the fixed base, with sufficient capacity to remove the heat loads listed in RD14 and environmental heat loads (air infiltration, solar heating etc.). via the chilled water cooling systems described in section 4.3.2) .

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

[REQ-1-OAD-5632] The air conditioning shall be capable of providing a total flow of $23.6 m^3/s$ at the following operating points with 80% of air being re-circulated :

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

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

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

4.4.2.8 Electrical Plant

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

4.4.2.9 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.

4.4.2.10 Grounding and Lightning Protection

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

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

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

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

4.4.2.11 Fire Protection and Safety

[REQ-1-OAD-5690] A fire suppression system shall be supplied throughout the summit facilities building. [REQ-1-OAD-5692] The summit facilities shall support first aid treatment of personnel.

[REQ-1-OAD-7000] The summit facility shall incorporate video and audio systems to allow operations staff to monitor the enclosure environment.

4.4.2.12 Summit Facility Servicing and Maintenance

[REQ-1-OAD-5700] The summit facility shall be designed to be consistent with the servicing and replacement intervals and scenarios shown in Table 34.

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

Table 34 Summit Facility Servicing Requirements

TBD

4.4.3 Headquarters

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

4.4.3.1 General

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

4.4.3.2 Administration

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

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

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

4.4.3.3 Remote Control Room

[REQ-1-OAD-5800] A remote control/observing room including two full observing consoles shall be provided at the headquarters building.

4.4.3.4 Lab & Shop Spaces

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

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

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

[REQ-1-OAD-5825] The headquarters shall provide a mask cutting facility including space for mask storage, mask cutter, handling carts, workstation and workbenches.

4.4.3.5 Storage

[REQ-1-OAD-5830] Storage and capacity shall be provided at the headquarters that is sufficient to house the equipment, tools and spares used to support sea level technical work.

Discussion: It is anticipated that the majority of the storage space required for observatory spares will be in rented warehouse space.

4.4.3.6 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.

4.4.3.7 Mechanical Plant

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

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

4.4.3.8 Electrical Plant

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

[REQ-1-OAD-5865] An emergency generator shall be provided to ensure that remote observing can take place in the event of a power outage.

4.4.3.9 Roads & 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.

4.5 SERVICING AND MAINTENANCE

4.5.1 Crane Systems

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

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

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

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

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

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

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

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

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

- The maximum reach shall be no less than R 0.0m to R 27.5m relative to the TCRS z-axis
- At 27.5 m radius, the maximum hook height shall be at least 30.9m above the TCRS XY plane
- At 0.0 m radius, the maximum hook height shall be at least 48.5 m above the TCRS XY plane
- The minimum hook vertical speed shall be no greater than 0.3 m/min.
- The minimum hook horizontal speed shall be no greater than 0.3 m/min.

- o The hoist shall have a mode in which the vertical hook acceleration is no greater than 0.05g.
- o The minimum horizontal hoist position resolution shall be no greater than Ø 50.0 mm.
- o The minimum increment of vertical motion shall be no greater than 2mm.

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

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

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

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

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

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

Discussion: Mass estimate for azimuth bogies is 2000 kg

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

Discussion: Mass estimate for azimuth bogies is 440 kg

[REQ-1-OAD-6240] There shall be a crane, 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 :Mass estimate for the laser head is 500 kg. This is the heaviest component in the laser system.

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

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

Overhead cranes shall be available in the following places:

- [REQ-1-OAD-6260] Freight and delivery area and mechanical workshop: monorail crane with 5 tonnes capacity, hoist with continuously variable speed control from 0.5 to 5m per minute, trolley with continuously variable speed control from less than 0.2m per minute to at least 20m per minute.
- [REQ-1-OAD-6270] M1 Mirror coating area: bridge crane with 1 ton capacity, hoist with continuously variable speed control from 0 to 4m per minute, trolley with continuously variable speed control from less than 2m per minute to at least 20m per minute and oil shields
- [REQ-1-OAD-6271] M1 Mirror segment maintenance area: monorail crane with 1 ton (TBC) capacity, hoist with continuously variable speed control from 0 to 4m per minute, trolley with continuously variable speed control from less than 0.2m per minute to at least 20m per minute and oil shields.
- *Discussion: A movable crane can be shared between the coating area and stripping area.*

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

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

- [REQ-1-OAD-6274] The engineering lab: monorail crane with 5t capacity hoist with continuously variable speed control from 0 to 4m per minute, trolley with continuously variable speed control from less than 0.2m per minute to at least 20m per minute.
- [REQ-1-OAD-6275] Mechanical workshops: 3 tonnes capacity bridge crane, 2-speed electric hoist with slow speed about 30 cm per minute, and oil shields.
- [REQ-1-OAD-6276] Utility Room: monorail crane with 1 ton capacity, hoist with continuously variable speed control from 0.5 to 5m per minute, trolley with continuously variable speed control from less than 0.2m per minute to at least 20m per minute.
- *Discussion: the monorail crane specified is to service the in-line coating chamber*

4.6 SAFETY

Discussion: Top level safety requirements are in the ORD.

4.6.1 General Requirements on Subsystems

[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-6905] Upon detecting a hazardous fault or condition, a subsystem shall independently and immediately take action to mitigate the hazard and reduce risk. The subsystem shall not require any interaction with, or the presence of, the OSS in order to do this.

[REQ-1-OAD-6910] Upon detecting a hazardous fault or condition, a subsystem shall send an interlock request signal to the OSS.

Discussion: The purpose of the interlock request signal is to allow the subsystem to be able to quickly and robustly inform the OSS that it has detected a hazardous fault or condition. Because the state of this signal is safety-critical it must be delivered a fail safe manner.

4.6.2 Observatory Safety System

Discussion: This section contains requirements applicable to the Observatory Safety System itself and to other subsystems that interface to it.

4.6.2.1 General

[REQ-1-OAD-7050] The Observatory Safety System shall be implemented as an independent PLC based sub-system whose operation does not rely on the availability of any other sub-systems.

[REQ-1-OAD-7051**]** The OSS shall provide fault, interlock and emergency stop monitoring and control in a manner consistent with the TMT Observatory Hazard Analysis document (RDX)

Discussion: The TMT Observatory Hazard Analysis document identifies the possible faults and hazardous conditions associated with the operation of the observatory and defines the necessary mitigating action(s) to be taken by each subsystem.

[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, rather than rely on the interlock request/interlock demand scheme, which in this case is unnecessarily complicated for the detection of such a simple event. This does not imply that the OSS provides sensors to detect faults or hazardous conditions.

[REQ-1-OAD-7060] All equipment with functions or malfunctions potentially capable of harming people or causing significant financial loss shall be monitored by the Observatory Safety System.

[REQ-1-OAD-7061] The OSS shall include a simple user interface 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 Mangement System (DMS) and the Executive Software (ESW) whenever an interlock request is received or an interlock demand is raised.

Discussion: How this is accomplished is TBD, but a publisher/subscriber model implemented between the OSS and the DMS/ESW and other interested systems may be appropriate.

[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 reason for the interlock event, the time the event occurred etc.)

Discussion: This is obviously only possible for subsystems with network access to the ESW & DMS and the means to publish the information. For less capable devices such as standalone sensors, switches etc., it is sufficient that the OSS inform the DMS & ESW of the event(s) per REQ-1-OAD-7062 above.

[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.

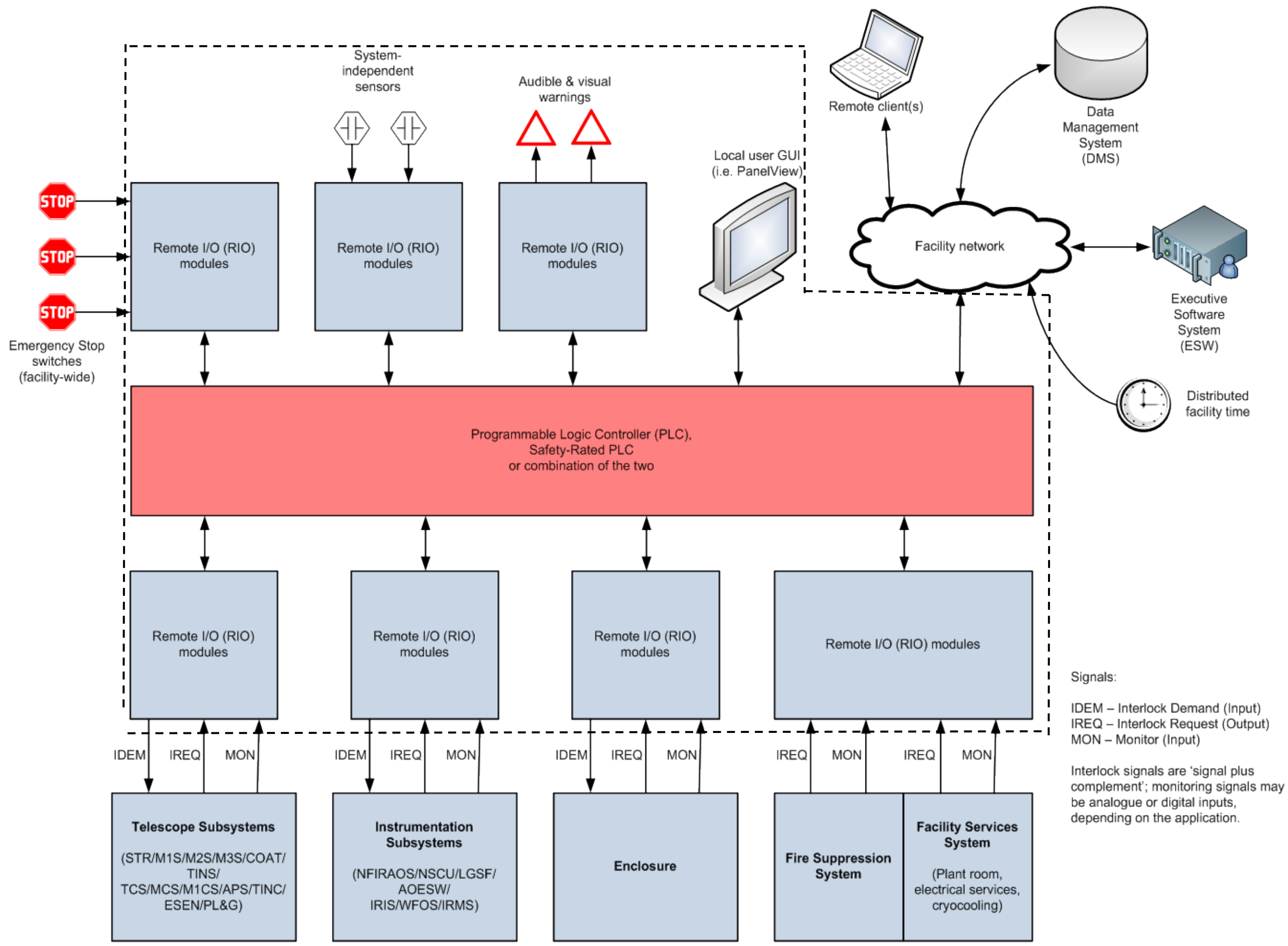


Figure 11- Observatory Safety System Architecture, equipment within dotted line indicates scope of OSS

4.6.2.2 Interlocks

[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.

Discussion: This implies that all subsystems shall receive an interlock demand signal from the OSS, as well as provide an interlock request signal to it. Both signals shall be transmitted in a 'signal plus complement' (or equivalent) form to allow for the detection of faults such as cable breakage or disconnection.

[REQ-1-OAD-7080] Once an interlock demand has been raised by the OSS, it shall remain raised (latched) until it is manually reset via the user interface at the telescope observing floor.

Discussion: It is suggested that resetting of interlock demands be disallowed over the remote interface, or from any location other than the interface located on the telescope observing floor. This forces the trouble-shooter to visit the locale of the telescope and encourages the best practise of undertaking a proper inspection before clearing a fault. This reduces the likelihood of hazards going undetected.

[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.

4.6.2.3 Emergency Stop (E-Stop)

[REQ-1-OAD-7100] The OSS shall incorporate a hardware based emergency stop (E-Stop) system that operates without reliance on any other observatory sub-system.

[REQ-1-OAD-7105] The OSS shall be responsible for continuously monitoring all 'global' 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: Two types of e-stops are envisaged; 'global' e-stops that are located throughout the observatory which when triggered initiate action by the OSS placing all sub-systems in a safe state; 'local' e-stops that are provided and monitored by the sub-system that provides them and when triggered affect only that sub-system.

Discussion: In general, a system would be shut down (made safe) when an emergency stop is triggered by asserting its interlock demand signal. This is not the only thing that could be done however; for example, the safety PLC in charge of the emergency stops could have a means of controlling circuit breakers so that power could be removed under direct PLC control.

[REQ-1-OAD-7110] Emergency stop switches shall be conveniently and appropriately located throughout the summit facility as necessary to ensure adequate coverage and access in the event of an emergency.

Discussion: Emergency stop switches should be located in and near areas where hazards may occur or be detected. The guiding principle should be that of common sense; locate emergency stop switches where they are easy to locate and operate in the event of an emergency and where they will not be accidentally activated. The distributed I/O capabilities of the RIO modules make this task relatively easy.

[REQ-1-OAD-7112] It is the responsibility of each subsystem to provide any emergency stop switches mounted at its location(s), and to connect them to the nearest interface to the OSS.

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

[REQ-1-OAD-7113] Global and local E-stop switches shall be appropriately identifiable via industry standards.

[REQ-1-OAD-7115] All subsystems and equipment interlocked by the OSS shall be capable of withstanding multiple emergency stop occurrences without damage.

[REQ-1-OAD-7120] The OSS shall be able to immediately identify and report the location of any triggered emergency stop switch.

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

4.6.3 Telescope Safety

4.6.3.1 General

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

[REQ-1-OAD-7205] The telescope shall incorporate earthquake stops on the elevation and azimuth axes that are capable of restraining the system during an Infrequent earthquake event as defined in the ORD.

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

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

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

[REQ-1-OAD-7230] Under an emergency stop condition, the deceleration rate of the telescope azimuth axis shall be 2 degrees/sec^2.

Discussion: For a maximum azimuth speed of 2.2 deg/s, the stopping time, stopping distance and deceleration at the edge of the Nasmyth platform are:

Table 35 Telescope azimuth stopping deceleration, time and distance

Azimuth deceleration rate, deg/s^2	Stopping time, sec	Stopping distance at Nasmyth platform edge, m	Deceleration at Nasmyth Platform edge, g
1.75	1.26	0.67	0.086
2.00	1.10	0.58	0.098
2.25	0.98	0.52	0.110

[REQ-1-OAD-7235] Under an emergency stop condition, the deceleration rate of the telescope elevation axis shall be 2.0 degrees/sec^2.

Discussion: For a maximum elevation speed of 0.6 deg/s, the stopping time, stopping distance and deceleration at the elevation journal and the top end are:

Table 36 Telescope elevation stopping deceleration, time and distance

Elevation deceleration rate, deg/s^2	Stopping Time, s	Stopping distance at elevation journal, m	Deceleration at elevation journal, g	Stopping distance at top end, m	Deceleration at top end, g
2.00	0.30	0.02	0.038	0.04	0.098
2.25	0.26	0.01	0.043	0.04	0.110
2.50	0.24	0.01	0.048	0.03	0.123

4.6.4 Enclosure Safety

4.6.4.1 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.

4.6.4.2 Enclosure Safety System

[REQ-1-OAD-7350] The Enclosure Safety System shall monitor and protect the system and personnel under the conditions identified in the TMT Enclosure Hazard Analysis document (RDX)

Discussion: These conditions may include Enclosure cap, base and shutter over-speed; enclosure cap, base and shutter drive over-current ;, enclosure control system failure; seismic events; unstowed cranes*; over temperature conditions; deployable platforms not correctly stowed.*

4.6.5 Laser Guide Star Facility

[REQ-1-OAD-7500] The System shall follow the safety rules defined for the class 4 lasers used in the LGSF system.

[REQ-1-OAD-7505]: The Laser Guide Star Facility Safety System shall monitor the LGSF systems and the associated environment in order to enforce safety of both personnel and the facility and to mitigate the risks and hazards associated with the system identified in the TMT LGSF Hazard Analysis Document (RDX)

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 a combination of visible all sky cameras, transponder based aircraft detection system and infrared boresighted narrow field cameras.

[REQ-1-OAD-7511] The All Sky Camera (ASCAM) shall be mounted in 2 locations, positioned 180 degrees from one another on opposite sides of the observatory, TBD metres from the observatory.

[REQ-1-OAD-7513] The Bore Sighted Camera (BOCAM) shall be mounted on the telescope top end and bore sighted with the telescope.

[REQ-1-OAD-7514] The BOCAM shall also detect clouds prior to the interference with the laser beams.

Discussion: This is a safety requirement. The clouds may prevent the detection of aircraft.

[REQ-1-OAD-7515]: The Observatory procedures and the Observatory Executive Software shall protect satellites from accidental laser illumination

[REQ-1-OAD-7520]: The Laser Guide Star Facility Safety System shall monitor and protect neighboring telescopes from projection of the laser beams within their field of view.

5. SYSTEM ARCHITECTURE

5.1 OBSERVATORY CONTROL ARCHITECTURE

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 **TMT.SEN.SPE.10.001**.*

5.1.1 Pointing, Offsetting, Tracking, Guiding and Dithering

Definition: Pointing is the blind operation establishing the initial alignment of the telescope and instrument foci to the sky. Pointing is not supported by optical feedback (like acquisition camera or WFS) as its very objective is to establish the appropriate conditions for closing any optical loop. Pointing is aided by the pointing model to achieve the required accuracy. The pointing model is a Look-Up-Table (LUT) based or best fit estimated correction to the theoretical commands to the mount actuators. The pointing model comprises the relevant imperfections of the telescope and its control systems for various environmental and operating conditions, most prominently temperature and elevation angle. It also contains astrometry corrections.

Definition: Offsetting is the process of moving from one pointing to another over a small angular distance.

Definition: Tracking i.e. following the virtual sky motion without the aid of any sky reference is a special sequence of pointing, possibly with pre-calculated trajectory. Tracking relies on calculating mount coordinates from the sky coordinates of the target, and correcting them with the pointing model. It is understood that a significant portion of tracking error comes from the imperfect smoothness of the required motion.

Definition: Guiding is defined as tracking with closed loop control based on optical position feedback from a guide star.

Definition: Dithering is the process of repetitively offsetting between two or more pointings.

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

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

[REQ-1-OAD-8015] The Telescope Optical Feedback System (TOFS) shall improve the alignment of the telescope relative to the sky by means of closed optical loop guiding.

[REQ-1-OAD-8020] Guiding shall correct residual image motions by reconstructing image motion (OPD tip/tilt) into mount elevation and azimuth angles

[REQ-1-OAD-8025] The bandwidth for the closed optical guide loop shall be 0.1 Hz.

[REQ-1-OAD-8030] In seeing limited operation, guiding errors shall be directly calculated from the slopes of a guiding NGS WFS or the centroids of a guide camera by the Active Optics Reconstructor & Controller (aORC), which is part of the Telescope Control System (TCS) (See Figure *12*).

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.

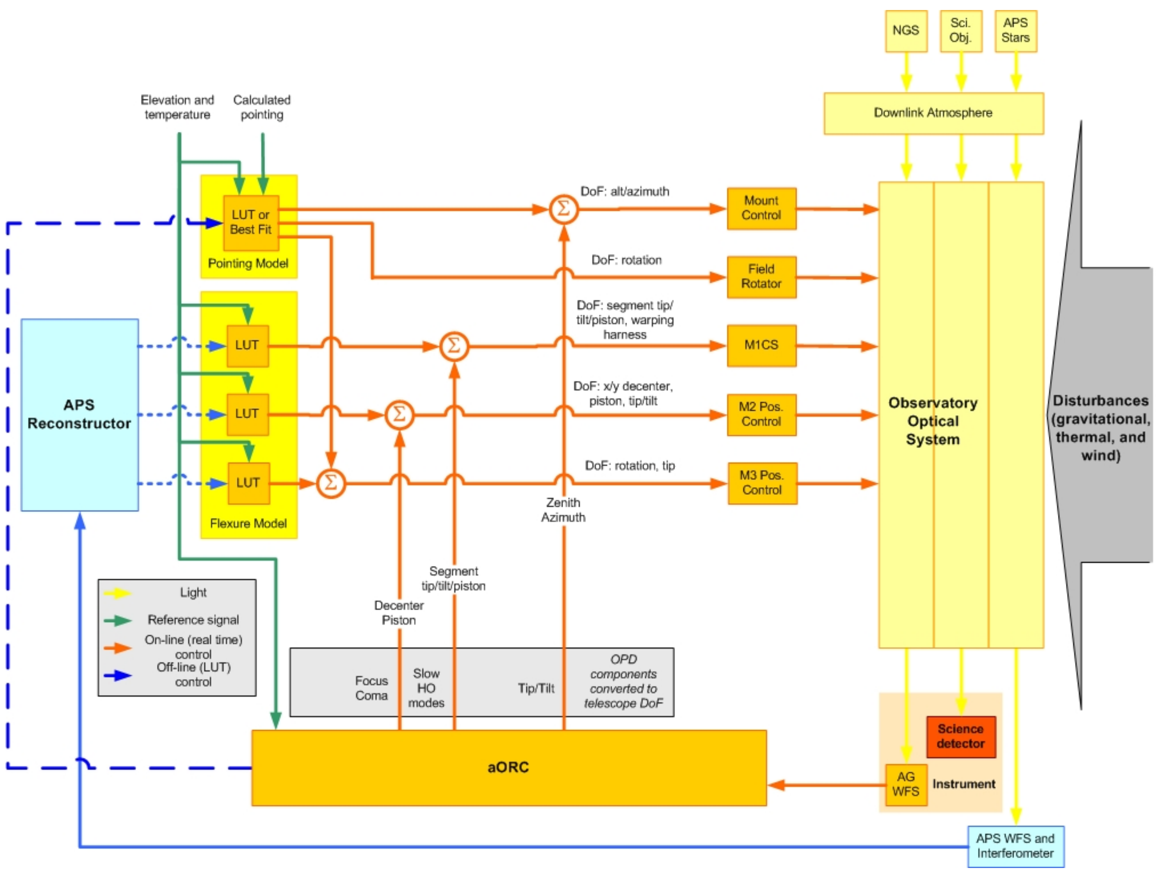


Figure 12 Control architecture for seeing limited observations

[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 13).

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

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

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

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

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

[REQ-1-OAD-8060] The system shall be able to validate pointing independent of an instrument

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

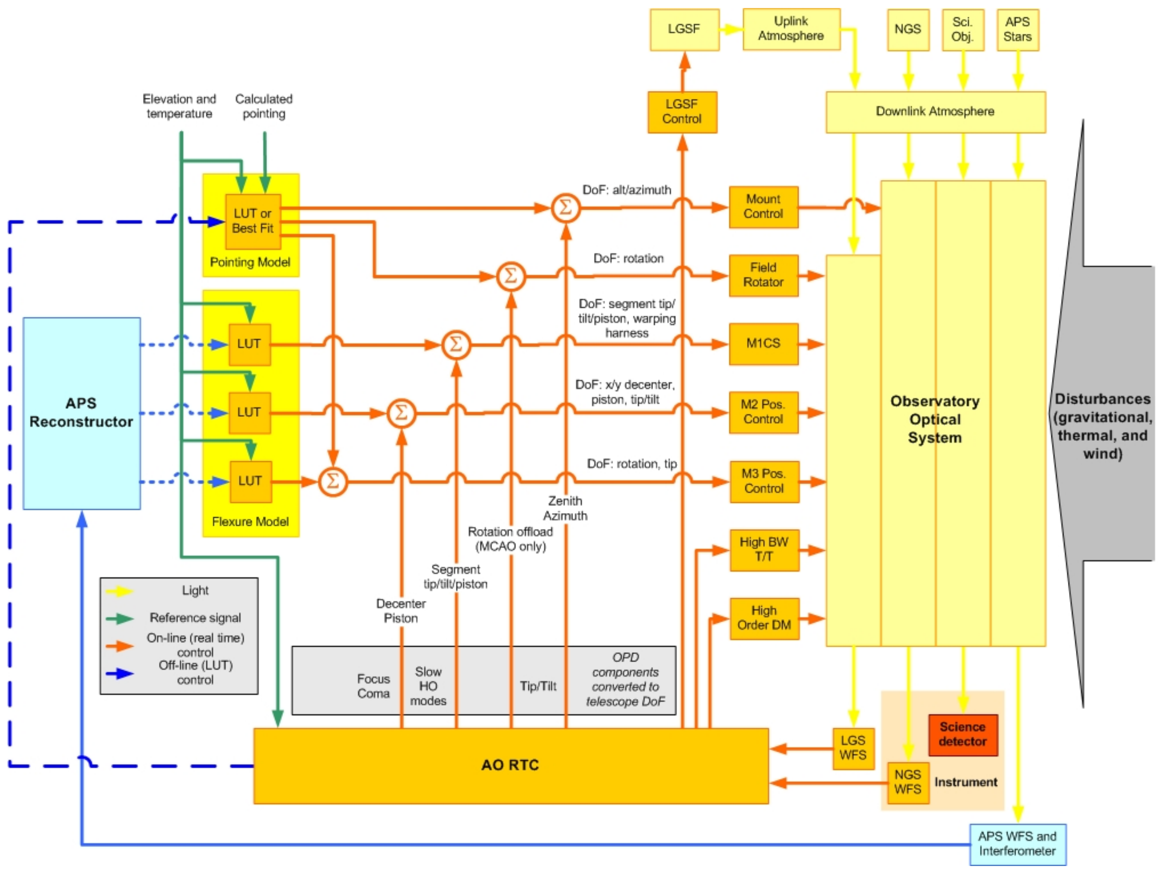


Figure 13 Control architecture for adaptive optics observations

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 12 and Figure 13).

Discussion: Since the calculation of field rotation requires RA, Dec, and sidereal time as inputs, this model is a part of the observatory. This results in a testable interface to instruments via mechanical angle commands.

[REQ-1-OAD-8110] Instruments and AO systems that need higher field de-rotation accuracy than the seeing limited requirements shall provide the means to calibrate their de-rotator, and/or correcting rotation errors by real time optical feedback.

Discussion: It is understood that detecting rotation errors requires an extension to the guiding/aO sensors, allowing off-axis measurements. It is also understood that relatively wide field adaptive optics systems, like an MCAO system, can provide rotation error off-loads.

5.1.3 Atmospheric Dispersion Compensation

[REQ-1-OAD-8200] Atmospheric dispersion compensation commands shall be "blind" i.e. open optical loop operation calculated by the pointing model. This pointing model shall be the responsibility of the telescope control system (TCS).

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

5.1.4 Active and Adaptive Optics Control Architecture

5.1.4.1 General

[REQ-1-OAD-8300] The system shall maintain the shape of the M1 optical surface and the alignment of M1, M2, and M3 relative to each other, i.e. the collimation of the telescope by means of active optics compensation of thermal, gravitational, and vibration disturbances (see Figures 12 and 13).

Discussion: The most prominent vibration disturbance is expected to be wind buffeting.

REQ-1-OAD-8310] The system shall be able to validate wavefront control independent of an instrument

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

[REQ-1-OAD-8320] The Telescope Optical Feedback System (TOFS) shall meet all performance requirements without degrading he sky coverage of the seeing limited science instruments: 95% for WFOS and TBD% for HROS at the galactic pole.

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

[REQ-1-OAD-8330] The Telescope Optical Feedback System (TOFS) shall operate and meet performance requirements even when not all primary mirror segments are installed.

5.1.4.2 Active Optics Actuators

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

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

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

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

[REQ-1-OAD-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 ydecenter) for each of up to 6 segments.

5.1.4.4 Compensation Strategy

[REQ-1-OAD-8600] The adaptive optics system, or in absence of it an “on-instrument” low order NGS WFS, shall provide time averaged wavefront errors to the Telescope Optical Feedback System (TOFS).

Discussion: This is necessary to limit drifts in the active optics system and correct for uncertainties due to the not completely resolved temperature distribution of the environment, structure, and glass.

[REQ-1-OAD-8605] The OPD information supplied to the TOFS shall be the same in both seeing limited and near diffraction limited observations.

[REQ-1-OAD-8610] OPD focus shall be reconstructed into M2 piston.

[REQ-1-OAD-8615] The bandwidth for the Telescope Optical Feedback System (TOFS) loop feeding OPD focus back to M2 piston shall be 0.0001 Hz.

[REQ-1-OAD-8620] OPD coma shall be reconstructed into M2 decenter

[REQ-1-OAD-8625] The integration time for the TOFS loop feeding OPD coma back to M2 decenter shall be 300 seconds (TBC).

Discussion: Both focus and coma is primarily controlled by LUT developed through APS measurements (see appendix table 41). 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: For illustrative purposes, Table 44 *in the appendix includes additional suggested architectural details regarding the mount and active optics actuators and corresponding sensors.*

[REQ-1-OAD-8635] In adaptive optics operation higher order OPD information including focus and coma shall be computed by averaging the ground conjugated deformable mirror commands, or, if AM2 is used, by averaging the AM2 modes. In both cases, the higher order OPD information are computed by the AO RTC.

[REQ-1-OAD-8640] In both seeing limited and adaptive optics operations the OPD information shall be scaled and rotated into telescope modes (degrees of freedom) that are transferred to the Telescope Control System.

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

[REQ-1-OAD-8650] The integration time for higher order OPD information fed back to M1 mirror modes shall be 300 seconds (TBC).

[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 inFigure 13.

Discussion: The architecture is an extension of the active optics control architecture. New features include (i) the control of high order DMs and high bandwidth tip/tilt stages using measurements from NGS and LGS wavefront sensors, (ii) offloads from these components to M1, M2, and the mount, and (iii) pointing and centering control of the beam transfer and projection optics in the LGS facility

5.1.5 Acquisition

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

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

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

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

5.1.5.1 Acquisition Process

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

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

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

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

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

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

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

5.1.5.2 Acquisition Sequences for Different System Configurations

Discussion: Section 0 of the Appendix illustrates some example acquisition sequences for seeing limited and adaptive optics modes of the observatory. These are for illustration purposes, and are not requirements on the system.

5.2 OBSERVATORY SOFTWARE ARCHITECTURE

5.2.1 High-level software system definition

5.2.1.1 Observation Execution System (OES)

[REQ-1-OAD-9000] An observation execution system (OES) shall be implemented to enable efficient observation of astronomical objects as well as efficient command, control, and monitoring of all observatory functions.

[REQ-1-OAD-9003] The OES shall consist of a set of software subsystems that interact through a software connectivity backbone layered on top of a physical communications network (see Figure 14).

Discussion: the OES follows a distributed (component-connector) architecture model. The connector is decomposed into a set of communication common services (discussed later).

[REQ-1-OAD-9006] It shall be possible to orchestrate a complete observation, including observatory configuration and target acquisition sequences, from an OES master process sequencer. This master sequencer shall be capable of system action flow control as well as system process synchronization and parallelization.

Discussion: OES can be viewed as a sequencing engine for the execution of science observations. Observation descriptions are generated by users using a variety of interface tools and submitted to the OES for action. Based on those descriptions, the OES orchestrates a sequence of system actions to accomplish the described observation. Science datasets are the primary output of this process.

[REQ-1-OAD-9009] The OES command-and-control architecture is hierarchical (see Figure 15). The transition from one system configuration ("observational setup") to another results from a sequence of activities initiated and coordinated by a master sequencer. This coordination is accomplished in concert with a set of lower tier sequencers.

[REQ-1-OAD-9012] The master sequencer shall establish the appropriate OES command-and-control hierarchy depending on the requested observation (or observatory system re-configuration).

Discussion: in a logical sense, different hierarchical relationships are established for different observational setups. For example, Figure 15 shows the logical hierarchical relationship established to execute an IRIS observation using laser guide stars.

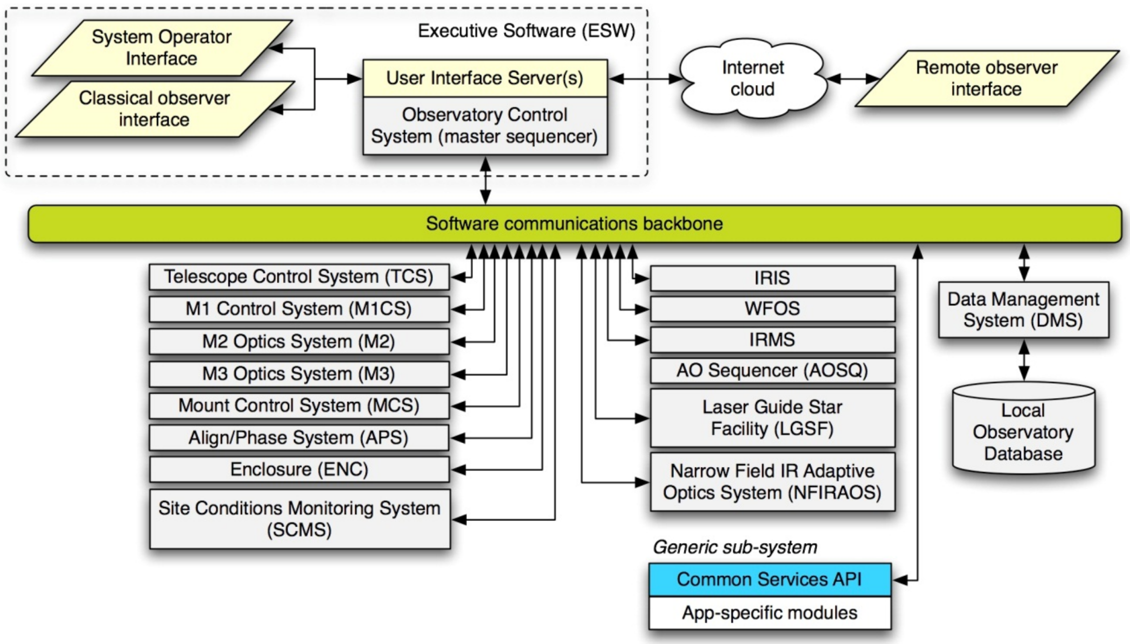


Figure 14: Observation execution system (OES) architecture (communication)

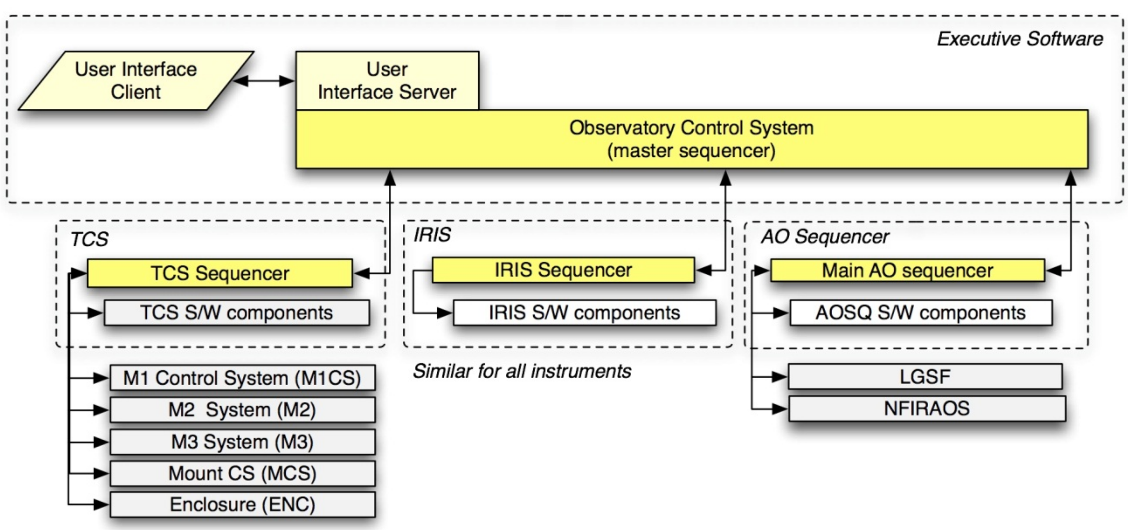


Figure 15: Observation execution system (OES) architecture (workflow)

[REQ-1-OAD-9015] OES user interfaces must be provided to accept user input, generate and submit observation requests, and process and display ("monitor") OES health and status information.

[REQ-1-OAD-9018] Only OES user interfaces running on trusted machines shall be allowed to interact with TMT. An access control system shall be implemented.

[REQ-1-OAD-9021] OES user interfaces shall be created for the following system user types shown in Table 37.

User Type	Description
System operator	On-duty TMT staff person who is responsible for controlling and monitoring the TMT software system on behalf of other system users (e.g. visiting scientists, technical teams, etc.)
Classical (on-site) observer	Anyone executing science observations and/or acquiring associated calibration data in near-real-time while physically present at TMT.
Remote (off-site) observer	Anyone executing science observations and/or acquiring associated calibration data in near-real-time while physically present at an approved remote observing facility.
Queue observer	Anyone who has submitted descriptions of science observations and/or associated calibration data acquisition sequences for the purposes of later execution as scientific priority and observing conditions permit.
Technical user	Anyone who is monitoring system performance, performing system maintenance tasks, and/or implementing system improvements.

Table 37 Software system user types

[REQ-1-OAD-9024] All TMT OES user interfaces shall have a common look-and-feel within each interface category (i.e. command-line interface, graphical user interface, Web interface).

[REQ-1-OAD-9027] Graphical user interfaces (GUIs) shall be the default interface for all normal scientific and technical operations. The standard TMT software framework shall include libraries and/or editors to support GUI development.

[REQ-1-OAD-9030] OES user interfaces shall use the communication services defined in Table 38.

[REQ-1-OAD-9033] Data visualization tools must be provided for the following situations:

- Target acquisition support (acquisition and WFS)
- Science data quick-look data quality assurance support
- Technical data presentation
- Environmental conditions presentation
- System status presentation

[REQ-1-OAD-9036] Whenever possible, data visualization tools shall re-use or be based on existing solutions.

[REQ-1-OAD-9039] Automatic system startup and shutdown processes shall be implemented.

[REQ-1-OAD-9042] It shall be possible to run the TMT software system in simulation mode.

[REQ-1-OAD-9045] All software servers shall be attached to an uninterruptible power system (UPS).

5.2.1.2 Program Execution System (PES)

Discussion: due to resource limitations, the PES shall be implemented incrementally. The PES architecture and subsystem design must take that limitation into account.

[REQ-1-OAD-9100] A program execution system (OES) shall be implemented to enable efficient management of astronomical programs from proposal creation to data delivery.

Discussion: a schematic program management workflow has been described in the OCD.

[REQ-1-OAD-9103] At each step of the way, a program shall additional information: allocated time, assigned scientific priority, observation descriptions, system status information, observing condition information, raw data frames, output from data processing systems, etc.

[REQ-1-OAD-9106] This information shall be stored in a well-structured, normalized observatory database (ODB).

[REQ-1-OAD-9109] Each PES subsystem shall support one key aspect of the PES workflow (e.g. proposal management, observation management, observation execution, data processing, and science archive management). Although each subsystem can be implemented independently, they share relational database structures within the observatory database (see Figure 16).

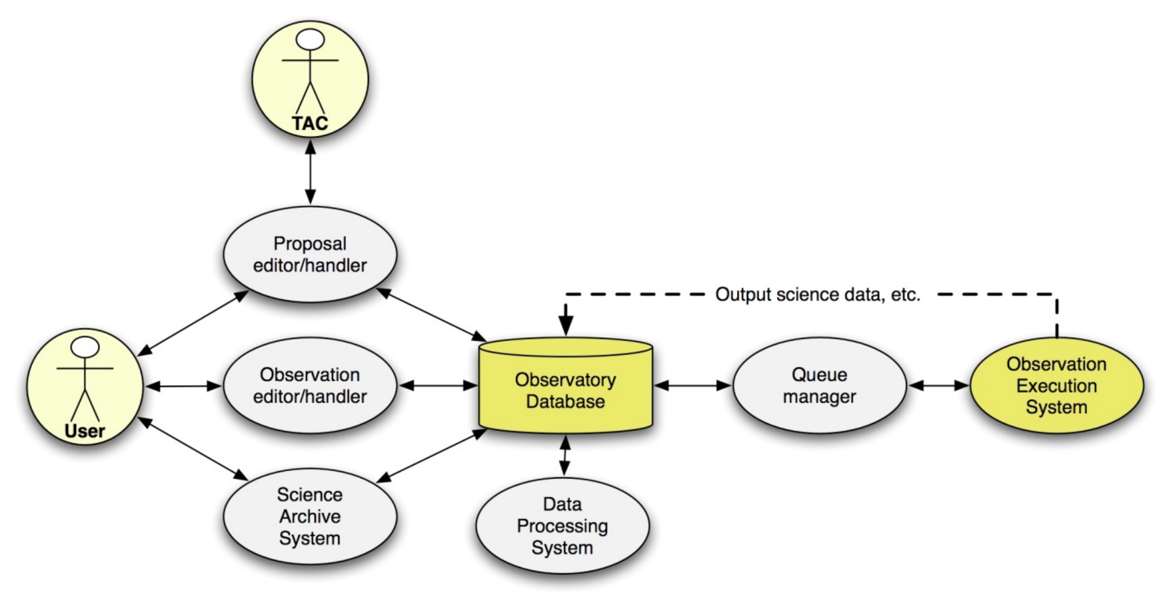


Figure 16: PES decomposition

[REQ-1-OAD-9112] Each subsystem can (but is not required to) use a different communication strategy for interacting with the observatory database. However, the chosen strategy shall always remain database server implementation neutral. It must also allow secure connections between remote clients and local servers.

5.2.2 Software system communications backbone

5.2.2.1 General communications backbone requirements

[REQ-1-OAD-9200] The TMT software system backbone shall be defined by a set of software communication services hereafter known as common services.

Discussion: Common services are often known as middleware in the commercial software development world.

[REQ-1-OAD-9203] Software subsystems shall access the communications backbone using TMT-provided and/or TMT-specified Application Programming Interfaces (APIs).

[REQ-1-OAD-9205] The communications backbone shall run on top of a communication protocol stack that has a physical IT communications network at its lowest level.

Discussion: it is a high priority goal to build TMT common services using the following principles: (1) use existing solutions, preferably from the open source community; (2) implement solutions that are operating system neutral to the largest extend possible; and (3) support more than one main stream software language. For example, Java Messaging Service (JMS), RTI Data Distribution Service (DDS; formerly NDDS), and Apache ActiveMQ (built on JMS) appear to satisfy the spirit of these goals already. By mid-2008, TMT will select a reference middleware solution and proceed to common services API specification.

5.2.2.2 General common services requirements

[REQ-1-OAD-9210] Each common service shall be asynchronous.

[REQ-1-OAD-9213] Each common service shall have an Application Programming Interface (API). It is a goal to make each API service implementation neutral, i.e. it shall be possible to change how a service is implemented without needing to make code modifications to subsystems using that service.

[REQ-1-OAD-9216] Common services shall run on top of a standards-based communications stack similar to what is shown in Table 38.

Discussion: this protocol stack is based on the 5-layer TCP/IP model, not the 7-layer OSI model. Actual stack implementations are service-dependent and will be described in Level-2 design documents. The physical layer is expected to be segmented (e.g. using structured cabling) to prevent data transfer collisions (e.g. between command-and-control, telemetry, and science data).

Layer	Possible solutions
TMT-specific standards and content	
Service-specific data structure content	TBD (TMT-specific)
Service-specific data structure syntax	TBD (TMT-specific)
Industry standards	
Data structure standard	HTML, XML, FITS
Application (inter-process communication, IPC)	HTTP, SMTP, Java RMI
Transport	TCP
Network	IP
Data Link	ATM, PPP
Physical	Ethernet, CAN, ISDN, WiFi

Table 38: Communications protocol stack

5.2.2.3 Specific common service definitions

Discussion: this is the current design reference list of common services. It will evolve as design work advances.

[REQ-1-OAD-9220] TMT software common services are listed in Table 39.

Service	Task
User single sign on	Manage user authentication/access control
Configuration	Manage system configuration
Location/connection	Manage inter-process communications connections
Event	Manage event publishing/subscription
Health	Manage health check signals
Logging	Capture/store log information
Bulk data store	Capture/store bulk data (e.g. science data)
Telemetry store	Capture/store telemetry
ODB access	Middle-tier for database access
Time	Standard GPS-based Network Time Protocol (NTP) service
Catalog	Interface to DMS astronomical catalog server

Table 39: Common services definition

[REQ-1-OAD-9223] The user single sign on (SSO) service shall enable OES users to authenticate once and gain access to authorized operations. For each user, an authorized operation profile shall be maintained.

[REQ-1-OAD-9226] The configuration service shall enable the command and control of a specific set of OES subsystems for a specific operation. A master process shall be defined. During a specific configuration, only the designated master process may command and control the OES.

[REQ-1-OAD-9229] The location service enables registered processes to find other registered process for the purpose of inter-process communication.

[REQ-1-OAD-9232] The event service enables the publication of messages indicating a change of state, completion of task etc. and the subscription to events from specific registered processes.

[REQ-1-OAD-9235] The health service enables the publication of process health, e.g. READY, FAULT, STANDBY.

Discussion: health service capability may be a subset of general event service capability and hence redundant. This needs further analysis.

[REQ-1-OAD-9238] The logging service allows processes to record a history of all actions (with time-stamps) in the local observatory database.

[REQ-1-OAD-9241] The bulk data store service facilitates the transmission of large data structures to the local observatory database.

[REQ-1-OAD-9244] The telemetry store service facilities the transmission of engineering telemetry to the local observatory database.

[REQ-1-OAD-9247] The observatory database (ODB) access service enables processes to query the local observatory database and retrieve data.

Discussion: the last four requirements imply a client-service like relationship between processes and the local observatory database. The services enable the client-side actions while the Data Management System (DMS) enables the server-side interaction.

[REQ-1-OAD-9250] The time service is a standard GPS-based Network Time Protocol (NTP) service.

[REQ-1-OAD-9253] The catalog service provides access to a defined set of astronomical catalogs stored on the local observatory database.

Discussion: a typical catalog service action is to request possible guide stars near a specific celestial coordinate.

5.2.3 High-level OES subsystem definition

5.2.3.1 General

[REQ-1-OAD-9300] Each software subsystem may consist of one or more lower-level software components.

[REQ-1-OAD-9303] It shall be possible to build, run, control, and monitor each software subsystems in stand-alone mode, i.e. without starting the entire TMT software system.

[REQ-1-OAD-9306] It shall be possible to run each software subsystem in simulation mode, either independently or in conjunction with the rest of the TMT software system.

[REQ-1-OAD-9309] Upon activation, each subsystem shall be able to initialize itself with a default configuration and be ready for operation without further human intervention. This activation process shall take less than one (1) minute (TBC).

[REQ-1-OAD-9312] All software subsystems shall be able to receive and parse TMT defined data structures containing command, control, and configuration instructions.

[REQ-1-OAD-9315] All software subsystems shall be able to transmit TMT-defined data structures containing health, status, and history (log) information as well as any science or technical data to be captured and stored by the local observatory database.

[REQ-1-OAD-9318] Each software subsystem shall transmit health information (e.g. active, idle, error, etc) at TBD intervals.

[REQ-1-OAD-9321] For the purposes of later diagnosis and analysis, each software subsystem shall transmit a time-stamped activity log to the local observatory database.

[REQ-1-OAD-9324] For the purposes of process control and synchronization, each software subsystem shall be able to transmit or receive events.

[REQ-1-OAD-9327] For the purposes of fault detection, each software subsystem shall transmit an alarm when an error that prevents normal operations occurs.

[REQ-1-OAD-9330] Each subsystem shall communicate with the rest of the system using the services listed in Table 38. Each service shall be accessed via a well-defined API (see REQ-1-OAD-9213).

[REQ-1-OAD-9333] Each subsystem shall be built using the standard TMT software framework (as described in OAD Section 5.2.7). The extent to which lower level software components must comply with the TMT software framework is still TBD.

5.2.3.2 Sequencer framework definition

[REQ-1-OAD-9340] A common sequencer framework shall be developed for use by all subsystems that contain sequencers.

Discussion: the sequencer framework definition description will be extended once more analysis is completed.

5.2.3.3 Defined OES software subsystems

[REQ-1-OAD-9350] Table 40 contains the design reference list of TMT OES subsystems.

Discussion: this list corresponds to the current TMT system decomposition (see Section 2). Some subsystems (e.g. WFOS) contain both hardware and software. For the purposes of this discussion, only the software components are considered. This list may evolve.

Subsystem Name	ShortName
Executive Software	ESW
Telescope Control System	TCS
M1 Control System	M1CS
M2 Optics System	M2
M3 Optics System	M3
Mount Control System	MCS
Alignment & Phasing System	APS
Enclosure	ENC
AO Sequencer	AOSQ
Laser Guide Star Facility Control System	LGSF
Narrow Field Infrared Adaptive Optics System Control System	NFIRAOS

Wide-Field Optical Spectrometer	WFOS
Infrared Imaging Spectrometer	IRIS
Infrared Multi-slit Spectrometer	IRMS
Site Conditions Monitoring System	SCMS
Data Management System	DMS

Table 40: Principal TMT software subsystems

Discussion: an interface to general facility management systems may also be necessary. To be investigated.

Discussion: TMT software subsystems listed in Table 40 shall be further described in Level-2 design requirement documents. A few subsystems deserve special mention here.

[REQ-1-OAD-9353] The Executive Software (ESW) contains the master system sequencer as well as the high-level user interfaces necessary to run the system. It accepts system configuration and observation requests from various user interfaces. The master sequencer then orchestrates the event sequence necessary to satisfy such requests. Finally, it returns status and completion information to those interfaces.

[REQ-1-OAD-9356] The Facility Control System (FCS) provides a standard interface wrapper to the various low-level facility hardware systems including (but not limited to) mechanical plant and electrical plant equipment and enclosure HVAC systems.

[REQ-1-OAD-9359] The Site Conditions Monitoring System (SCMS) provides a standard interface wrapper to the equipment external to the enclosure used to monitor such things as air temperature, wind speed, and free-air seeing.

[REQ-1-OAD-9362] The Data Management System (DMS) provides the necessary software front-end services to the local observatory database. The primary service is to capture, format (as necessary), validate, and store a range of data types. Secondary DMS services include: an astronomical catalog server for the use of all other TMT software subsystems and a data package creation server (such packages to include all related science, calibration, and technical data as well as any associated information such as nightlogs).

[REQ-1-OAD-9365] Each instrument shall have an Instrument Control System (ICS) that encompasses all the software subsystems (e.g. sequencer, component controller, detector controller, etc) needed to command and control the instrument as well as interface it to the rest of the TMT software system.

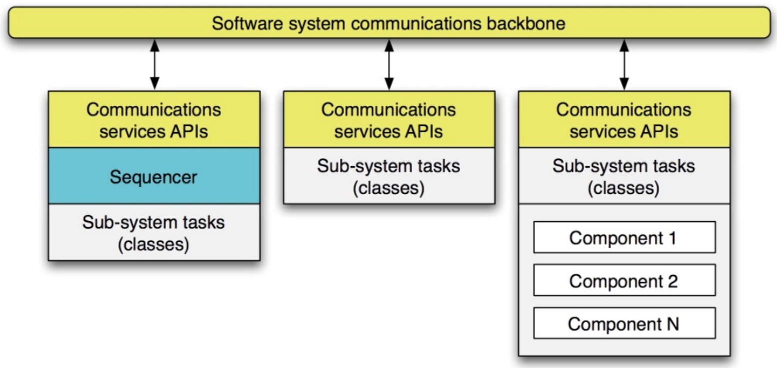


Figure 17: OES subsystem architecture templates

Discussion: for reference, Figure 17 shows three possible internal architectures for OES subsystems. On the left is the template for a sequencer subsystem (e.g OCS, TCS_SC, AOSQ). In the center is the template for monolithic application or a wrapper around a vendor supplied component (e.g. ENC, SCMS). On the right is the template for a subsystem with several key lower-level software components (e.g. LGSF, ICS-WFOS).

5.2.4 High-level PES subsystem definition

5.2.4.1 General

[REQ-1-OAD-9400] Unless otherwise noted, PES subsystems shall follow the same user interface guidelines as OES subsystems.

[REQ-1-OAD-9403] Unless otherwise noted, PES subsystems shall follow the same communication stack concept as OES subsystems.

[REQ-1-OAD-9406] Unless otherwise noted, PES subsystems shall follow the same communication backbone concepts as OES subsystems.

[REQ-1-OAD-9409] Unless otherwise noted, PES subsystems shall follow the same communication stack concept as OES subsystems.

5.2.4.2 Defined PES software subsystems

[REQ-1-OAD-9420] The proposal editor/handler (name TBC) subsystem contains all the functionality required by users to create and submit proposals and by the TMT Observatory to orchestrate the time allocation and long-term scheduling process. Additional functionality shall be provided to enable the secure, user-specific distribution of time allocation information as well as any record keeping and report generation requirements established by the TMT Board and/or partners.

[REQ-1-OAD-9423] The observation editor/handler (name TBC) subsystem contains all the functionality required by users to create and submit Observation Blocks (OBs) (as well as any required associated information) and by the TMT Observatory to orchestrate OB verification and scheduling.

[REQ-1-OAD-9426] The queue manager (name TBC) subsystem contains the functionality needed to browse the valid OB collection in the observatory database, select one or more

OBs for execution, and send the selected OB(s) to the OES. It also contains the functionality needed to manage the post-execution review and fault resolution process.

[REQ-1-OAD-9429] The data processing system (DPS) subsystem contains all the functionality necessary to orchestrate automatic data processing for the purposes of quick-look analysis, system performance evaluation, and the production of science-quality data products. The DPS acts as a wrapper around instrument-specific data processing applications. A DPS goal is to be hardware compute engine independent – it should not matter if the hardware engine is a desktop machine or a multi-processor cluster, as long as the data processing applications are compiled to run on the target hardware system.

Discussion: this hardware engine independence goal is aligned with common grid computing concepts related to high throughput computing (HTC). For one example, see the Condor project page: http://www.cs.uwisc.edu/condor.

[REQ-1-OAD-9432] The science archive system (SAS) contains all the functionality necessary for users to browse an external data center containing TMT data and download data of interest. Implementation of the SAS (if and when) is expected to be a joint venture between the TMT Observatory and a TBD existing data center.

[REQ-1-OAD-9435] Each instrument may have one or more tools for instrument simulation, integration time estimation, and configuration setup support (e.g. multi-object mask definition). As necessary, PES subsystems must be able to ingest and parse output from those instrument-specific tools.

5.2.5 Local observatory database

[REQ-1-OAD-9500] The local observatory database (ODB) shall provide a persistent data store for the following use cases:

- Science data produced by science instruments
- Telemetry data produced by technical systems
- Logging (history) data from all subsystems
- Astronomical catalogs
- TMT software systems that require long-term data caches (e.g. APS)
- User login and contact information

[REQ-1-OAD-9503] Two copies of all data objects shall be kept in physically separate locations. The physical separation must be large enough that local catastrophic events do not destroy both data copies.

Discussion: the minimal separation solution is one copy on summit, one copy in support facility. A more desirable solution is a separation of 10s of kilometers or more.

[REQ-1-OAD-9506] Data consistency checks between the two copies shall be run automatically on a regular basis.

[REQ-1-OAD-9509] The local observatory database shall be able to store update-oriented data – small (few byte to several KByte) data objects oriented towards an update-many, read-many, fast access model (e.g. status flags, mutable business objects). Data volume is expected to be tens of GB. These data shall be stored within relational databases.

[REQ-1-OAD-9512] The local observatory database shall be able to store read-oriented data – small (few byte to several KByte) data objects oriented towards a write-once, read-many, fast access model (e.g. subsystem telemetry data). Data volume is expected to be a tens of TB.

[REQ-1-OAD-9515] The local observatory database shall be able to store bulk data – large (several to many MByte) data objects oriented towards a write-once, read-many, slow access model (e.g. science detector pixel data). Data volume is expected to be at least 100 TB.

[REQ-1-OAD-9518] The large volume, bulk data shall be written to a disk-oriented storage system with location pointers stored in relational databases. These pointers shall be linked to the meta-data that describe the bulk data objects. This linkage enables the ability to query meta-data tables to locate appropriate bulk data objects and then use the pointers to find the bulk data objects in the bulk storage device.

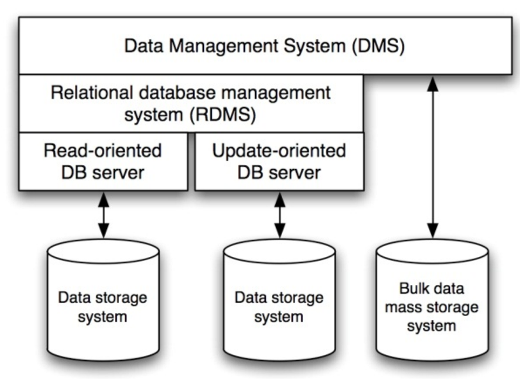


Figure 18: Observatory database architecture

[REQ-1-OAD-9521] The high-level reference design ODB architecture is shown in Figure 18.

[REQ-1-OAD-9524] For data retrieval, subsystems (clients) use the ODB access service to query and retrieve information from the observatory database.

[REQ-1-OAD-9527] Data formats, database table structures, and file system structures are all TBD.

5.2.6 Data structures

5.2.6.1 General

[REQ-1-OAD-9600] All OES and PES data formats, data structures, database table structures, and files system structures shall be documented in the TMT Data Interface Control Document (Data ICD or DICD).

5.2.6.2 Science operations business objects

[REQ-1-OAD-9610] There shall be a hierarchical set of linked science operations business objects. The reference set of such business objects is shown in Table 41.

[REQ-1-OAD-9613] Each business object references data from its predecessors(s) in a relational way.

[REQ-1-OAD-9616] Each business object shall have a defined state (e.g. READY, FAULT, COMPLETED). During the design phase, an extensible list of valid states shall be defined for each business object class.

[REQ-1-OAD-9619] Each business object shall have a revision history.

Business Object	Description
Proposal	The original user request to use the TMT Observatory, a proposal contains all the scientific and technical information needed to evaluate the scientific merit and technical feasibility of the described observing program relative to all other concurrent proposals.
Program	A proposal that has been accepted for execution (priority and conditions permitting). Fundamentally, a program consists of one or more observing runs
Observing Run	A program subset scheduled for a specific major mode of a specific instrument during a fixed time period. Each observing run contains one or more observation blocks.
Observation Block	An OB contains all the information necessary to setup, schedule, and execution a specific observation. An OB can be executed more than once. The information within an OB can be modified.
Data Frame	A self-contained data object, usually associated with a single science instrument detector readout or the hardware-averaged result of many such readouts. Raw data frames have not been processed further, while processed data frames (sometimes known as data products) have been processed.
Execution Block	When executed, each OB produces a static copy of itself known as an Execution Block.
Association Block	Contains all the information needed to process a data frame set including: all other raw data frames associated with that set, all calibration data needed to process that set, data processing module needed to process set.

Table 41: Science operations business objects

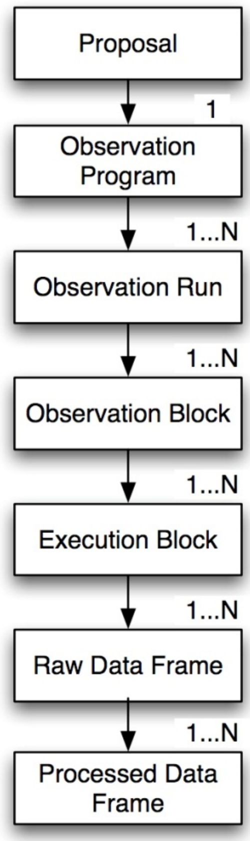


Figure 19: Science operations business objects

5.2.6.3 Observation description

[REQ-1-OAD-9630] The fundamental OES observation descriptor shall be known as an Observation Block (OB). It shall contain the following information:

- Target description
- Guide star description
- Instrument configuration
- AO system configuration
- Scheduling constraints
- TO BE COMPLETED

[REQ-1-OAD-9633] Each OB shall contain a TBD minimal set of self-describing parameters. Additional parameters shall be added as the situation warrants.

[REQ-1-OAD-9636] Internal OB structure and syntax are TBD. The design reference syntax is (keyName, value) pairs (e.g. targRA = "00 24 34.5", wfosGrism01 = "blue"). The reference syntax may be replaced by a more sophisticated syntax based on (e.g.) XML during the design phase.

Discussion: OB parameters are input arguments to lower level software system control and configuration procedures (scripts) within the OES master sequencer. These scripts will be developed in collaboration with the instrument development teams.

[REQ-1-OAD-9639] All observation description generators shall generate OBs. Example generators include standard text editors, observer GUIs, and operator GUIs.

[REQ-1-OAD-9642] It shall be possible to create an OB as a plain text file using standard text processing tools. An application shall be available to import such OB text files and submit them to the OES for action.

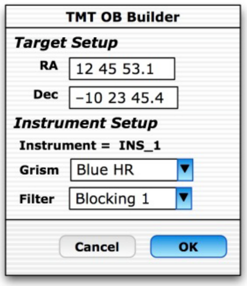
[REQ-1-OAD-9645] It shall be possible to filter and group OBs arbitrarily by any parameter.

[REQ-1-OAD-9648] It shall be possible to define ordered OB sequences using the following concepts:

- Time interval between successive OBs
- Absolute execution time windows for each OB
- Conditional execution based on outcome of previous observations
- TO BE COMPLETED

[REQ-1-OAD-9651] OB sequences shall be encoded as data structures that contain pointers to OBs – such sequences shall not be encoded into the OBs themselves.

Discussion: a simple OB example is shown in Figure 20. Further OB specifications will be provided in Science Operations Software Business Objects Specifications.




```
#
# Simple TMT OB example
#
obBegin
targRA = "12 45 53.1"
targDec = "-10 23 45.4"
insID = "INS_1"
insGrism = "Blue HR"
insFilter = "Blocking 1"
obEnd
```

```
#
# Simple sequence script
#
seqBegin
setConfig(TEL,targRA,targDec)
setConfig(INS,insID,insGrism,insFilter)
waitForConfigReady(TEL)
waitForConfigReady(INS)
startObservation(INS_1)
seqEnd
```

Figure 20: Simple observation block (OB) example

5.2.7 Software development framework definition

Discussion: Such a software framework has been called common software by other projects. More complete requirements shall be provided in the TMT Software Framework Definition Document.

[REQ-1-OAD-9700] All TMT software system components shall be implemented within a standard TMT software framework.

[REQ-1-OAD-9703] This framework shall have three high-level goals:

- Adopt and/or adapt commercial and/or open source solutions that are already widely used and supported within the IT industry.
- Minimize time and effort needed to install, integrate, and verify the TMT software system on-site and make it operational.
- Minimize time and effort needed to maintain and extend the TMT software system during operations.

[REQ-1-OAD-9706] The standard TMT software framework shall include (but is not necessarily limited to):

- Middleware APIs and/or supporting libraries
- GUI builders
- Data structure editors
- Build tools and process specification (e.g. Unix makefiles)
- Centralized configuration control server
- Centralized and automatic build, integrate, and test process
- Standards for
  - Data and meta-data structures
  - Languages
- Specifications for:
  - Development environment (OS, hardware, compilers…)
  - Deployment environment (OS, hardware)
  - Associated documentation

[REQ-1-OAD-9709] Items specific to real-time mechanism control and science data processing shall be added to this list after further discussion.

[REQ-1-OAD-9712] Whenever possible, the TMT software framework shall use widely used, industry standard commercial and/or open source tools, libraries, data structures, etc. Solutions that have high, long-term maintenance or licensing costs (e.g. commercial enterprise-class middleware and libraries) shall be avoided unless specifically approved by the TMT Project.

[REQ-1-OAD-9715] All non-real-time software subsystems shall have the same target deployment platform. The target platform shall be some Unix or Linux variant. The exact target deployment platform is TBD.

[REQ-1-OAD-9718] All non-real-time software subsystems shall be built using a common build strategy (e.g. Unix makefiles).

[REQ-1-OAD-9721] A centralized software problem reporting and tracking system (e.g. bugzilla) shall be maintained by the TMT project.

[REQ-1-OAD-9724] The TMT Project shall develop a TMT software system release plan that consists of intermediate releases tied to specific functionality.

[REQ-1-OAD-9727] A centralized software configuration control server shall be implemented. At TBD intervals during development, all TMT software shall be delivered to the central server and placed under configuration control.

[REQ-1-OAD-9730] The TMT Project shall implement an automatic build, integrate, and test process. This process shall run at TBD periodic intervals (e.g. every 24 hours).

[REQ-1-OAD-9734] Software stored on the central configuration server shall be considered the master copy.

[REQ-1-OAD-9737] Software installed in the operational, on-site environment shall not be considered the master copy. Changes to software made to software installed in the operational, on-site environment shall not be considered official or permanent. All such changes shall be tagged and checked into the central configuration control server as soon as possible.

[REQ-1-OAD-9740] It shall be possible to remove (completely or partially) all software from the TMT operational environment without warning and re-install it in less than eight (8) (TBC) hours based on information stored on the central configuration server supplemented by various high-level installation kits (for, e.g. operating system, common software packages, etc.) At the end of this reinstallation process, the system shall be restored to its operational state at the time of software removal.

6. DEFINITIONS

6.1 COORDINATE SYSTEMS

[REQ-1-OAD-9900] The following coordinate system are standards for the thirty meter telescope project (see RD11 for full definition).

Table 42 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 (α) is defined as angle between TCRS x-axis and ACRS x-axis caused by rotation about the Z axis. By convention this increases in a clockwise direction when viewed from above. (This is the opposite to that stated by the RH rule)	
Elevation (ECRS)	The intersection of the Z axis of ACRS with the elevation axis of the telescope	Parallel to the X axis of the ACRS, collinear with the elevation axis of the telescope	Rotated around the X axis according to the RH rule, by the zenith angle	Right hand complement to the X and Y axes; points to zenith at zero zenith angle	Zenith angle (ζ) 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-

Coordinate System	***Origin***	***X axis***	***Y axis***	***Z axis***	***Rotation Angle Definition***	***Notes:***
						OAD-1255
Reference (RCRS)	The intersection of the Z axis of ACRS with the elevation axis of the telescope	Parallel to the X axis of the ACRS.	Parallel to the Y axis of the ACRS	Identical to TCRS		The RCRS rotates with the azimuth axis but does not rotate with changes of telescope zenith angle This is plane in which all the instrument optical axes lie
Primary Mirror (M1CRS)	The intersection of the Z axis of the ECRS with the M1 optical surface	Parallel to the X axis of the ECRS	Parallel to the Y axis of the ECRS	Right hand complement to the X and Y axes		The origin of the M1CRS relative to the ECRS is defined in REQ-1-OAD-1315
Secondary Mirror (M2CRS)	The intersection of the Z axis of the ECRS with the M2 optical surface	Parallel to the X axis of the ECRS	Right hand complement to the X and Z axes	Points to the origin of the ECRS, in the line of the Z axis of the ECRS		The origin of the M2CRS relative to the M1CRS is defined in REQ-1-OAD-1056
Tertiary Mirror (M3CRS)	Identical to ECRS origin	Aligned with ECRS + Y axis when M3 rotation angle (θ) = 0. Collinear with M3 tilt axis.	Right hand complement to the X and Z axes	Normal to M3 surface; points away from the reflective surface.	θ is the rotation angle of M3 about the ECRS z-axis, defined as the angle between the ECRS Y axis and the M3 X axis. Φ 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 Φ of the M3CRS Z axis in the ECRS.
Focal Surface (FCRS)	The center of the focal surface	Right hand complement to the Y and Z axes	Projection of the ACRS Z axis on the plane perpendicular to the FCRS Z axis	Normal to the focal surface at the origin; points towards the tertiary mirror		The location of the focal surface for different instruments is defined by the instrument bearing angle. This is the angle between the ECRS X axis and the FCRS Z-axis. The distance between the origin of the FCRS and the

Coordinate System	Origin	X axis	Y axis	Z axis	Rotation Angle Definition	Notes:
						origin of the ECRS is given by REQ-1-OAD-1020
Segment ($SCRS_j$)	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 $SRCS_j$ 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		
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 (β) = 0	Right hand complement to the X and Z axes	Identical to TCRS Z-axis	Enclosure Base Rotation Angle (β) is defined as angle between TCRS x-axis and ECCRS x-axis caused by rotation of the enclosure base about the ECCRS z-axis. Angle increases in a clockwise direction when viewed from above	The highest point of the cap base interface plane is defined as being coincident with a line parallel to the EBCRS +ve Y axis.

Coordinate System	***Origin***	***X axis***	***Y axis***	***Z axis***	***Rotation Angle Definition***	***Notes:***
Enclosure Cap (ECCRS)	Coincident with ECRS origin	Parallel to EBCRS x-axis when $\varepsilon = 0$	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 ε is defined as clockwise rotation (when viewed from above) of the enclosure cap about the ECCRS z axis, $\varepsilon = 0$ when ECCRS x axis is parallel to EBCRS x-axis.	The enclosure shutter is zenith pointing when $\varepsilon = 0$.

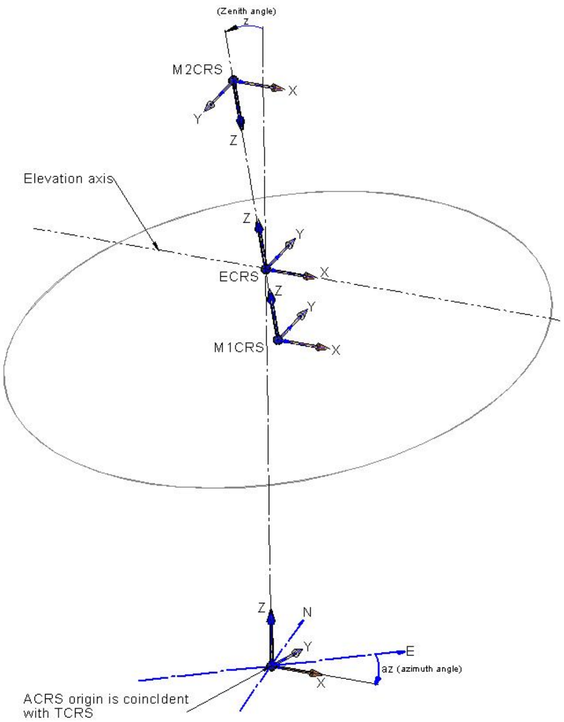


Figure 21 The basic coordinate systems of the telescope

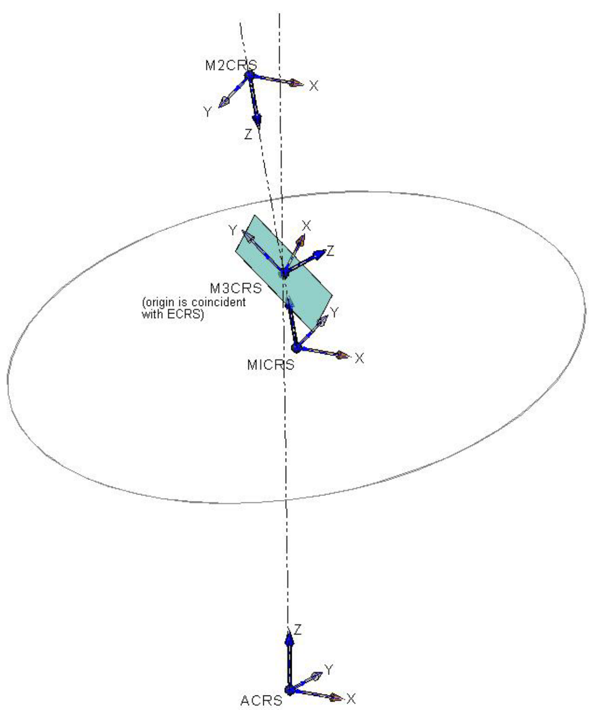


Figure 22 Tertiary mirror coordinate system (M3CRS) shown in the context of the M1CRS and M2CRS

6.2 WAVELENGTH BANDS

6.2.1 Astronomical Filters

Table 43 Astronomical Filters

Band	Center wavelength	Bandwidth
U	0.3663 μm	0.0650 μm
B	0.4361 μm	0.0890 μm
V	0.5448 μm	0.0840 μm
R	0.6407 μm	0.1580 μm
I	0.7980 μm	0.1540 μm
J	1.250 μm	0.16 μm
H	1.635 μm	0.29 μm
K'	2.12 μm	0.34 μm
K_s	2.15 μm	0.32μm
K	2.2 μm	0.34 μm
L	3.77 μm	0.7 μm
M	4.68 μm	0.22 μm
N	10.47 μm	5.2 μm
Q	20.13 μm	7.8 μm

Data in the table is from [RD6].

6.2.2 Atmospheric Transmission Windows

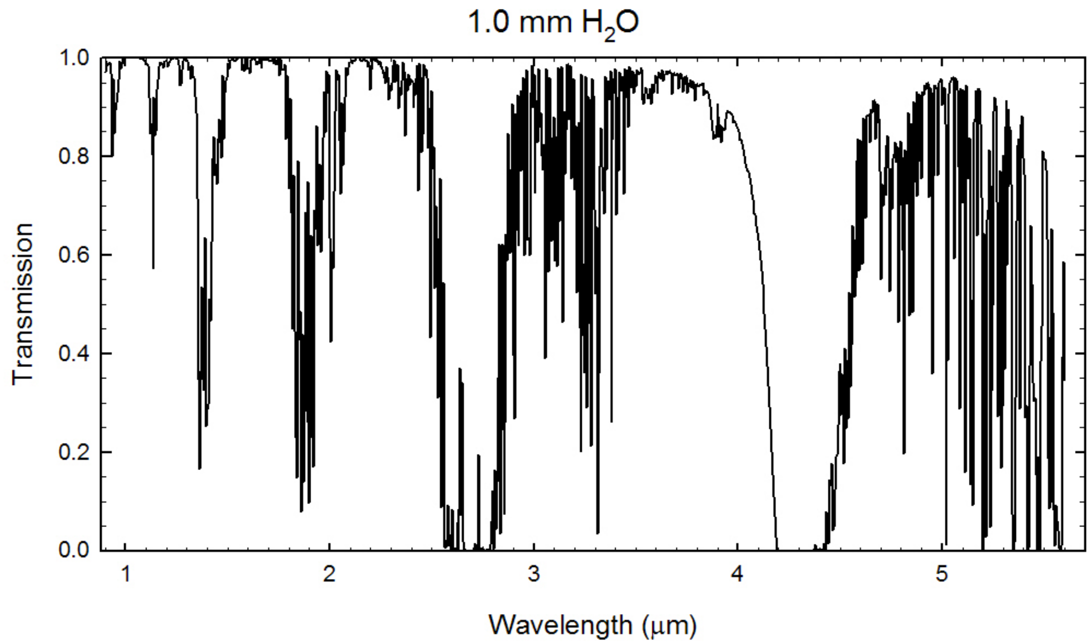


Figure 23 Near and mid infrared atmospheric transmission windows for 1 mm precipitable water vapor [RD5]

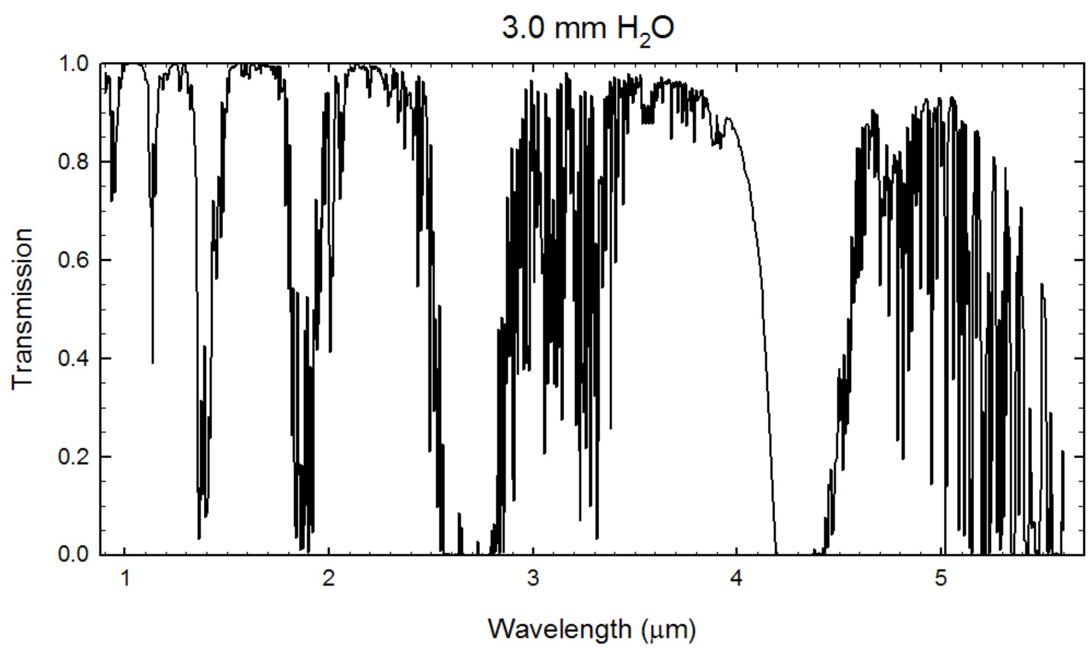


Figure 24 Near and mid infrared atmospheric transmission windows for 3 mm precipitable water vapor [RD7]

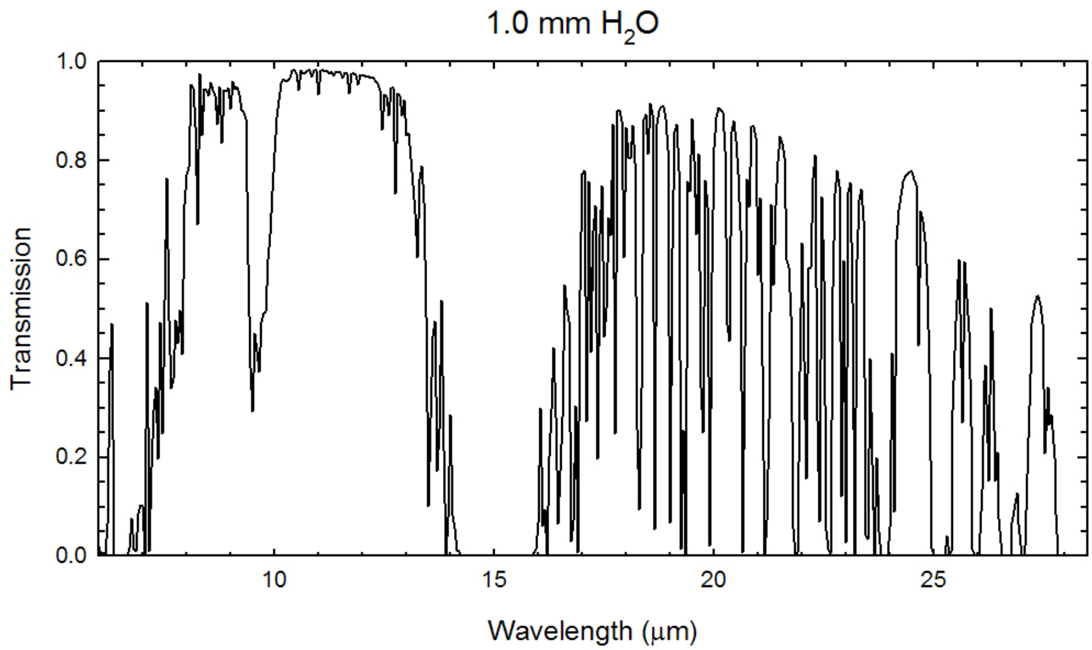


Figure 25 Infrared atmospheric transmission windows for 1 mm precipitable water vapor [RD7]

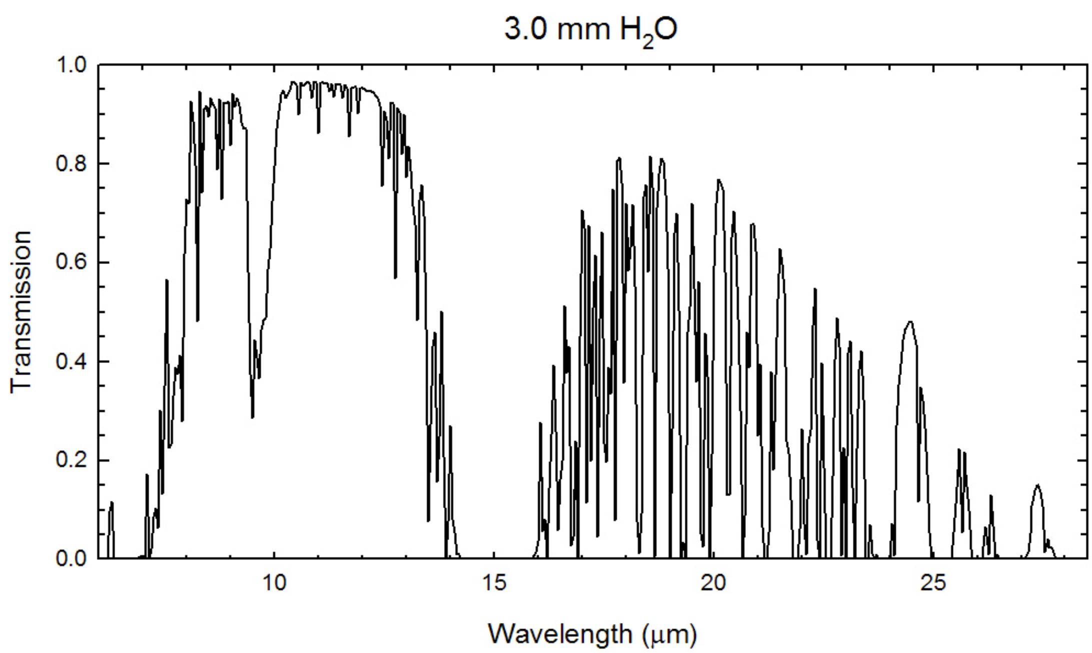


Figure 26 Infrared atmospheric transmission windows for 3 mm water vapor [RD7]

6.3 ACQUISITION

Figure 27, Figure 28, and Figure 29 show characteristic acquisition sequences for seeing limited, NGS and LGS AO operating modes. These sequences illustrate current best estimates; they do not meet the SRD and ORD requirement of 5 minutes between observations.

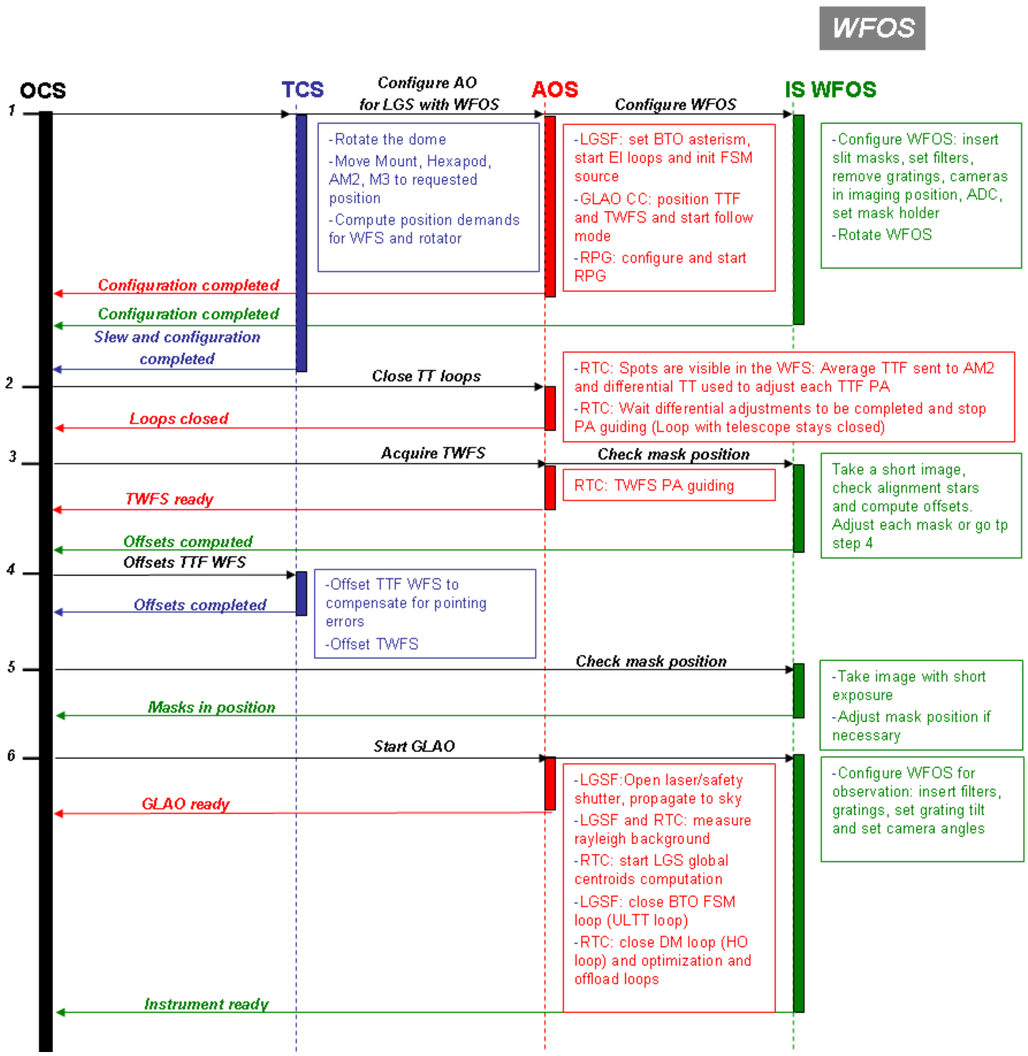


Figure 27 Example acquisition scheme for a GLAO system configuration (WFOS). FOV of guide (TT) WFS is large enough to acquire guide star in one step.

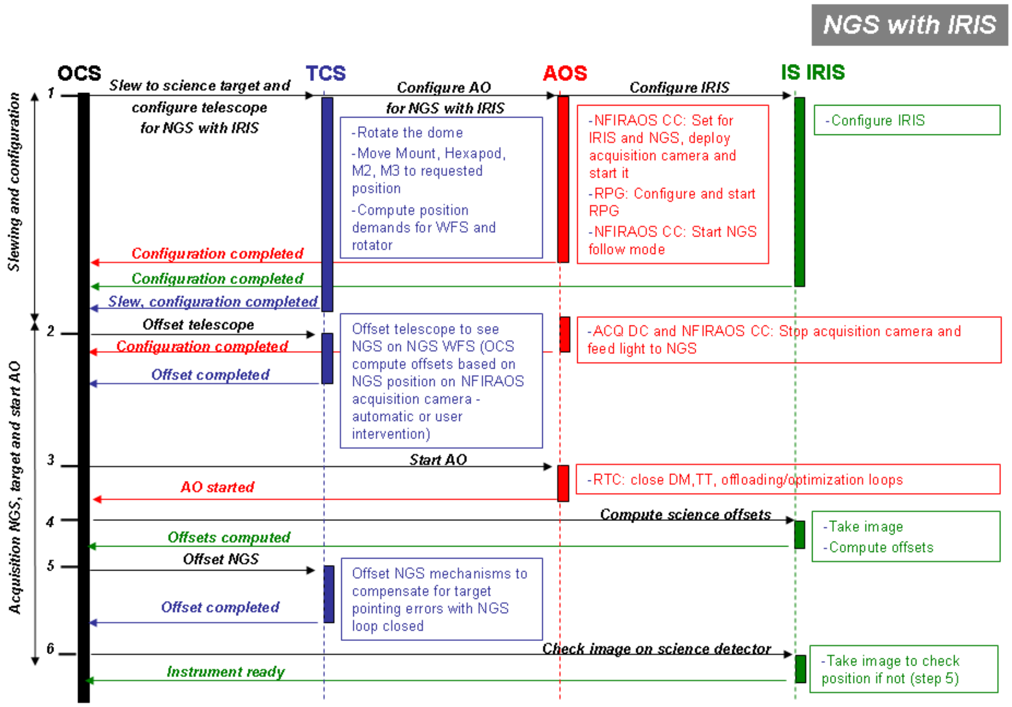


Figure 28 Example acquisition scheme for a NGS MCAO system configuration (IRIS). FOV of guide (TT) WFS is not enough for blind pointing the telescope on the WFS; Instrument acquisition camera is needed.

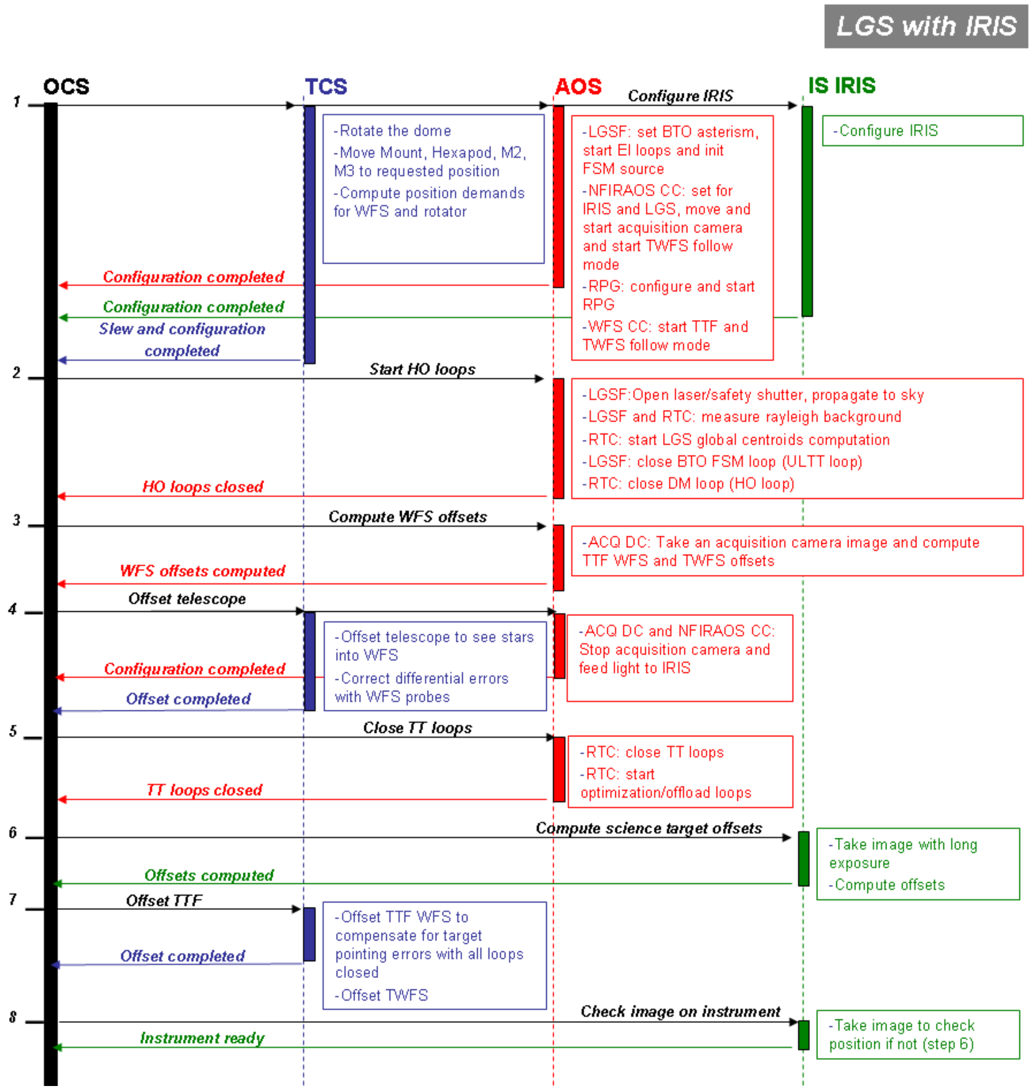


Figure 29 Example acquisition scheme for a LGS MCAO system configuration (IRIS). Procedure is similar to Figure 28, but for faint guide stars. The faint natural guide stars are enhanced by higher order, LGS based AO correction.

6.4 OBSERVATORY CONTROL ARCHITECTURE

Table 44 Mount and active optics actuators and corresponding sensors with control bandwidths

		Inner Control Loops Local Encoder Feedback						Middle Control Loop LUT Feedback		Outer Control Loop TOFS		
Name		DOF	Actuators	Sensors	Sample/ Update Rate (Hz)	Loop BW (Hz)	LUT(ZA,T)[1] Command Rate[2] (Hz)	LUT(ZA,T) Source	LUT(ZA,T) Refresh Rate	Sensor	Sample/ Update Rate (Hz)	Loop BW (Hz)
Mount	Azimuth & Elevation	2	DDL motors[3]	Tape encoder	≥ 40	~ 1	20	Pointing tests	Monthly	AGWFS[4]	1	0.1
M1	Global Tip, Tilt, Piston	3	Segment actuators	Actuator sensors	≥ 1	< 0.1[5]	0.1	Surveying	>>1 year	No outer control loop		
M1	Segment Tip, Tilt, Piston	1476	Segment actuators	Edge sensors	≥ 10	~ 1[5]	0.1	APS	2 to 4 weeks[6]	AGWFS[7]	0.003	0.0001
M1	Warping Harness	10,332	Warping harness	Strain gauge	na[8]	na[8]	na[8]	APS, but no LUT	> 1 year[8]	No outer control loop		
M2	De-center	2	Hexapod	Local encoders	≥ 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	Rotation	1	DC drive	Local encoder	≥ 10	< 1	0.1	APS & surveying	> 1year	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)

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[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 motion feedback is not based on the AGWFS but rather via an offload of the time averaged position of the AO tip/tilt stage.
[5] The global M1 control bandwidth is 1.0 Hz. The control bandwidths of the individual actuators will be 5 Hz to 10 Hz with individual update rates >100Hz.
[6] Zero point only. Zenith angle and temperature dependence will be updated on approximately a yearly basis or whenever M2 and M3 are recoated (~ every 2 years).
[7] In seeing limited mode 2nd and 3rd radial order OPD modes will be corrected on the M1. In AO mode the outer loop feedback is not based on the AGWFS but rather on an offload based on the time averaged shape of the AO deformable mirror (DM); up to ~ 100 modes will be offloaded.
[8] Warping harness will be adjusted by APS measurement after segment exchange/installation. Infrequent calibration updates may happen, but a bandwidth requirement is not relevant.
[9] The GMS may be used on a nightly basis to correct the zero point drifts of the M2 LUTs as a result of un-modeled (primarily temperature) error sources.
[10] On a 2 to 4 week basis (based on the frequency of segment exchanges) APS will realign focus and two of the remaining four M2 DOF. The remaining two degrees of freedom will be measured by APS on approximately a yearly basis or whenever the M2 is recoated. The selection of which two DOF will be measured by APS more frequently is TBD.
[11] Coma will be corrected on M2 via tip/tilt, de-center, or rotation about the neutral point. The optimum approach is TBD; the architecture will easily support any of these three possibilities.
[12] Focus will be corrected via M2 piston
[13] The instruments and the APS will have the ability to slowly control pupil position via M3 tilt.

6.5 FIRST DECADE INSTRUMENT LAYOUT

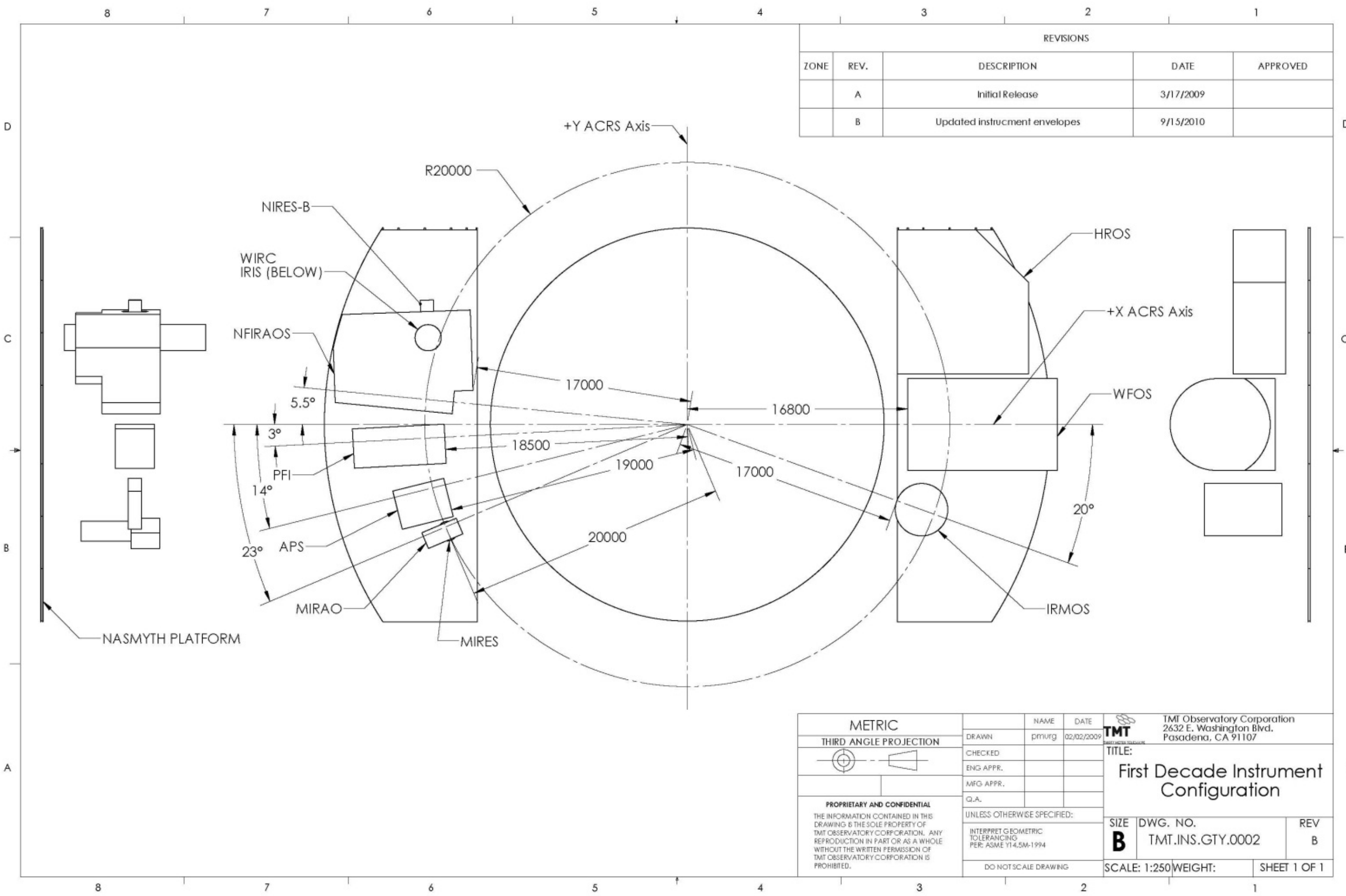

Figure 30 Full SAC Instrument Layout

Discussion:

The –X Nasmyth is configured as follows: NFIRAOS and its associated instruments (any three of IRIS, IRMS, NIRES and WIRC) are located at the 174.5 degree position. PFI is located at the +183 degree position, APS at its desired +194 degree position, and MIRES/MIRAO is at +203 degrees.

The +X Nasmyth is configured as follows: WFOS is oriented horizontally on the elevation axis (0 degrees). HROS is located at the back of this platform, within the trimmed envelope, and is fed by the M3 at +5 degrees. The beam to HROS must be deflected in front of WFOS to reach the instrument. IRMOS is located at the -20 degree location on this platform.

6.6 ENCLOSURE GEOMETRY

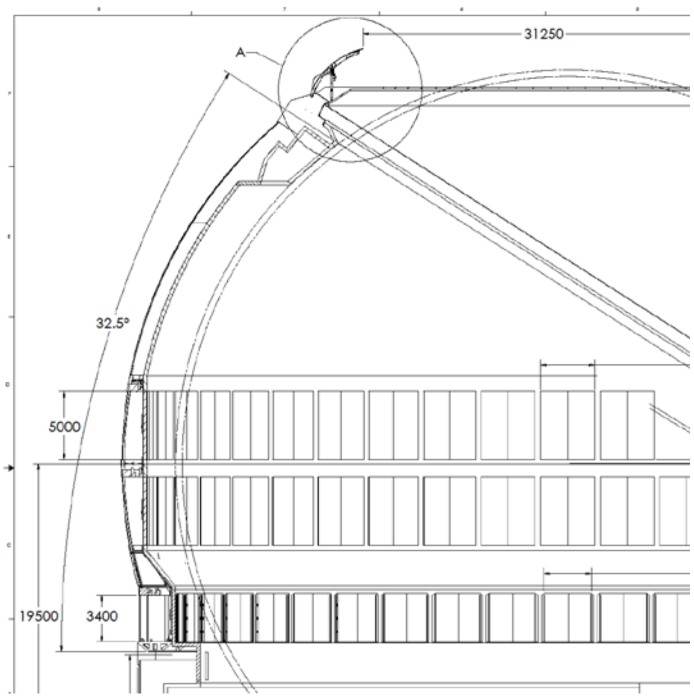

Figure 31TMT Enclosure Geometry

6.7 EXAMPLE MIRROR COATING REFLECTANCE CURVES

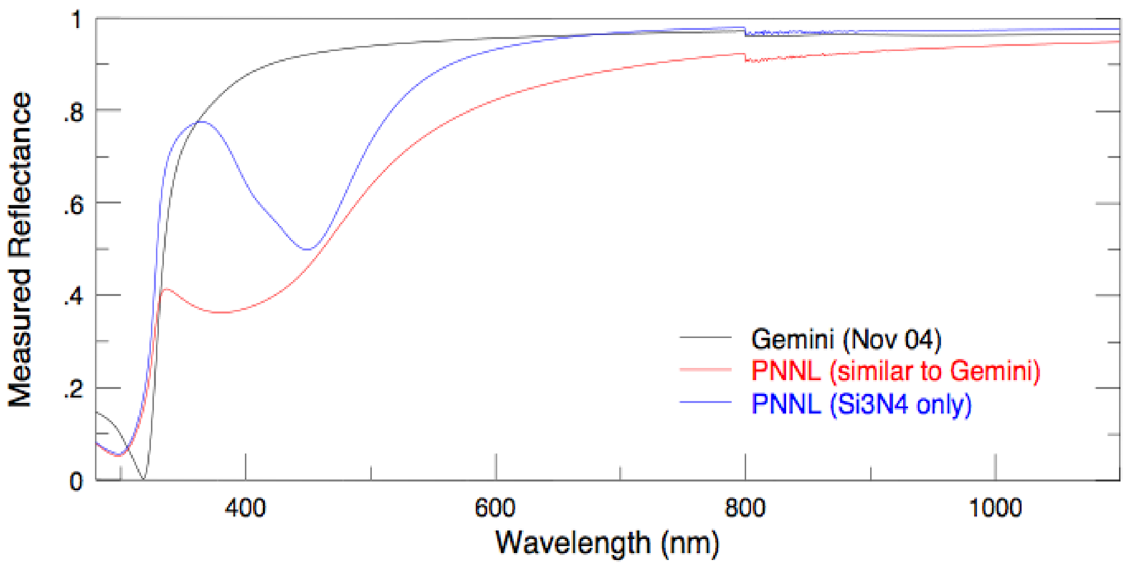

Figure 32 Gemini coating plus other coatings in development. Dip in reflectivity other coatings is caused by surface Plasmon resonances.