



TMT.SEN.DRD.05.001.CCR26

OBSERVATORY REQUIREMENTS DOCUMENT

Page 1 of 60

NOVEMBER 27, 2013



THIRTY METER TELESCOPE

# OBSERVATORY REQUIREMENTS DOCUMENT

TMT.SEN.DRD.05.001.CCR26

November 27, 2013

## TABLE OF CONTENTS

<b>1.</b>	<b>INTRODUCTION</b>	<b>5</b>
1.1	Introduction.....	5
1.2	Purpose.....	5
1.3	Scope.....	5
1.4	Applicable Documents.....	6
1.5	Reference Documents.....	6
1.6	Change Record.....	7
1.7	Abbreviations.....	8
<b>2.</b>	<b>OVERALL DESCRIPTION</b>	<b>9</b>
2.1	Perspective.....	9
2.1.1	System Inputs.....	9
2.1.2	System Outputs.....	10
2.2	System Functions.....	10
<b>3.</b>	<b>SPECIFIC REQUIREMENTS</b>	<b>13</b>
3.1	Constraints.....	13
3.1.1	General Constraints.....	13
3.1.2	Environmental Constraints.....	13
3.1.2.1	Site.....	13
3.1.2.2	Observing Performance Conditions.....	13
3.1.2.3	Facility Performance Conditions.....	15
3.1.2.4	Component Functional conditions.....	16
3.1.2.5	Survival Conditions.....	17
3.1.2.6	Frequent Earthquakes.....	19
3.1.2.7	Infrequent Earthquakes.....	19
3.1.2.8	Very Infrequent Earthquakes.....	19
3.2	Observation Operational Support.....	20
3.2.1	General.....	20
3.2.2	Target acquisition requirements.....	21
3.3	Telescope and Instrumentation Requirements.....	22
3.3.1	General.....	22
3.3.2	Wavelength Range.....	22
3.3.3	Light Collection Geometry.....	23
3.3.4	Pointing on the Sky.....	24
3.3.5	Acquisition.....	25
3.3.6	Guiding and Field De-Rotation.....	25
3.3.7	Offsetting and Nodding.....	27
3.3.8	Image Quality.....	31
3.3.8.1	Seeing Limited Mode.....	31
3.3.8.2	Adaptive Optics Mode.....	31
3.3.9	Plate Scale Uniformity.....	32
3.3.10	Pupil Shift.....	32
3.3.11	Telescope Optical Throughput.....	32
3.3.12	Thermal Background.....	33
3.3.13	Baffling.....	33
3.3.14	Atmospheric Dispersion Compensation.....	33



**OBSERVATORY REQUIREMENTS DOCUMENT**

NOVEMBER 27, 2013

3.3.15	Laser Guide Stars and Laser Guide Star Wavefront Sensing .....	33
3.3.16	Instrument Reconfiguration and Availability .....	33
3.3.17	Nasmyth Platform Requirements .....	33
3.3.18	Early Light Instrumentation Requirements .....	34
3.3.18.1	NFIRAOS .....	34
3.3.18.2	IRIS – Infrared Imaging Spectrometer .....	36
3.3.18.3	IRMS .....	37
3.3.18.4	WFOS .....	38
3.3.19	First Decade Instrumentation Requirements .....	40
3.3.19.1	General .....	40
3.3.19.2	Upgraded NFIRAOS MCAO System .....	40
3.3.19.3	IRMOS – Near Infrared Multi Object Spectrometer .....	40
3.3.19.4	MIRES – Mid Infrared Echelle Spectrometer .....	41
3.3.19.5	PFI – Planet Formation Imager .....	42
3.3.19.6	NIRES-B – Near Infrared Echelle Spectrometer (Blue) .....	43
3.3.19.7	NIRES-R – Near Infrared Echelle Spectrometer (Red) .....	44
3.3.19.8	HROS – High Resolution Optical Spectrometer .....	45
3.3.19.9	WIRC - Wide Field Infrared Camera .....	46
3.4	Facility Requirements.....	48
3.4.1	Operations Support.....	48
3.4.2	Summit Facility.....	48
3.4.2.1	General .....	48
3.4.2.2	Enclosure .....	48
3.4.2.3	Lightning Protection .....	49
3.4.3	Road.....	49
3.5	System Attributes .....	50
3.5.1	Reliability and Maintainability.....	50
3.5.1.1	Maintenance Driven System Attributes .....	50
3.5.1.2	Maintenance Plan .....	50
3.5.1.3	Engineering Databases .....	50
3.5.1.4	Reliability .....	50
3.5.2	Operational Efficiency.....	51
3.6	Environmental, Health, and Safety Requirements .....	51
3.6.1	Safety .....	51
3.6.1.1	General .....	51
3.6.2	Health .....	51
3.6.3	Environment .....	51
3.6.4	Security .....	52
3.7	High Level Software Requirements .....	53
3.7.1	General requirements .....	53
3.7.2	Communications network requirements .....	53
<b>4.</b>	<b>APPENDIX</b> .....	<b>54</b>
4.1	Reference Atmospheric Parameters .....	54
4.1.1	Meteorological Parameters.....	54
4.1.2	Turbulence Parameters .....	54
4.1.3	Mesospheric Sodium Layer .....	55
4.2	Wavelength Bands.....	57
4.2.1	Astronomical Filters .....	57
4.2.2	Atmospheric Transmission Windows .....	58
4.3	Temporal Temperature Gradients .....	60

## TABLE OF FIGURES

Figure 1 The observatory system with its inputs and outputs.....	9
Figure 2 illustrating the move time and settling band specification. $T_M$ is the move time, $B_S$ is the settling band.....	24
Figure 3 Example of nodding between two points 1 arcsecond apart.....	29
Figure 4 – illustration of extent of dither pattern. Dimensions are defined on sky, square can be in any orientation on sky and tracks objects.....	29
Figure 5 Example of non-redundant dither. $T_A$ is the time between dither moves as per REQ-1-ORD-2774, i.e. the open shutter/dwell time ( $T_A \geq 20s$ ), $T_M$ is move time or dither loss.....	30
Figure 6 Near and mid infrared atmospheric transmission windows for 1 mm precipitable water vapor [RD7].....	58
Figure 7 Near and mid infrared atmospheric transmission windows for 3 mm precipitable water vapor [RD7].....	58
Figure 8 Infrared atmospheric transmission windows for 1 mm precipitable water vapor [RD7].....	59
Figure 9 Infrared atmospheric transmission windows for 3 mm water vapor [RD7].....	59

## LIST OF TABLES

Table 1 Observing Performance Conditions.....	14
Table 2 Facility Performance Conditions.....	15
Table 3 Component Functional conditions.....	17
Table 4 Survival Conditions.....	18
Table 5 Summary of Accuracy and Timing Requirements for Motion during offsetting, nodding and dithering.....	28
Table 6 Telescope Optical Throughput Requirements.....	32
Table 7 IRIS Requirements.....	36
Table 8 IRMS Requirements.....	38
Table 9 WFOS Requirements.....	39
Table 10 MIRES Requirements.....	42
Table 11 PFI Requirements.....	43
Table 12 NIRES-B Requirements.....	44
Table 13 NIRES-R Requirements.....	45
Table 14 HROS Requirements.....	46
Table 15 WIRC Requirements.....	47
Table 16: ISP Bandwidth Requirements.....	53
Table 17: Night time temporal temperature gradients.....	60

## 1. INTRODUCTION

### 1.1 INTRODUCTION

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

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 flow down to the ORD from the TMT Science Requirements Document (SRD), and the Operations Concept Document (OCD).

As necessary, new requirements implied by the current document flow down into:

- TMT Observatory Architecture Document (OAD)
- 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

This document shall be used as guidance for the top level engineering function and performance requirements of the observatory.

The requirements documented in the OCD and the ORD are intended to fully describe the top level engineering requirements and operational concepts to satisfy the criteria of the Science Requirements Document, and by reference, the Science Case for the Observatory. By this definition, the ORD will change in response to changes in the SRD or OCD, but will not require modification when changes are made to the Observatory Architecture Document (OAD), or to the Sub-System Requirements Documents.

### 1.3 SCOPE

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

- General Constraints
- Environmental Constraints
- Observation Operational Support
- Telescope and Instrumentation Requirements
- Facility Requirements
- System Attributes
- Environmental, Health and Safety Requirements
- High Level Software Requirements

#### 1.4 APPLICABLE DOCUMENTS

- AD1 – [Science-Based Requirements Document](#) v15 (TMT.PSC.DRD.05.001)
- AD2 – [Operations Concept Document](#) (TMT.OPS.MGT.07.002)
- AD3 – [TMT Acronym List](#) (TMT.SEN.COR.06.018)

#### 1.5 REFERENCE DOCUMENTS

- RD1 – NFPA 780 Standard for the Installation of Lightning Protection Systems  
([http://www.nfpa.org/catalog/product.asp?category%5Fname=&pid=78004&target%5Fpid=78004&order\\_src=A292](http://www.nfpa.org/catalog/product.asp?category%5Fname=&pid=78004&target%5Fpid=78004&order_src=A292))
- RD2 - Civil Engineering Standard ASCE 7-98 "Minimum Design Loads for Buildings and Other Structures"  
(<http://www.pubs.asce.org/>)
- RD3 – [URS Report : Site-Specific Seismic Hazard Assessment](#),  
TMT.STR.TEC.10.001.REL01
- RD4 – [Tertiary Mirror Equations of Motion for an "off-altitude-axis" Nasmyth Focus](#)  
(TMT.SEN.TEC.07.022.REL01)
- RD5 - G. Z. Angeli, S. Roberts, and K. Vogiatzis, Proceedings of SPIE vol. 7017,  
TMT.SEN.JOU.07.004,REL02
- 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 - Establishing Environmental Requirements, [TMT.SEN.TEC.09.031](#)
- RD9 - [Accuracy Definition](#), TMT.SEN.TEC.05.029

## 1.6 CHANGE RECORD

Revision	Date	Section	Modifications
CCR26	November 27 <sup>th</sup> 2013		Updated as per Change Request 126
CCR25	June 6 <sup>th</sup> 2012		<ul style="list-style-type: none"> <li>Incorporated Change Request 107. Updates as per Level 1 DRD Change History Document, TMT.SEN.TEC.07.038.REL10</li> </ul>
CCR24	October 12 <sup>th</sup> 2011		<ul style="list-style-type: none"> <li>Incorporated Change Request 79. Updates as per Level 1 DRD Change History Document, TMT.SEN.TEC.07.038.REL09</li> </ul>
CCR23	April 27 <sup>th</sup> 2010		<ul style="list-style-type: none"> <li>Incorporated Change Request 72. Updates as per Level 1 DRD Change History Document, TMT.SEN.TEC.07.038.REL07</li> </ul>
CCR22	December 17 <sup>th</sup> 2009		<ul style="list-style-type: none"> <li>Incorporated Change Requests 56, 60 and 63. Updates as per Level 1 DRD Change History Document, TMT.SEN.TEC.07.038.REL06</li> </ul>
CCR21	March 26 2009		<ul style="list-style-type: none"> <li>Updates as per Level 1 DRD Change History Document, TMT.SEN.TEC.07.038.REL05</li> </ul>
CCR20	January 28 2009		<ul style="list-style-type: none"> <li>Updates as per Level 1 DRD Change History Document, TMT.SEN.TEC.07.038.REL04</li> </ul>
CCR19	September 5, 2008		<ul style="list-style-type: none"> <li>Updates as per Level 1 DRD Change History Document, TMT.SEN.TEC.07.038.REL03</li> </ul>
CCR18	March 19, 2008		<ul style="list-style-type: none"> <li>Updates as per Level 1 DRD Change History Document, TMT.SEN.TEC.07.038.REL02</li> </ul>
CCR17	November 14, 2007		<ul style="list-style-type: none"> <li>Updates as per Level 1 DRD Change History Document, TMT.SEN.TEC.07.038.REL01</li> </ul>
CCR 16	October 19, 2007		<ul style="list-style-type: none"> <li>Updates as per systems engineering watch list document TMT.SEN.TEC.07.025.REL14</li> </ul>

CCR 15	August 13, 2007	3.3.6 3.3.7  3.3.18.1	<ul style="list-style-type: none"> <li>• Updates as per ORD CCR15 change history as documented in TMT.SEN.TEC.07.025.DRF12, including: <ul style="list-style-type: none"> <li>▪ Addition of REQ-1-ORD-2740</li> <li>▪ Change to REQ-1-ORD-2755</li> <li>▪ Addition of REQ-1-ORD-2756</li> <li>▪ Addition of REQ-1-ORD-2757</li> <li>▪ Change to REQ-1-ORD-2760</li> <li>▪ Addition of REQ-1-ORD-2761</li> <li>▪ Addition of REQ-1-ORD-2762</li> <li>▪ Addition of REQ-1-ORD-2785</li> <li>▪ Change to REQ-1-ORD-3505</li> <li>▪ Change to REQ-1-ORD-3655</li> </ul> </li> </ul>
CCR 14	May 25, 2007	3.3.19.3 3.3.19.4	<ul style="list-style-type: none"> <li>• Updates as per proposed errata and updates as documented in TMT.SEN.TEC.07.025.DRF05, including: <ul style="list-style-type: none"> <li>▪ Change to [REQ-1-ORD-4310]</li> <li>▪ Change to [REQ-1-ORD-4385]</li> </ul> </li> </ul>
DRF 13	May 12, 2007	3.2.2 3.3.3 3.3.11 3.3.5 3.5.2 3.8	<ul style="list-style-type: none"> <li>• Consolidated acquisition requirements into a single section. Merged previous software requirements with pointing requirements.</li> <li>• Reorganized and renumbered Light Collection Geometry Section</li> <li>• Added a telescope optical throughput section</li> <li>• Added REQ-1-ORD-2670</li> <li>• Added an Operational Efficiency section</li> <li>• Moved software requirements section to the end of chapter 3.</li> </ul>
DRF 12	May 7, 2007	1.5 3.3.3 3.3.12 3.3.19.3 3.3.19.5 3.4.4.1	<ul style="list-style-type: none"> <li>• Updated References</li> <li>• Updated pupil obscuration requirement</li> <li>• Updated thermal background requirement</li> <li>• Updated IRMOS requirements</li> <li>• Updated [REQ-1-ORD-4570]</li> <li>• Updated [REQ-1-ORD-5505]</li> </ul>
DRF11	May 1, 2007	Numerous changes	<b>Update after April 24<sup>th</sup> and 25<sup>th</sup> review</b>
DRF10	March, 2007		<b>Complete reorganization and rewrite</b>

## 1.7 ABBREVIATIONS

The abbreviations used in this document are listed in the project acronym list [AD3]



## 2. OVERALL DESCRIPTION

### 2.1 PERSPECTIVE

The observatory collects the light of celestial objects, and extracts information about the characteristics of those objects from the collected light. The primary extracted information is the spatial (angular) and spectral intensity distribution of the light of celestial objects in a defined field of view.

The observatory as a system with its basic interactions to its environment is shown in Figure 1.

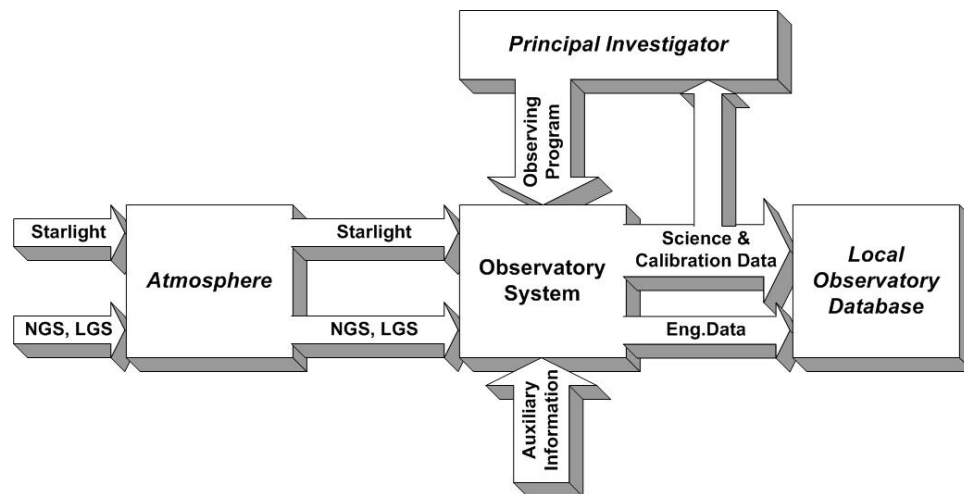


Figure 1 The observatory system with its inputs and outputs

#### 2.1.1 System Inputs

The *primary input* to the system is the light from celestial objects under investigation (i.e. science targets) after it has passed through the atmosphere of the Earth. This light is sometimes known as the science beam (or beams if multiple sub-field-of-views are observed simultaneously). When passing through the atmosphere, the wavefront of the original science beam is distorted by time-variable refractive index changes caused by turbulence at various elevations above the surface of the Earth.

The *secondary input* to the system is the light from celestial sources located near the science beam on the celestial sphere. These sources are called natural guide stars (NGS) and are used for two purposes: (i) to measure telescope tracking errors and misalignments, as well as (ii) to measure atmospheric wavefront distortion so that the effect of these distortions can be removed from the science beam.

Since suitable NGS may not be present near all desired science targets, the observatory will generate artificial guide stars to measure atmospheric turbulence.

The input light interface is above the observatory, where the air flow disturbance and thermal effects of the observatory buildings become negligible.

The *tertiary input* to the system is a science observation request. This observation request defines what science target(s) to observe, what guide stars to use, how to configure the system for that observation, and how long to collect photons from the science target(s). In classical observing, such a request may be developed in near-real time by an on-site PI assigned a specific time window by fiat or by a time allocation

committee. When queue (dynamic) scheduling is used, such requests are generated in advance and executed in order of scientific priority when the system configuration, weather, and atmospheric conditions are suitable.

Various *auxiliary inputs* are required for setting operating conditions and evaluate data collected, including universal time, local weather and atmospheric (seeing) conditions and system readiness. For safety reasons, information about work on or near the telescope is needed as well as information about the presence of aircraft in the observatory air space.

### 2.1.2 System Outputs

The *primary output* of the system will be the science data stream; that is, the digitally encoded spatial and spectral information collected by the focal-plane instruments. These science data will be tightly bound to system status information recorded during the science observation, such as time of observation, telescope pointing, AO system configuration and status, focal-plane instrument configuration and status.

The *secondary output* of the system will be the calibration data stream necessary to remove the signatures of the science instruments and the atmosphere from the science data stream. These data will be based on observations of on-board calibration sources or astronomical objects. These data will be tightly bound to system status information as described for the science data stream.

The *tertiary output* of the system will be engineering data for performance characterization and optimization.

## 2.2 SYSTEM FUNCTIONS

The basic functions of the observatory are:

- a. **Observation preparation.** The system will provide user interfaces to allow the submission of observation and/or configuration change requests to the system.
- b. **Light collection.** The system collects the light of celestial objects, as science targets, natural guide stars (NGS), and reference stars for calibration and acquisition, and focus this light into images of the objects. The system will be able to sense its own status and estimate self induced wavefront distortions in the science beams, in order to reduce these aberrations by properly aligning and shaping the optical surfaces
- c. **Light processing.** The system will process the light collected in order to deliver specific spatial and/or spectral intensity distributions to the science detector. The system will also be able to estimate and modify the wavefront of the science beam with adaptive optics to reduce the effects of the atmospheric turbulence and residual system misalignments. In order to make these estimates, status of the atmosphere around the science beams will be probed with natural and laser guide stars (NGS and LGS).
- d. **Data generation.** The system will digitally encode and record image (undispersed) or spectral (dispersed) light intensity distributions delivered to the surface of the science detectors. When such data result from observations of science targets, they will be known as science data. When such data result from the observations of celestial calibration targets or terrestrial (built-in) calibration sources, they shall be known as calibration data. Both kinds of data will be time-stamped and linked to information about system configuration and status as well as environmental conditions during data acquisition. These meta-data will be complete enough to

allow users to link science and calibration data for the purposes of removing the artificial signatures caused by the terrestrial atmosphere and the instrument.

- e. **Data storage.** All science and data (as well as all environmental conditions and engineering telemetry) generated by the system will be captured and stored. Storage duration requirements are specified elsewhere in this document.
- f. **Data processing.** It will be possible extract information from the generated data for data quality control purposes. It will also be possible to remove artificial signatures caused by the terrestrial atmosphere and the instrument from science data.

In order to perform its basic functions, the system needs to provide operational infrastructure, including utilities, operational environment, and boarding/lodging

The methods of light collection, processing and data generation are classified as operating modes and system configurations

*System configurations* are realized by specific combinations of adaptive optics and instruments. The different system configurations are identified by their characteristic science measurement:

- a. IRIS, i.e. the Infra-Red Imaging Spectrometer, including the appropriate configuration of the Laser Guide Star Multi Conjugate AO System (MCAO);
- b. IRMS, i.e. the Infra-Red Multi-Object Spectrometer, including the appropriate configuration of the Laser Guide Star Multi Conjugate AO System (MCAO);
- c. WFOS, i.e. the seeing limited Wide Field Optical Imaging Spectrometer
- d. NIRES, i.e. the Near Infra-Red Echelle Spectrometer, including the appropriate configuration of the Multi Conjugate AO System (MCAO);
- e. IRMOS, i.e. the Near Infra-Red Multi-Object Spectrometer, including a Laser Guide Star multi-object AO System (MOAO);
- f. MIRES, i.e. the Mid Infra-Red Echelle Spectrometer, including a small field, low emissivity, Laser Guide Star mid-IR AO system (MIRAO);
- g. HROS, i.e. the seeing limited High Resolution Optical Spectrometer;
- h. PFI, i.e. the Planet Formation Instrument, including an extreme AO system (ExAO) and coronagraph enabling very high contrast imaging.
- i. WIRC, i.e. the Wide Field Infrared Camera, including the appropriate configuration of the Multi Conjugate AO System (MCAO);

Several *operating modes* are defined for the observatory, and there are specific requirements related to each of these. The defined operating modes are:

- a. In **Seeing Limited Operating Mode** the telescope delivers light directly to the instrument, without introducing further optical elements beyond the telescope mirrors. Wavefront correction is limited to closed loop active optics.
- b. In **Adaptive Optics Operating Mode** the telescope delivers the light of the science object to the instrument with aberrations significantly reduced by means of adaptive optics compensation of atmospheric turbulence effects and residual telescope aberrations. The entire TMT observatory system is designed with adaptive optics capabilities to improve science potential over a broad range of wavelengths and fields of view. The AO performance requirements are qualitatively very different for each class of TMT configuration, and different AO system concepts are most suitable for each case:

- The needs of near infra-red spectroscopy and imaging instruments (IRIS and IRMS) are well met by a multi-conjugate AO (**MCAO**) system that utilizes multiple laser guide stars (LGSs) and deformable mirrors (DMs) to measure and correct atmospheric turbulence in three dimensions, thereby providing diffraction-limited image quality over a field-of-view significantly larger than the conventional isoplanatic angle.
  - The degree of atmospheric turbulence compensation required for observations in the mid-IR is comparatively modest, but system emissivity must be limited by minimizing the number of warm surfaces in the optical path. This mandates a separate mid-IR AO (**MIRAO**) system in support of MIRES system configuration
  - Ground-layer adaptive optics (**GLAO**), which estimates and corrects low-altitude atmospheric turbulence by averaging wavefront sensor (WFS) measurement from multiple widely-spaced guide stars, is the preferred approach to enhancing atmospheric seeing (and thereby improving observational efficiency) for wide-field imaging and spectroscopy, like WFOS
  - Because the five arc minute field specified for multi-object spectroscopy is too large to be corrected by a practical MCAO system, multi-object AO (**MOAO**) is proposed as a means of providing separate wavefront corrections for multiple small scientific fields based upon a three-dimensional atmospheric turbulence estimate obtained using multiple laser guide stars. In principal, MOAO can be coupled to integral field unit (IFU) multi-object spectrographs like IRMOS, but the concept requires open-loop control of high-order MEMS wavefront correctors.
  - Finally, the AO requirements for very-high-contrast imaging and IFU spectroscopy will be addressed by an Extreme AO (**ExAO**) system combining very high-order atmospheric compensation, a nulling interferometer or similar diffraction suppression system, and an additional second-stage wavefront sensor used for detecting and correcting the systematic errors in the AO system that would otherwise introduce “superspeckles” and degrade the achievable contrast. The ExAO design concept is developed for the Planet Formation Instrument (PFI)
- a. **Service and Maintenance Mode** is the typical mode of daytime operations at the observatory. In this mode, the observatory systems are available, but may be powered down, depending on the current servicing and maintenance currently underway. Various observatory system configurations will be required for service and maintenance
  - b. In **Stow Mode** the observatory subsystems are parked and not immediately available. Few operational, service and maintenance tasks are possible. This is the typical mode when the observatory is shut down.

## 3. SPECIFIC REQUIREMENTS

### 3.1 CONSTRAINTS

#### 3.1.1 General Constraints

[REQ-1-ORD-1000] The observatory shall be able to operate and meet all the requirements for 50 years with preventive maintenance. Preventive maintenance means servicing, repairing, and replacing components and subsystems based on their expected lifetime, as opposed to their failure.

[REQ-1-ORD-1005] The observatory shall comply with all local and national standards and regulations relevant to the construction and operation of the observatory. In justified cases, when (i) meeting the requirements of these standards would incur significant additional expenses, and (ii) deviation from the standard does jeopardize neither personal safety, nor the technical integrity of the system, the Project Manager may grant an exception to meeting a standard.

#### 3.1.2 Environmental Constraints

##### 3.1.2.1 Site

[REQ-1-ORD-1050] The observatory shall be located at the 13N site on Mauna Kea, Hawaii, at latitude N 19°49'57.4", longitude W 155°28'53.4" at an altitude of 4012m.

*Discussion: Standard year data is expected to be representative of the operating conditions and is used for performance modelling.*

##### 3.1.2.2 Observing Performance Conditions

[REQ-1-ORD-1200] In seeing limited and adaptive optics operating modes, the system shall be able to carry out astronomical observations under the conditions listed in Table 1.

[REQ-1-ORD-1210] Unless otherwise stated, all requirements shall be met over the range of the Observing Performance Conditions.

[REQ-1-ORD-1250] The system shall not carry out observations when any precipitation (rain, snow, or hail) is present.

*Table 1 Observing Performance Conditions*

Ambient air temperature range	-5°C to +9°C
Ambient air pressure range	600 hPa to 618 hPa (TBC)
Temporal air temperature gradient	0-100th percentile range as per data in section 4.3
Ambient air relative humidity	all non-condensing conditions
External wind speed	up to 18 m/s (1 minute average velocity at 20m elevation)

*Discussion: The intent of the Observing Performance conditions is to describe the range of conditions over which all requirements (unless they specify their own specific range) are met. The observatory is designed to produce science over this range and requirements are verified with respect to this range (again unless specifically stated otherwise). This does not necessarily mean that no science is possible beyond this temperature range nor does it mean that the observatory must be shut down beyond this range. Such decision points are operational issues that depend on numerous specific details of the design and as such are not defined here.*

*Discussion: Local circumstances for some equipment obviously can result in significantly different temperature and wind speed ranges for that specific item. The purpose of this requirement is to describe the range of conditions external to the observatory. Locally it must be shown that ranges corresponding to these external ranges are addressed.*

*Discussion: The selected air temperature range spans from 0.1% to the 99.99% of the measured night time temperature over three years of data collection at the 13N site. The choice of going to higher percentiles at the top end of the temperature range is deliberate as more nights of good seeing are associated with the high temperature extremes. The selected wind speed range covers 99.11% of the data collected over three years at the 13N site. The intent is to cover a total of 99% of the cumulative probability distribution of concurrent wind and temperature data. The larger loss (0.89% due to wind) vs. loss due to temperature (0.11%) is also deliberate as it is assumed that higher than 99<sup>th</sup> percentile wind speeds for this site cannot be covered without excessive cost. For more details on the data selection, as well as the statistics (mean, median) of the data collected at 13N of Mauna Kea by TMT site selection instrumentation, see RD8.*

*Discussion: “Condensing” and “non-condensing” conditions cannot sensibly be defined for all components simultaneously due to differing emissivities and view factors to the night sky. For the purposes of this document condensing conditions are defined as being when the air temperature is within 2°C of the dew point. With this definition condensing conditions need not be covered by the Observing Performance conditions as the observatory will shut down observations when the temperature is within 2°C of the dew point.*

*Discussion: The wind speed is scaled to 20m elevation from data taken at 7m, The corresponding limit at 7m elevation is 17 m/s.*

*Discussion: The ambient air pressure limits correspond to the absolute maximum and minimum recorded by the TMT site testing instruments at 13N of Mauna Kea.*

*Discussion: The temporal temperature gradient data supplied in section 4.3 is based on air temperature measurements external to the enclosure. Local effects inside the enclosure or other areas of the observatory may result in significantly different values for sub-systems and components.*

[REQ-1-ORD-1255] The system shall be able to carry out astronomical observations right after any accumulated snow and ice is removed from the critical areas of the enclosure. An area is critical if snow, ice, or water can reach the inside of the enclosure from that area through an open observing slit or vent.

[REQ-1-ORD-1260] The summit facility, including the enclosure, shall be fully operational up to 150 kg/m<sup>2</sup> snow and ice load (vertical projection) after removal of ice and snow from critical areas.

### 3.1.2.3 Facility Performance Conditions

[REQ-1-ORD-1300] The summit facility, including the enclosure as well as other systems necessary to support servicing and maintenance shall be able to operate over the range of conditions listed in Table 2.

*Table 2 Facility Performance Conditions*

Ambient air temperature range	-10°C to +13°C
Ambient air pressure range	600 hPa to 618 hPa (TBC)
Ambient air relative humidity	0% to 100%, condensing conditions external to the enclosure, non-condensing internal to the enclosure
External wind speed	up to 30 m/s (3 s gust at 20m elevation)
External rainfall	up to 0.04 m/hour
External lightning strike	per standard NFPA 780 [RD1]

*Discussion: The intent of the Facility Performance conditions is to describe the range of conditions over which all requirements relating to the enclosure and summit facilities are met as well as requirements relating to any other parts of the observatory used for servicing or maintenance activities. While these ranges are defined for maintenance and service assumed to be carried out with closed enclosure, the enclosure may be open and observations may also be feasible. However, the enclosure is expected to be closed when conditions are outside of Facility Performance ranges.*

*Discussion: The low end of this temperature range is selected to be 5°C below the minimum Observing Performance temperature. This ensures that the enclosure and internal equipment are able to operate beyond the Observing Performance conditions. This allows the enclosure to be closed and equipment stowed even as conditions degrade from the Observing Performance conditions. The upper bound of the Facility Performance conditions temperature is selected to correspond to 99.9% of the fitted cumulative temperature probability distribution covering both day and nighttime. The upper bound of the Facility Performance conditions wind speed is also selected to correspond to 99.9% of the fitted cumulative wind speed probability distribution covering both day and nighttime.*

*Discussion: The wind speed is scaled to 20m elevation from data at 7m elevation. It is further scaled to be a 3 second gust value from one minute averaged data. The corresponding limit at 7m elevation using 1 minute averaged data is 22 m/s.*

*Discussion: Local circumstances for some equipment obviously can result in significantly different temperature and wind speed ranges for that specific item. The purpose of this requirement is to describe the range of conditions external to the observatory. Locally it must be shown that ranges corresponding to these external ranges are addressed.*

*Discussion: As above condensing conditions are defined as occurring when the air temperature is within 2°C of the dew point. During servicing and maintenance or other facility activities condensing conditions or rainfall can occur external to the enclosure. However under condensing conditions internal to the enclosure, such activities would be suspended.*

*Discussion: Higher external wind speeds than those defined here need not be considered for equipment inside the enclosure as it will be closed when external wind speeds exceed these values. This external wind speed therefore corresponds to the survival limit on wind speed for equipment internal to the enclosure. Note however that this does not account for local variation in wind speed which could result in higher values in specific areas. For example this external wind speed may correspond to a slightly higher value around some areas of the telescope top-end if particular features cause local wind acceleration.*

*Discussion: Note that in order to safely meet the requirement to be closed at the wind speed defined here, the enclosure must be capable of closing with some margin at these wind speeds. This is handled in the corresponding requirements in the ENC DRD.*

*Discussion: The lightning strike requirement is not intended to apply to subsystems internal to the enclosure. They will be subjected to power supply transients that cannot be completely mitigated on their electrical supply lines. These power supply characteristics will be defined in the OAD.*

*Discussion: The external rainfall limit is the 200 year return period event for Mauna Kea. There is a 22% probability of this value being exceeded during the 50-year lifetime of the observatory.*

[REQ-1-ORD-1350] The system shall be able to operate in this mode when precipitation (rain, snow, or hail) is present

[REQ-1-ORD-1355] The summit facility, including the enclosure, shall be operational in this mode with up to TBD kg/m<sup>2</sup> snow and ice load (vertical projection).

### **3.1.2.4 Component Functional conditions**

[REQ-1-ORD-1375] All mechanical and electrical components of the system shall be designed to function over the range of the Component Functional conditions listed in Table 3.



Table 3 Component Functional conditions

Ambient air temperature range	-13°C to +25°C
Ambient air pressure range	600 hPa to 1015 hPa (TBC)
Ambient air relative humidity	0% to 100%, condensing conditions for components external to the enclosure, non-condensing internal to the enclosure

*Discussion: The intent of this section is to define the range of conditions over which any subcomponent of the system can be expected to function. For example motors, pumps, mechanisms, computers, valves, actuators, hydraulics and electronics all must function over this range. In principle any removed subcomponent should be capable of functioning over this range. This does not imply that any system requirements are met over this range.*

*Discussion: The minimum temperature for the Component Functional conditions is selected to correspond to the expected minimum temperature that occurs once in any 10-year period. The maximum temperature is chosen to be the typical temperature expected in a laboratory environment, which exceeds the 10-year maximum temperature event for the 13N site. For more detail on the data selection see RD8.*

*Discussion: It is expected that any component of the observatory can be operated in a room temperature laboratory.*

*Discussion: Components internal to the observatory are not required to be functional with condensation on them. Components external to the observatory must remain functional in the presence of condensation.*

*Discussion: Wind is not relevant for this requirement as there is no level of system performance associated with these conditions.*

*Discussion: The ambient air pressure range is extended to the expected sea level air pressure in a laboratory.*

### 3.1.2.5 Survival Conditions

*Discussion: The system will be designed to survive these conditions without damage and without the need for optical re-alignment etc.*

[REQ-1-ORD-1400] Under any state, the system shall be designed to survive repeated exposure to the Survival conditions shown in Table 4 without damage.

*Discussion: No prior warning is available for this condition and subsystems can not assume that their equipment will have been manually switched to an off or standby state prior to arrival of these conditions. No system may be damaged by onset of the Survival conditions in any operating state. The exception to this is the enclosure which can be assumed to be closed at wind speeds in excess of the Facility Performance conditions maximum wind speed or in the presence of any precipitation.*

*Discussion: Consumable or one time safety measures are not permitted.*

[REQ-1-ORD-1410] It shall be possible for the normal observatory operations staff to perform an inspection of the system in 6 hours. The inspection shall be sufficient to ensure it is in a safe condition to allow astronomical observations or regular maintenance operations to take place.

*Discussion: Inspection would be expected to start after any potentially damaging event once the danger has passed and staff have returned to work*

[REQ-1-ORD-1415] Survival Conditions occur when any of the following conditions arise and they exceed the Facility Performance conditions listed in Table 2.

*Table 4 Survival Conditions*

Ambient temperature range	-16°C to +30°C
Ambient air pressure range	590 hPa to 1025 hPa (TBC)
Temporal temperature gradient	TBD
Ambient relative air humidity	0% to 100%, condensing inside and outside enclosure
External wind speed	up to 83.7 m/s (3 s gust at 20m elevation)
External rainfall	0.04 m/hour
External lightning strike	per standard NFPA 780 [RD1]

*Discussion: The intent of this section is to define the range of conditions which the observatory must survive.*

*Discussion: The minimum temperature for the Survival conditions is selected to correspond to the expected minimum temperature that occurs once in any 200-year period. This means that there is a 22% probability of this value being exceeded during the 50-year lifetime of the observatory. The maximum temperature is selected to correspond to an unusually hot area in a laboratory environment and exceeds the 200-year maximum temperature event at the 13N site.*

*Discussion: Note that transportation and storage conditions are not addressed by these requirements. It is quite likely that transportation and storage conditions will exceed this maximum temperature. Those requirements are currently TBD.*

*Discussion: The maximum wind speed for the Survival conditions is also selected to correspond to the expected maximum that occurs once in any 200-year period. This wind speed is scaled to 20m elevation from estimated values at 7m elevation. It is further scaled to be a 3 second gust value from one minute average estimates. The corresponding limit at 7m elevation for 1 minute average wind speed is 61 m/s.*

*Discussion: The lightning strike requirement is not intended to apply to subsystems internal to the enclosure. They will be subjected to power supply transients that cannot be completely mitigated on their electrical supply lines. These power supply characteristics will be defined in the OAD.*

[REQ-1-ORD-1420] The system shall be designed to withstand survival conditions when there is no power to the observatory.

[REQ-1-ORD-1425] The system shall be designed such that loss of power will not cause damage to the observatory.

*Discussion: For example, it is not acceptable that a loss of power causing a hydrostatic bearing oil pressure drop could cause damage to the azimuth and elevation bearing surfaces.*

[REQ-1-ORD-1430] The system shall be able to support snow loads up to 150 kg/m<sup>2</sup>.

[REQ-1-ORD-1435] The system shall be able to support ice loads up to  $68\text{kg/m}^2$ . The snow and ice loading are assumed to act concurrently.

*Discussion: Snow and Ice load values are based on Mauna Kea and require revision for Armazones.*

### 3.1.2.6 Frequent Earthquakes

[REQ-1-ORD-1502] The observatory and all subsystems shall withstand earthquakes up to the levels of the 10-year return period earthquake with no damage. Inspection by the normal operations staff, as described in [REQ-1-ORD-1410] shall be sufficient to ensure that the observatory can be returned to normal operations after such an earthquake.

*Discussion: The observatory shall be designed such that earthquakes of this size cause no damage and the observatory can continue to operate without interruption. This implies that inspection should not be necessary. However the observatory must also be designed to allow for easy inspection so that the normal operations staff can conduct an inspection in less than six hours to ensure that in fact no significant damage has occurred.*

*The levels of a 10-year period return earthquake have a 10% probability of being exceeded in a one year period.*

### 3.1.2.7 Infrequent Earthquakes

[REQ-1-ORD-1510] After exposure to an earthquake up to the levels of the 200-year return period earthquake, once the observatory staff has resumed regular duty, the system shall be able to resume normal operations within two weeks using spares that are on-site, the available staff and normally available equipment.

*Discussion: It is expected for example that this work may include replacement of one-time consumable items such as seismic restraints. At least one set of such 'expected' replacement items will therefore be required on-site.*

*The levels of a 200-year return period earthquake have a 22% probability of being exceeded in a 50 year period*

[REQ-1-ORD-1550] An earthquake up to and including the severity of the 200 year return period in some servicing modes may result in extensive damage to the observatory, or danger to personnel. Any operation that falls under this description shall be specifically identified in the appropriate system or sub-system Hazard Analysis, and the operational procedure shall be designed to minimize the time spent in this state.

*Discussion: Some operations involving large optics etc may be impossible to accomplish in a manner that is always safe in a 200 year return period earthquake.*

### 3.1.2.8 Very Infrequent Earthquakes

[REQ-1-ORD-1560] The enclosure, telescope structure, instrument support structure, optical mounts and the optics and structures of both the telescope and the instruments shall be designed to withstand the loads resulting from an earthquake up to the levels of the 1000-year return period earthquake.

*Discussion: The telescope needs to limit loads to the telescope mounted subsystems resulting from such an earthquake to the values specified in the OAD. The primary structure of all telescope mounted subsystems and their optics must be designed to withstand these same specified loads imparted by the telescope. This requirement is a structural design requirement only and no expectation is made about either the time or cost*

*to repair other damage to the observatory. The following are not required to be designed against this level of earthquake provided they do not pose a hazard to optics: Structure whose failure would not cause a hazard to personnel safety; fluid and electrical services; computers and other ancillary systems:*

*The summit facilities and the enclosure are also covered by the additional need to meet building code requirements which in general terms require collapse prevention at the 2500-year return period MCE level*

*The levels of a 1000-year return period earthquake have a 5% probability of being exceeded in a 50 year period.*

[REQ-1-ORD-1565] All sub-system components shall be designed so as to not damage the optics or present a hazard to personnel in the event of their failure under the loads resulting from an earthquake up to the levels of the 1000 year return period.

*Discussion: Any sub-systems, components, hoses, etc. that may fail under the conditions resulting from a 1000-year return period earthquake and whose failure could cause damage to the telescope optics shall be identified. The failure modes will be identified and where necessary measures shall be put in place to prevent or reduce the probability of failures causing damage to the optics.*

## 3.2 OBSERVATION OPERATIONAL SUPPORT

### 3.2.1 General

[REQ-1-ORD-1715] The system shall monitor the environmental and observational conditions to support the real-time selection of observing programs.

*Discussion: Sensing environmental conditions will enable the selection of observing programs to suit the conditions.*

[REQ-1-ORD-1720] The system shall monitor its own status to enable the assessment of whether a particular observation can be successfully completed.

### 3.2.2 Target acquisition requirements

[REQ-1-ORD-1800] Within 3 minutes, the telescope and enclosure shall be able to point from any one position on the sky to any other in a way ensuring the uninterrupted execution of the next observation, and settle control loops and structural dynamics sufficiently to be ready for object acquisition.

*Discussion: The telescope motion ensuring the uninterrupted execution of the next observation may include un-wrapping the cables running from the observing floor to the azimuth structure.*

*Discussion: The following requirements apply for targets anywhere on the accessible sky.*

[REQ-1-ORD-1805] The system shall be capable of coordinating all observatory activity so that the complete target acquisition sequence (e.g. telescope configuration, enclosure configuration, instrument configuration, AO system configuration, and guide star acquisition), can be completed in five (5) minutes if an instrument change is not needed.

[REQ-1-ORD-1810] If an instrument change is required, the maximum time from the end of an observation on one instrument to the start of observation on another shall be ten (10) minutes.

[REQ-1-ORD-1815] If a major instrument reconfiguration is required, the maximum time from the end of an observation in one configuration to the start of observation in another shall be ten (10) minutes.

*Discussion: The meaning of "major instrument reconfiguration" must be defined for each instrument. This is envisioned to include such things as changes from imaging to spectroscopy. It is not intended to include minor changes such as movement of guide probes, changing filters etc.*

### 3.3 TELESCOPE AND INSTRUMENTATION REQUIREMENTS

#### 3.3.1 General

[REQ-1-ORD-2500] The telescope system shall collect the light of celestial objects, as science targets, natural guide stars (NGS), and reference stars for calibration and acquisition, and focus this light into images of the objects.

[REQ-1-ORD-2505] The observatory shall be able to be used in both seeing limited and adaptive optics mode.

[REQ-1-ORD-2510] The system shall be able to sense its own status and estimate self induced wavefront distortions in the science beams, in order to reduce these aberrations by properly aligning and shaping the optical surfaces.

[REQ-1-ORD-2515] The system shall be able to sense its local environment, including but not limited to temperature and wind speed.

*Discussion: Wind speed and temperature gradient cause independent image degradation due to local seeing effects. By monitoring these and configuring the enclosure vents the overall seeing degradation can be managed.*

[REQ-1-ORD-2520] The system shall be able to probe the status of the atmosphere around the science beams by sensing natural and laser guide stars (NGS and LGS) in order to estimate the science beam aberrations due to the atmosphere.

[REQ-1-ORD-2525] The system shall be able to modify the wavefront of the science beam with adaptive optics to reduce the effects of the atmospheric turbulence and residual system misalignments.

[REQ-1-ORD-2530] The system shall process the light collected in order to deliver specific spatial or spectral intensity distributions to the science detector.

[REQ-1-ORD-2540] The science data shall be linked to calibration and time data as well as system and environmental status data comprising all the information relevant to the evaluation of the science data.

[REQ-1-ORD-2545] The system shall generate enough calibration data to allow the removal of system signatures from the science data. Such calibration data are obtained via the observation of both celestial and terrestrial (built-in) sources.

#### 3.3.2 Wavelength Range

[REQ-1-ORD-2550] The telescope shall be designed to enable science over the wavelength range of 0.34 – 28  $\mu\text{m}$ , with a goal of 0.31 to 28  $\mu\text{m}$ .

*Discussion: Specific modes will be optimized for specific wavelength ranges, but the telescope must pass wavelength over this entire range.*

*Discussion: Limitations in coating recipes and commissioning of the coating equipment may limit the UV throughput at early light. It is highly desirable to provide throughput shortward of 0.34 microns if optical mirror coatings can be developed that provide this capability.*

*Discussion: Unless a wavelength range is quoted in a wavelength dependent requirement, it shall be assumed that it applies over wavelengths from 0.34 to 28 microns.*

### 3.3.3 Light Collection Geometry

[REQ-1-ORD-2570] The telescope optical design shall be aplanatic, consisting of 3 mirrors (M1, M2 and M3), including aspheric primary and secondary mirrors, and a flat tertiary mirror.

[REQ-1-ORD-2575] The primary mirror shall consist of hexagonal segments, each controlled in tip/tilt and piston to allow phasing of the primary mirror.

[REQ-1-ORD-2580] The system shall have an entrance pupil whose circumscribing circle is 30 m diameter.

[REQ-1-ORD-2585] The entrance pupil shall have a maximum of 4% obscuration due to the shadow of the secondary mirror and its support structure.

[REQ-1-ORD-2590] The obscuration of the primary mirror must be a simple shape, capable of being masked by a cold stop in an instrument.

[REQ-1-ORD-2595] The M3 mirror shall be located in front of the primary mirror (between the primary and secondary mirrors).

[REQ-1-ORD-2600] The M3 mirror shall be steerable to address several focal stations on the Nasmyth platforms.

*Discussion: The tertiary mirror equations of motion for an off-altitude-axis Nasmyth focus are presented in TMT Report 22 [RD4].*

[REQ-1-ORD-2605] The telescope system will be in a Nasmyth configuration, with several available foci on each side of the primary mirror.

[REQ-1-ORD-2610] The system shall provide a 20 arcminutes diameter field on the elevation axis at the Nasmyth foci.

[REQ-1-ORD-2615] The M2 and M3 mirror optical clear aperture diameters shall be sized to provide an unvignetted field of view of 15 arcminutes diameter on the elevation axis at the Nasmyth foci.

*Discussion: This results in 10.2% vignetting at the edge of the 20 arcminute field, which is acceptable for wide field science.*

[REQ-1-ORD-2620] The unobscured field and unvignetted field of view diameters are permitted to decrease at Nasmyth foci locations off the elevation axis as long as the complete SRD instrument suite can be housed on the Nasmyth platform such that the field required by each instrument is not further infringed upon.

*Discussion: Some Nasmyth foci locations will require M3 to tilt beyond 45 degrees to deliver the beam, causing a foreshortening effect which will decrease the unvignetted field at that location. Also at some foci the primary mirror will obscure the field as the telescope tilts towards horizon. The above specification says that this is ok as long as all the SAC instruments (defined as the early light plus future instruments described in this document) can be housed on the Nasmyth Platform, and none of them have large enough fields to experience the degraded field obscurations or vignetting caused at the off-axis locations.*

### 3.3.4 Pointing on the Sky

*Discussion: Pointing is the blind operation establishing the initial alignment of the telescope 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 mount encoder readings. 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.*

*Discussion: Requirements in this and subsequent sections that define an RMS pointing, offsetting, nod or dither accuracy should be interpreted as:*

$$Accuracy_{RMS} = \sqrt{\sigma_{systematic}^2 + \sigma_{random}^2}$$

Where  $\sigma_{random}^2$  is the variance over repeated realization of the same move (i.e. from A to B) and  $\sigma_{systematic}^2$  is the variance over the ensemble of all possible moves in a class (RD9)

*Discussion: Where a move time is specified, the specification is for the time taken for the system to reach its new position and stay within the specified settling band for that move. For all moves, the settling band is chosen to be the peak to peak value of the image motion specification, assumed to be 4 x the RMS image motion specified in [REQ-1-ORD-2720], see Figure 2.*

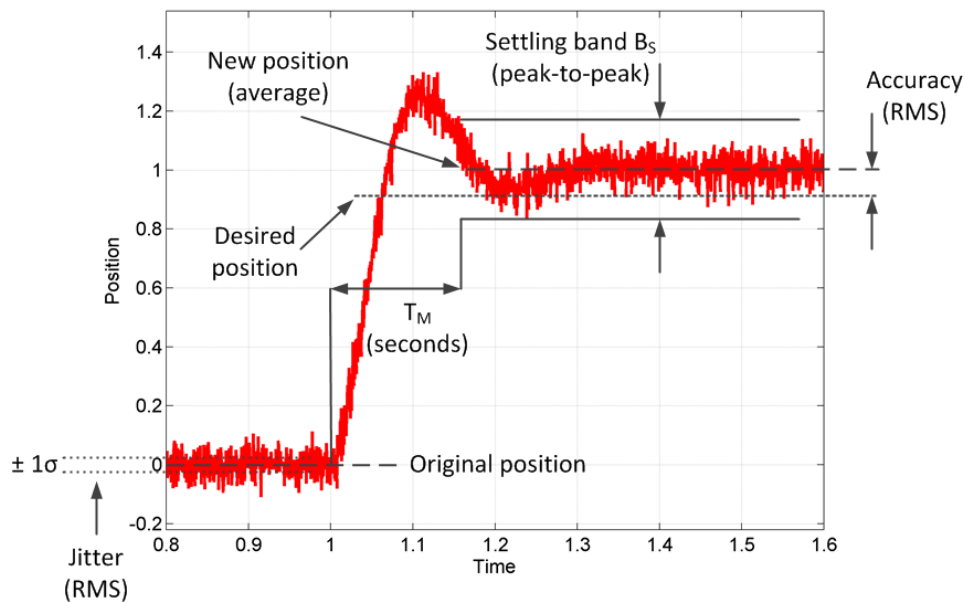


Figure 2 illustrating the move time and settling band specification.  $T_M$  is the move time,  $B_S$  is the settling band.

[REQ-1-ORD-2625] The system shall establish the alignment of the telescope relative to the sky primarily by means of the mount control system and actuators setting the telescope azimuth and elevation angles.



[REQ-1-ORD-2630] The system shall be able to observe anywhere on the sky from  $1^\circ$  to  $65^\circ$  zenith angle.

[REQ-1-ORD-2635] The system shall be able to move additional distances in zenith angle to allow for servicing, maintenance and parking positions, and safety, as required.

*Discussion: It is expected that the telescope will have to point to horizon and approximately 1 degree to the other side of zenith.*

[REQ-1-ORD-2640] The system shall be able to observe anywhere on the sky from  $0^\circ$  to  $360^\circ$  azimuth angle.

[REQ-1-ORD-2645] The system shall provide sufficient continuous azimuth range coverage to enable a continuous observation across any 180 degree range of azimuth angles.

*Discussion: This specification is intended to set minimum requirements on the range of cable wraps etc.*

[REQ-1-ORD-2650] The system shall point to a target in the whole accessible sky with an RMS accuracy of 1 arcsec in each axis on the sky. The goal is to achieve 0.5 arcsec RMS.

*Discussion: It is understood that pointing is an operation without direct sky references (guide stars).*

[REQ-1-ORD-2654] A  $1^\circ$  move on the sky shall be achieved within 7.5s with an accuracy of 0.1 arcsec RMS.

*Discussion: Traces from REQ-0-SRD-0215.*

[REQ-1-ORD-2656] The long term average slew time between science targets shall be less than 60 seconds.

*Discussion: This requirement applies to the long term average over many different science programs. A typical year of slewing data from either Gemini or Keck is an acceptable standard to verify this requirement against.*

### 3.3.5 Acquisition

*Discussion: 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-ORD-2670] It shall be the responsibility of the instruments and adaptive optics systems to implement hardware including the cameras or wavefront sensors to support guide star acquisition.

[REQ-1-ORD-2680] The system shall be able to acquire natural guide stars onto guiding wavefront sensors.

[REQ-1-ORD-2685] The system shall be able to align science targets onto instruments.

### 3.3.6 Guiding and Field De-Rotation

*Discussion: It is understood that 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. It is understood that guiding is the process of tracking an object using closed loop feedback from an instrument or AO system based natural guide star wavefront sensor.*

[REQ-1-ORD-2700] The system shall improve the alignment of the telescope relative to the sky by means of guiding, over the whole accessible sky.

[REQ-1-ORD-2705] The instruments or adaptive optics systems shall de-rotate the astronomical field as they require. The telescope shall have no provision for de-rotating the science field.

*Discussion: We assume this will be accomplished either by rotating the instrument or implementing a K mirror within the instrument.*

[REQ-1-ORD-2710] The system shall be able to guide with a speed of up to 1.1 times the sidereal rate.

*Discussion: The system is required to track solar system targets, using "fixed" natural guide stars as the guiding reference. This is a maximum of 16.5 arcsec/s on the sky.*

*Discussion: This results in a maximum speed in azimuth of 895 arcseconds/second and a maximum elevation speed of 15.5 arcseconds/second.*

[REQ-1-ORD-2715] It shall be the responsibility of the instruments and adaptive optics systems to implement hardware including the cameras or wavefront sensors to provide guiding error feedback.

[REQ-1-ORD-2720] In seeing limited mode, the RMS image motion contribution of guiding and field de-rotation anywhere in the field of view of the given instrument shall be less than 0.05 arcsec.

[REQ-1-ORD-2725] In certain adaptive optics system configurations (AO – instrument combinations) the maximum allowable image jitter shall be  $\lambda/10D$  RMS.

[REQ-1-ORD-2730] The system must support adaptive optics mode guiding, where the image motion contribution of guiding anywhere in the field of view of a given instrument shall be less than 0.002 arcsec RMS after AO correction.

*Discussion: This requirement includes only the residual windshake and atmospheric turbulence. This requirement is understood to qualify [REQ-1-ORD-3525] NFIRAOS sky coverage.*

[REQ-1-ORD-2732] During adaptive optics mode guiding, image smearing anywhere in the field of view of a given instrument shall be less than 0.0005 arcsec RMS after AO correction.

*Discussion: Image smearing budget is added in quadrature to the guiding error budget in [REQ-1-ORD-2730], and consists of rotator errors, ADC motion and optical errors, OIWFS probe motion errors, differential flexure between probes and science detectors, atmospheric refraction and dispersion modeling errors. It was set during discussions with the IRIS science team 2008-08-08.*

[REQ-1-ORD-2740] The telescope shall open-loop track without the assistance of real time optical feedback to the following accuracies for no less than the respective durations.

RMS Accuracy (arcseconds)	Time
TBD	10 seconds
0.1	10 minutes
0.5	1 hour (nautical night time)
1.0	1 hour (day time)

*Definition: Tracking is an open loop process, accomplished without feedback from guiding cameras.*

*Discussion: The difference in accuracy requirements identified for day and night one hour duration open loop tracks acknowledges that the temperature of the telescope structure may be different between the day and night. Since pointing models will be built based on data collected at night there will be some degradation in performance when the model is applied to the telescope during the day.*

*Discussion: The traceability of the open loop tracking requirement is a bit soft. None the less experience has shown that many observing programs benefit from good open loop tracking performance. One example is when a laser guide star assisted AO observation is interrupted by an aircraft sighting. An aircraft sighting would result in the laser being turned off for approximately 1 minute. During this time the telescope mount is not receiving guide updates and is tracking open loop. If the performance of the telescope open loop tracking can maintain the spot on the approximately 1 arcsecond field of view On Instrument wavefront sensor during the laser off time a re-acquisition sequence will not be necessary when the laser is turned back on. This results in a time savings; on the average aircraft sightings occur six times per night (TBC).*

### 3.3.7 Offsetting and Nodding

*Discussion: It is understood that offsetting is the process of moving from one pointing to another over a small angular distance.*

*Definition: **Acquisition offsetting**, is the process of repointing of the telescope over small angles without any feedback.*

*Definition: **Guider offsetting**, is the process of repointing of the telescope from one guiding location to another with the assistance of guider feedback.*

*Definition: **AO Guider offsetting**, is the process of repointing of the telescope from one guiding location to another with the assistance of guider feedback and adaptive optics image correction.*

*Definition: **Nodding** is the process of repetitively offsetting the telescope between two positions on the sky, with a dwell time at each end point where the system is in guiding mode.*

*Definition: **Dithering** is the process of repetitively offsetting the telescope between more than two positions on the sky, with a dwell time at each end point where the system is in guiding mode.*

*Discussion: All motions in this section are defined 'on sky'. In practice this means that at observing angles close to zenith the telescope azimuth motion required to achieve the moves in the required time is unachievable. For the telescope azimuth axis, reduced performance against these timing requirements at zenith angles less than 30 degrees is acceptable..*

[REQ-1-ORD-2752] In seeing limited mode, the system without adaptive optics or guider assistance shall offset to a target not more than 0.1° away within 3.5s with an RMS accuracy of 0.1 arcsec.

Discussion: Addresses [REQ-0-SRD-0225]

[REQ-1-ORD-2755] The telescope system must be able to perform **Guider Offsetting**.

[REQ-1-ORD-2756] During a guider offset, the system must be able to offset with a positional error of at most 0.05 arcsec RMS on the sky over distances up to 1 arcmin within the times defined in Table 5.

*Discussion: The goal is to increase the offset range to 2 arcmin and maintain the same accuracy.*

[REQ-1-ORD-2760] The telescope system must be able to perform **AO Guider Offsetting**.

[REQ-1-ORD-2761] During an AO guider offset, the system must be able to offset with a positional error of at most 0.002 arcsec RMS on the sky over distances up to 30 arcsec within the times stated in Table 5.

*Discussion: We assume that motion control at the diffraction limit will be achieved by use of the AO tip-tilt optics and the AO wavefront sensor.*

Distance (on sky)	Time to Move	Seeing Limited Accuracy	AO Accuracy	Type of move
1 arcsec	<2s	0.05 RMS arcsec	0.002 RMS arcsec	Nod, Dither, Guider Offset, AO Guider Offset
5 arcsec	<2.5s	0.05 RMS arcsec	0.002 RMS arcsec	Nod, Dither, Guider Offset, AO Guider Offset
10 arcsec	<4s	0.05 RMS arcsec	0.002 RMS arcsec	Nod, Dither, Guider Offset, AO Guider Offset
30 arcsec	<5s	0.05 RMS arcsec	0.002 RMS arcsec	Nod, Dither, Guider Offset, AO Guider Offset
1 arcmin	<5s	0.05 RMS arcsec	N/A	Guider Offset
0.1°	3.5s	0.1 arcsec RMS	N/A	Acquisition Offset

Table 5 Summary of Accuracy and Timing Requirements for Motion during offsetting, nodding and dithering

[REQ-1-ORD-2765] The system shall be able to repetitively offset and settle between two or more given positions up to 30 arcsec apart within the accuracy and time requirements stated in Table 5.

*Discussion: As defined above this requirement applies to both 'nodding' between two points and dithering between multiple points. During a dither, the maximum move between two points is 30 arcseconds on the sky. All points within the dither pattern are contained within a 30 x 30 arcsecond square moving at sidereal rates and in any orientation and on the sky. This is illustrated in Figure 4.*

[REQ-1-ORD-2775] The system shall spend at least 80% of the period at the dwell points of nodding and dithering.

*Discussion: Requirements [REQ-1-ORD-2765], and [REQ-1-ORD-2775] apply to all of TMT in general, but apply to NFIRAOS only when the guide star asterism brightness is sufficient for NFIRAOS to meet its performance requirements as stated in [REQ-1-ORD-3530]. For*

fainter stars the percentage of time spent moving and settling between end points may exceed 20%.

Discussion: An example of a nod sequence between two points 1 arcsecond apart is shown in Figure 3.

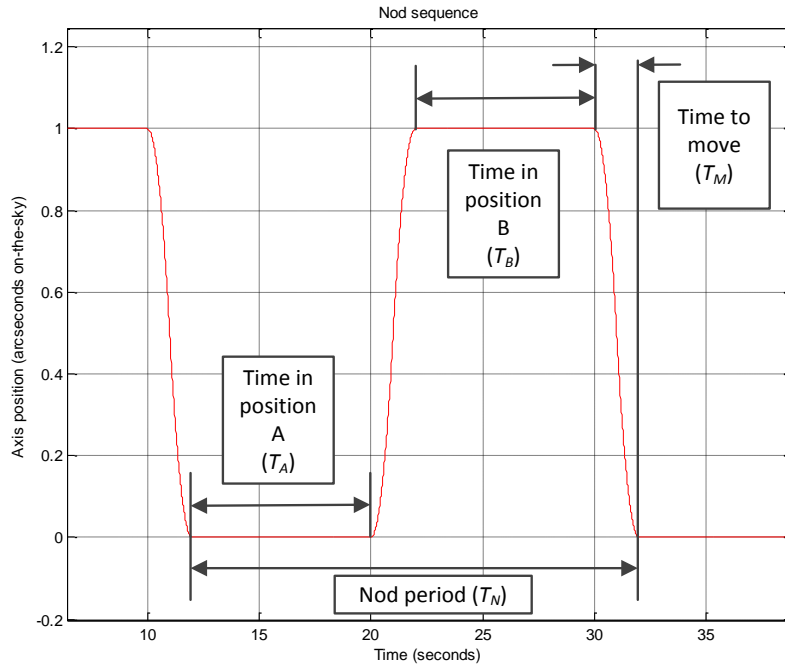


Figure 3 Example of nodding between two points 1 arcsecond apart.

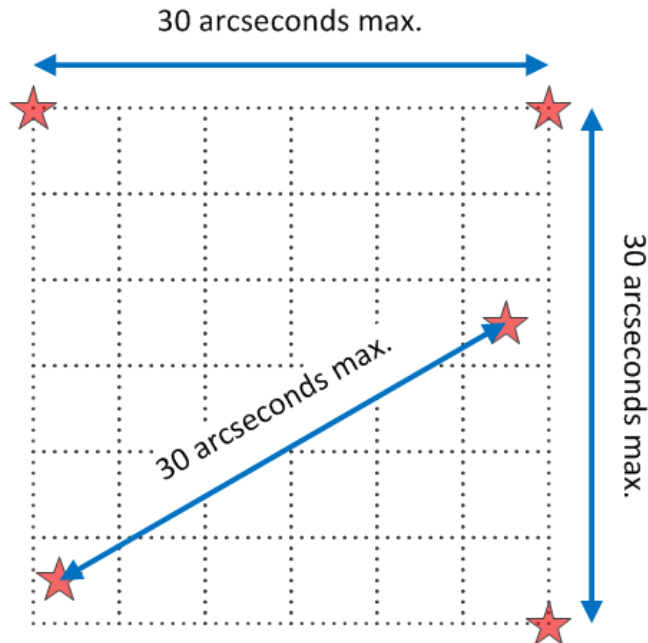


Figure 4 – illustration of extent of dither pattern. Dimensions are defined on sky, square can be in any orientation on sky and tracks objects.

[REQ-1-ORD-2774] Telescope motions shall be able to support a pattern of non-redundant dithers extending over a period of 4 hours with a time interval between two consecutive dithers ( $T_A$  in Figure 5) as short as 20 seconds.

*Discussion: This assumes dithers of up to 30 arcseconds. An example of a 'non-redundant' dither is shown in Figure 5. Non-redundant in this requirement means that each point in the dither pattern sequence is used only once. The time and accuracy requirements from Table 5 apply to the moves used in this dither pattern.*

*Discussion: Addresses [REQ-0-SRD-0280]*

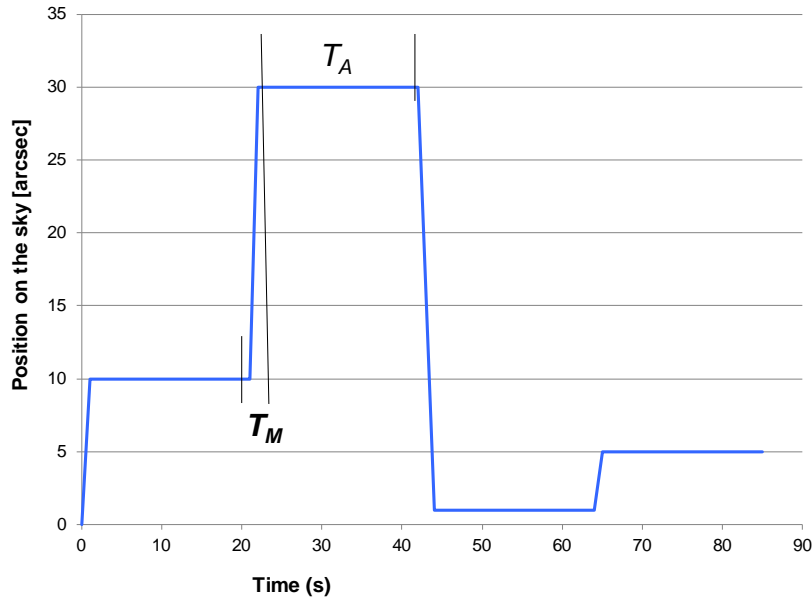


Figure 5 Example of non-redundant dither.  $T_A$  is the time between dither moves as per REQ-1-ORD-2774, i.e. the open shutter/dwell time ( $T_A \geq 20s$ ),  $T_M$  is move time or dither loss.

[REQ-1-ORD-2780] At the dwell points of nodding and dithering the system shall meet the guiding requirements for the current observing mode.

### 3.3.8 Image Quality

#### 3.3.8.1 Seeing Limited Mode

[REQ-1-ORD-2800] At 0.5  $\mu\text{m}$  wavelength, the Science Productivity Metric (SPM) of the observatory on the optical axis shall be 0.8 or higher.

*Discussion: The Science Productivity Metric is defined as follows [RD5]:*

$$SPM = \frac{\left\langle \iint_{\infty} PSF_{total}^2 d\alpha \right\rangle}{\left\langle \iint_{\infty} PSF_{atm}^2 d\alpha \right\rangle}$$

Here  $PSF_{total}$ ,  $PSF_{atm}$ , and  $\alpha$  stands for the Point Spread Function of the entire aberrated system including atmosphere, the Point Spread Function of the atmosphere, and the field angle, respectively. Furthermore,  $\langle \rangle$  denotes ensemble average, i.e. long term time average over operating conditions as per the standard year (add reference).

*Discussion: The Science Productivity Metric is normalized to the actual atmospheric seeing. Correspondingly, it accounts for atmospheric conditions, including atmospheric seeing degradation due to increasing zenith angle. With increasing zenith angle, the normalized SPM is not expected to degrade.*

[REQ-1-ORD-2815] The seeing limited image quality delivered by the telescope optical system at the Nasmyth focus shall be allowed to degrade with increasing telescope field angle, provided the aberration is largely a low order mode (astigmatism for example) that can be compensated with field correctors in instruments and AO systems.

*Discussion: It is understood that this is largely a result of the expected optical design of the telescope, and that off-axis astigmatism is the major component of the increased image size. It is expected that the image quality can be restored to nearly that of the on-axis requirement through the implementation of a corrector within the instrument. It is understood that the fabrication and implementation of the optics will further degrade the off-axis image quality.*

#### 3.3.8.2 Adaptive Optics Mode

*Discussion: The overall adaptive optics corrected image quality requirements are stated in the instrumentation sections of this document: sections 3.3.18 and 3.3.19.*

[REQ-1-ORD-2820] The residual on-axis wavefront error ( $W_{RMS}$ ) of the zenith pointing telescope and enclosure system that are not correctable by an idealized 120 x 120 deformable mirror AO system with infinite temporal bandwidth is 25 nm. The residual wavefront error includes residual mirror and dome seeing but not atmospheric seeing.

*Discussion: This requirement is intended to limit the high-spatial frequency errors for the entire observatory system, to enable high order adaptive optics system performance.*

[REQ-1-ORD-2825] The residual on-axis wavefront error ( $W_{RMS}$ ) of the zenith pointing telescope and enclosure system that are not correctable by an idealized 60 x 60 deformable mirror AO system with infinite temporal bandwidth is 45 nm. The residual wavefront error includes residual mirror and dome seeing but not atmospheric seeing,

*Discussion: This requirement is intended to limit the high-spatial frequency errors for the entire observatory system, to enable high order adaptive optics system performance.*

[REQ-1-ORD-2830] The residual on-axis wavefront error, ( $W_{RMS}$ ), after correction by idealized 60 x 60 and 120 x 120 AO systems with infinite temporal bandwidth, of the zenith

pointing telescope at the Nasmyth focus is allowed to degrade with increasing telescope zenith angle:  $W_{RMS} \propto \sqrt{\sec z}$  relative to the requirement at zenith.

*Discussion: This is the same rate as the AO corrected atmospheric seeing degrades with zenith angle.*

### 3.3.9 Plate Scale Uniformity

[REQ-1-ORD-2850] In seeing limited mode, after subtraction of the average image motion and the average field rotation, the position of each point in the field of view at the telescope Nasmyth foci shall not shift relative to the center of the field of view by more than 0.06 arcsec, over any length of time. In addition, it is a goal to limit any such shift to no more than 0.02 arcsec.

*Discussion: Points in the telescope field of view shall be stable relative to the center of the field of view, that is, the mapping of angles on the sky to positions in the focal surface shall be repeatable. This requirement shall limit the effects of changing plate scale as well as changes in other, non-rotationally-symmetric distortion effects. It is understood that 0.06 arcsec corresponds 100 ppm change at the edge of the field of view (10 arcmin), while 0.02 arcsec corresponds to 33 ppm.*

### 3.3.10 Pupil Shift

[REQ-1-ORD-2875] The telescope, not including instruments or AO systems, shall maintain the position of the exit pupil, centered within  $\pm 0.3$  % peak to valley of the pupil diameter.

### 3.3.11 Telescope Optical Throughput

[REQ-1-ORD-2900] After in-situ cleaning, the optical throughput of the telescope delivered to the Nasmyth foci shall exceed the values given in Table 6.

Table 6 Telescope Optical Throughput Requirements

Wavelength Range	Requirement	Goal
0.31 - 0.34 $\mu\text{m}$	N/A	0.50
0.34 - 0.36 $\mu\text{m}$	0.50	0.73
0.36 - 0.40 $\mu\text{m}$	0.50 $\rightarrow$ 0.73	0.73 $\rightarrow$ 0.86
0.4 - 0.5 $\mu\text{m}$	0.73 $\rightarrow$ 0.86	0.86 $\rightarrow$ 0.94
0.5 - 0.7 $\mu\text{m}$	0.86 $\rightarrow$ 0.91	0.94
0.7 - 28 $\mu\text{m}$	0.91	0.94

*Discussion: Where a range is given, it applies linearly over the wavelength range. This requirement is the throughput for the three combined telescope mirrors (Primary, Secondary and Tertiary).*

[REQ-1-ORD-2905] The observatory shall provide means for in-situ cleaning of the telescope optics to maintain throughput.

[REQ-1-ORD-2910] The observatory shall provide means for re-coating of the telescope optics to maintain throughput.

[REQ-1-ORD-2915] The throughput shall not degrade faster than TBD due to dust accumulated on the optical surfaces and the ageing of the coating.



### 3.3.12 Thermal Background

[REQ-1-ORD-2925] Thermal radiation collected at the focal surface, in the FOV of the system, from the primary, secondary, and tertiary mirror assemblies together shall not exceed 7% of the radiation of a 273 K black body, assuming that a cold stop is used to mask out the telescope top end obstructions.

*Discussion: All radiation sources are included (not limited to but including coatings, gaps between segments contaminants on the surfaces of the mirrors, telescope structure and enclosure).*

### 3.3.13 Baffling

[REQ-1-ORD-2940] Baffling shall be provided by the instruments and AO systems as required by the science cases, and in addition a baffle shall be provided around the clear aperture of the M3 such that when the M3 system is pointing the telescope optical beam along the elevation axis (either toward the +X Nasmyth platform or toward the -X Nasmyth platform), no light from behind the M3 can pass through an instrument field stop 20 arcmin in diameter centered on the optical axis and then pass through a pupil stop inside the instrument (i.e., a stop at an image of the M1 formed by the instrument optics).

### 3.3.14 Atmospheric Dispersion Compensation

[REQ-1-ORD-2950] Instruments shall provide atmospheric dispersion compensation as required by the TMT science cases.

*Discussion: It has been generally agreed that the ADC will be accomplished at the instrument / AO system level. NFIRAOS will not provide atmospheric dispersion compensation of the science light, implying that NFIRAOS fed instruments must in some manner cope with atmospheric dispersion.*

### 3.3.15 Laser Guide Stars and Laser Guide Star Wavefront Sensing

[REQ-1-ORD-2960] The facility AO system shall utilize laser guide stars to improve sky coverage.

[REQ-1-ORD-2965] The system shall be able to project several laser guide star asterisms, pre-defined and fixed to suit the instrument requirements, to the sodium layer.

[REQ-1-ORD-2970] As required by the science cases, adaptive optics systems and instruments shall incorporate laser guide star wavefront sensors to collect and analyze the returned 589 nm sodium light to provide active and adaptive optics corrections to the system.

### 3.3.16 Instrument Reconfiguration and Availability

[REQ-1-ORD-2990] The system shall be able to keep at least 4 instruments concurrently on standby, ready for observing.

### 3.3.17 Nasmyth Platform Requirements

[REQ-1-ORD-3000] The Nasmyth platforms shall provide support for large instruments, with masses up to 50,000 kg, and volumes of 500 m<sup>3</sup>.

*Discussion: This requirement covers all parts of the instrument, including electronics cabinets and cabling.*

[REQ-1-ORD-3005] Each Nasmyth platform shall be sized to support a maximum total distributed mass of up to 120,000 kg of instruments, electronics and support equipment.

*Discussion: The Nasmyth platform that houses HROS, WFOS and IRMOS will have approximately this mass of instrumentation upon it at the end of the first decade. This does not include the structure itself or the stairways and elevators etc.*

[REQ-1-ORD-3010] The Nasmyth areas shall be reconfigurable, and shall accommodate instruments that protrude up to 6 meters below and 4 meters above the optical axis.

[REQ-1-ORD-3015] Sufficient space shall be provided on the Nasmyth areas to accommodate the early light and first decade instruments, their support electronics, services and regularly used servicing and maintenance equipment.

[REQ-1-ORD-3020] Instrument maintenance and servicing shall be done on the Nasmyth Platforms.

### 3.3.18 Early Light Instrumentation Requirements

*At early light, the observatory shall provide the following instrument and adaptive optics capabilities:*

#### 3.3.18.1 NFIRAOS

[REQ-1-ORD-3500] NFIRAOS shall be a multi-conjugate adaptive optics system utilizing laser guide stars, and shall feed near-diffraction limited images to TMT instruments working in the near infrared.

[REQ-1-ORD-3505] NFIRAOS shall meet its requirements for image quality, sky coverage, throughput, and background simultaneously over a wavelength range of 1.0 to 2.5  $\mu\text{m}$ , with a strong goal to simultaneously meet these requirements down to 0.8  $\mu\text{m}$ .

*Discussion: Extending the short wave cutoff from 1.0  $\mu\text{m}$  to 0.8  $\mu\text{m}$  may reduce sky coverage, since a brighter natural guide star will be required for real-time calibration of the LGS WFS measurement errors arising due to sodium layer variability and Rayleigh backscatter variability. Observations at 0.8  $\mu\text{m}$  will definitely be possible, (cf [REQ-1-ORD-3655]) even if the sky coverage requirement is not met. This agrees with SAC thinking, and it is technically feasible with no real modification to the current NFIRAOS design.*

[REQ-1-ORD-3510] NFIRAOS shall provide a transmitted technical field with a focal ratio of f/15

[REQ-1-ORD-3515] NFIRAOS shall pass an unvignetted field of view of at least 2 arcminutes diameter to the science instruments.

[REQ-1-ORD-3520] NFIRAOS shall provide mounting for three separate instrument focal planes.

[REQ-1-ORD-3523] NFIRAOS shall permit instrument rotation at the instrument mounting points.

[REQ-1-ORD-3525] NFIRAOS shall enable 50% sky coverage at the galactic pole.

[REQ-1-ORD-3530] At early light NFIRAOS will deliver images at the science instrument focal plane, with an RMS wavefront error of 187 nanometers (nm) on axis and 191 nm over a 17 arcsec FOV under reference atmospheric seeing conditions (see Appendix) with 50% sky coverage at the galactic pole.

*Discussion: The post early light upgraded version of NFIRAOS shall achieve on the order of 120 nm high order RMS wavefront image quality on-axis. See change request #10 for more information.*

[REQ-1-ORD-3532] At early light NFIRAOS will deliver diffraction-limited images at the science instrument focal plane, with an RMS wavefront error of 208 nm over a 30 arcsec

diameter FOV under reference atmospheric seeing conditions (see Appendix) with 50% sky coverage at the galactic pole.

*Discussion: This is about 82 nm RMS worse (in quadrature) than the 191 nm RMS error on the 10" square FOV.*

[REQ-1-ORD-3533] Under median conditions, the J band enclosed energy for a 160mas slit should be at least 30% at the edge of the 2 arcmin unvignetted field of view

[REQ-1-ORD-3534] Under median conditions, the K band enclosed energy for a 160mas slit should be at least 50% at the edge of the 2 arcmin unvignetted field of view

[REQ-1-ORD-3535] NFIRAOS shall operate at zenith angles from 1 to 65 degrees.

[REQ-1-ORD-3540] NFIRAOS shall operate with values of  $r_0$  (in the direction of the observation) as small as 0.10 m.

[REQ-1-ORD-3645] NFIRAOS shall enable measurement of differential photometry at the 2% level for 10 minute integrations at 1  $\mu$ m wavelength over a 30" field of view assuming a single standard star is in each image.

[REQ-1-ORD-3650] NFIRAOS shall enable precise differential astrometry measurements, where one-dimensional time-dependent rms astrometric positional uncertainties, after fitting distortion measured with field stars, and over a 30 arcsecond field of view, shall be no larger than 50  $\mu$ -arcseconds in the H band for a 100s integration time. Errors should fall as  $t^{-1/2}$ . Systematic one-dimensional rms position uncertainties shall be no more than 10  $\mu$ as.

[REQ-1-ORD-3652] The AO system should provide sufficient calibration information to not degrade the astrometric capabilities beyond the limits set by the atmosphere.

[REQ-1-ORD-3655] NFIRAOS throughput shall exceed 85% over the 0.8-2.5 micron wavelength range, goal is 90% from 0.6 to 2.5 microns.

*Discussion: This requirement will be met one band at a time due to chromaticity of windows.*

*Discussion: NFIRAOS may include a provision for at least two different spectral passbands, e.g. by incorporating a beamsplitter changer: For example, the second beamsplitter might be designed with a bluer short wave cutoff to enable observations at shorter wavelengths with reduced sky coverage.*

[REQ-1-ORD-3660] NFIRAOS shall not increase the (inter-OH) background by more than 15% over natural sky + the telescope for median night time temperatures on the TMT site.

*Discussion: The telescope background for the purpose of this requirement shall include the emissivity computed as (1-throughput), with throughput defined in [REQ-1-ORD-2900], plus the contribution of gaps in the M1 geometry as per [REQ-1-OAD-1715], both at the median temperature as defined in [REQ-1-ORD-1200], and assuming that a cold stop within an instrument is used to mask out the telescope top end obstructions*

[REQ-1-ORD-3665] NFIRAOS shall include or make allowance for all necessary components and processes for self-calibration or calibration of the instruments that NFIRAOS feeds.

[REQ-1-ORD-3670] NFIRAOS shall provide a natural guide star operational mode, delivering Strehl ratios of 0.5 in K-Band with a 16th magnitude guide star.

*Discussion: This specification includes both implementation errors and first-order (servo lag, fitting, measurement noise) AO errors, and assumes an electron-multiplying low noise CCD.*

[REQ-1-ORD-3675] NFIRAOS shall include a seeing limited mode to provide uncorrected images to client instruments on nights when conditions do not allow AO observations.

*Discussion: In this mode, with IRMS as the client instrument, NFIRAOS provides fast guiding using its Tip/Tilt stage and signals from OIWFS(s). The deformable mirrors' figures will be commanded to static shapes to correct precalibrated aberrations in NFIRAOS and instrument. NFIRAOS also offloads tip/tilt to the telescope and reports wavefront sensor measurements of telescope low order quasi-static modes.*

### 3.3.18.2 IRIS – Infrared Imaging Spectrometer

[REQ-1-ORD-3700] IRIS is intended to provide diffraction-limited moderate spectral resolution (~ R=4000) NIR spectra using an integral field unit (IFU), and images over a small field of view.

[REQ-1-ORD-3710] IRIS shall be fed MCAO corrected light from the NFIRAOS adaptive optics system.

[REQ-1-ORD-3715] IRIS, or the IRIS to NFIRAOS interface, shall provide both field derotation and pupil derotation.

[REQ-1-ORD-3720] IRIS shall include three NGS on instrument wavefront sensors (OIWFS) to provide guide star position feedback to maintain plate scale.

[REQ-1-ORD-3725] The NGS OIWFS shall provide pixel intensities to NFIRAOS.

*Discussion: From these pixel intensities, the NFIRAOS RTC will compute: - the tip-tilt modes necessary to perform fast guiding - the focus mode necessary to calibrate the focus biases in the LGS WFS induced by the variations in the range to the sodium layer - the DM Tilt anisoplanatism modes, which compensates for tilt anisoplanatism over the extended FOV without introducing higher order wavefront errors. Additional requirements for IRIS are presented in Table 7.*

Table 7 IRIS Requirements

Requirement #	Description	Requirement
[REQ-1-ORD-3740]	Wavelength Range	0.8 – 2.4 $\mu\text{m}$
[REQ-1-ORD-3745]	Image quality	Aberrations uncorrectable by an order 60x60 AO system should not add wavefront errors larger than 30 nm RMS
[REQ-1-ORD-3750]	Field of View, IFU	Up to 3 arcsec for integral field mode
[REQ-1-ORD-3755]	Field of View, Imaging	15x15 arcsec for imaging mode
[REQ-1-ORD-3760]	Detector Sampling	0.004 arcsec per pixel (Nyquist sampled ( $\lambda/2D$ )) over 4096 pixels for IFU)
[REQ-1-ORD-3765]	Detector Sampling	Plate scale adjustable 0.004, 0.010, 0.025, 0.050 arcsec/pixel for IFU
[REQ-1-ORD-3770]	Detector Sampling	Nyquist sampled ( $\lambda/2D$ ) (0.004 arcsec) over 10x10 arcsec for imaging
[REQ-1-ORD-3775]	Detector Sampling	Smaller wavelength coverage ( $\Delta\lambda/\lambda \leq 0.05$ ) is acceptable for area coverage equivalent to 128*128 spatial pixels.
[REQ-1-ORD-3780]	Spectral Resolution	R=4000 over J,H,K bands, one band at a time R=5-100 for imaging mode
[REQ-1-ORD-3785]	Throughput	>30%, Not including telescope or NFIRAOS

[REQ-1-ORD-3790]	Instrument background	The instrument should not increase the (inter-OH) background by more than 5% (TBC) over the sum of: inter-OH sky, telescope and NFIRAOS background.
[REQ-1-ORD-3792]	Instrument Background	In imaging mode the instrument should not increase the K-band background by more than 15% over natural sky.
[REQ-1-ORD-3795]	Detector	Detector dark current and read noise should not increase the effective background by more than 5% for an integration time of 2000s.

### 3.3.18.3 IRMS

[REQ-1-ORD-3800] IRMS is a near infrared multiple slit spectrometer fed by an adaptive optics corrected beam from NFIRAOS.

*Discussion: IRMS is a early light instrument that provides some of the science capability envisioned for IRMOS.*

[REQ-1-ORD-3805] To the maximum extent possible, the IRMS instrument shall be a clone of the Keck MOSFIRE instrument.

*Discussion: This is for cost and ease of implementation reasons.*

[REQ-1-ORD-3810] IRMS shall include one NGS wavefront sensor to provide guide star position feedback

[REQ-1-ORD-3815] As a goal, the interfaces and components of the IRMS wavefront sensor shall be common with those of the IRIS WFS.

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

[REQ-1-ORD-3825] The IRMS to NFIRAOS interface must permit instrument rotation to provide field derotation.

[REQ-1-ORD-3830] The IRMS must provide pupil derotation.

[REQ-1-ORD-3835] The IRMS wavefront sensor shall be designed to minimize vignetting, especially in the central 1/3 of the field where slits will be located.

Additional requirements for IRMS are presented in Table 8

Table 8 IRMS Requirements

Requirement #	Description	Requirement
[REQ-1-ORD-3840]	Wavelength Range	0.95 – 2.45 $\mu$ m
[REQ-1-ORD-3845]	Wavelength Coverage	The instrument shall cover an entire band at a time.
[REQ-1-ORD-3850]	Image quality	>80% ensquared energy in 0.12" by 0.16" (2 pixel) box in spectroscopic mode; rms image diameters <0.07" in direct imaging mode over full bandwidth without re-focus
[REQ-1-ORD-3855]	Field of View	Shall utilize the 2 arcminute NFIRAOS technical field.
[REQ-1-ORD-3856]	Spatial Sampling	Sampling will be 0.060 arcsec/pixel in the spatial direction and 0.08 arcsec/pixel in the dispersion direction, for a 2Kx2K detector with a detector pitch of 18 $\mu$ m pixels that covers 2.05 arcmin 2.05 arcmin.
[REQ-1-ORD-3860]	Spectral Resolution	R> 3270 with 3 pixel slit (0.24 arcsec)
[REQ-1-ORD-3861]	Spectral Resolution	R> 4660 with 2 pixel slit (0.16 arcsec)
[REQ-1-ORD-3862]	Spectral Coverage	All of Y, J, H or K for slits placed at the center of the field. Dispersion achieved with a reflection grating used in order 6, 5, 4, and 3 with two grating angles, optimized for Y/J or H/K. )
[REQ-1-ORD-3865]	Throughput	>40% for imaging; >30% on order blaze in each band.
[REQ-1-ORD-3870]	Imaging mode	Entire NFIRAOS 2 arcmin field of view with 0.06 arcsec sampling for 2k x 2k 18micron pitch detector; goal 0.033" sampling for 4k x 4k 10 micron device.
[REQ-1-ORD-3875]	Background	Instrument background should not increase the inter-OH background by more than 10% over the natural sky+telescope +AO system background. Spectroscopic observations shall be background-limited for any exposure > 60 seconds.

### 3.3.18.4 WFOS

[REQ-1-ORD-3900] WFOS is a wide field, seeing limited multi-object optical spectrometer and imager.

[REQ-1-ORD-3905] WFOS shall be able to take images of the sky over the same field as it collects spectra.

[REQ-1-ORD-3910] WFOS shall provide atmospheric dispersion correction.

[REQ-1-ORD-3912] WFOS shall provide a tip-tilt-focus WFS/guider for each sub-field of the instrument.

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

[REQ-1-ORD-3913] WFOS shall provide LOWFS (Low order wavefront sensor) to supply active optics feedback signals.

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

[REQ-1-ORD-3915] A goal is to record the entire wavelength range in a single exposure. However, this wavelength range can be covered through multiple optimized arms covering suitable wavelength ranges.

[REQ-1-ORD-3920] A goal is to provide enhanced image quality using Ground Layer Adaptive Optics, over the full wavelength range, and the full field of the spectrograph.

[REQ-1-ORD-3925] A goal is to provide imaging through narrow band filters.

[REQ-1-ORD-3930] A goal is to provide a cross-dispersed mode for smaller sampling density and higher spectral resolution.

[REQ-1-ORD-3935] A goal is to provide an integral field unit (IFU) mode.

[REQ-1-ORD-3940] WFOS shall provide internal baffling.

Additional requirements for WFOS are presented in Table 9.

*Table 9 WFOS Requirements*

Requirement #	Description	Requirement
[REQ-1-ORD-3950]	Wavelength Range	0.31 – 1.0 $\mu$ m
[REQ-1-ORD-3955]	Image quality: Imaging	$\leq$ 0.2 arcsec FWHM over any 0.1 $\mu$ m wavelength interval (not including contributions from the telescope or the atmosphere)
[REQ-1-ORD-3960]	Image quality: Spectroscopy	$\leq$ 0.2 arcsec FWHM at every wavelength
[REQ-1-ORD-3965]	Field of View	40.5 arcmin <sup>2</sup> . The field need not be contiguous.
[REQ-1-ORD-3970]	Total Slit Length	$\geq$ 500 arcseconds
[REQ-1-ORD-3975]	Spatial Sampling	< 0.15 arc-sec per pixel, goal < 0.1 arc-sec
[REQ-1-ORD-3980]	Spectral Resolution	R = 500-5000 for a 0.75 arc-sec slit, 150-7500 (goal)
[REQ-1-ORD-3985]	Throughput	$\geq$ 30% from 0.31 – 1.0 $\mu$ m, or at least as good as that of the best existing spectrometers
[REQ-1-ORD-3990]	Sensitivity	Spectra should be photon noise limited for all exposure times >60 sec. Background subtraction systematics must be negligible compared to photon noise for total exposure times as long as 100 Ksec. Nod and shuffle capability in the detectors may be desirable
[REQ-1-ORD-3995]	Wavelength Stability	Flexure at a level of less than 0.15 arc-sec at the detector is required.

### 3.3.19 First Decade Instrumentation Requirements

*Discussion: This section is a summary of the basic requirements for the envisioned first decade system configurations.*

#### 3.3.19.1 General

[REQ-1-ORD-4200] The TMT observatory shall be designed and built in a manner that supports, in the first decade of operation, the implementation of the instrumentation defined in this section.

[REQ-1-ORD-4205] Implementation and commissioning of any of the first decade instruments described in this section shall not result in the loss of more than 10 (TBC) nights per instrument of productive science observing time.

*Discussion: This requirement limits the amount of rework and commissioning required to implement new capabilities on the observatory, and places a requirement on the early light facility to be implemented in a fashion that supports seamless upgrades to these capabilities.*

#### 3.3.19.2 Upgraded NFIRAOS MCAO System

[REQ-1-ORD-4225] The on-axis performance of the upgraded NFIRAOS system shall be equal or better than 133 nm RMS on-axis.

*Discussion: The on-axis performance of a future NFIRAOS upgrade is estimated to be about 130 to 135 nm RMS, assuming that (i) the ground-layer order 61 by 61 DM is replaced by a 121 by 121 mirror with 2.5 mm inter-actuator pitch, (ii) an adaptive secondary mirror (AM2) is available to provide low-order, large, amplitude corrections, if 10  $\mu$ m of stroke with the new DM is not feasible due to the smaller inter-actuator pitch and (iii) advanced, pulsed laser systems are available to eliminate wavefront sensing errors associated with the nonzero thickness of the sodium layer.*

#### 3.3.19.3 IRMOS – Near Infrared Multi Object Spectrometer

[REQ-1-ORD-4250] IRMOS is a near infrared spectrometer configuration with several (>10) integral field units (IFU) and a Multiple Object Adaptive Optics (MOAO) system capable of correcting small fields for these IFUs over a large (5 arcmin) patrol field.

[REQ-1-ORD-4255] The wavelength range for IRMOS and the MOAO adaptive optics system shall be 0.8 to 2.5  $\mu$ m.

[REQ-1-ORD-4260] The IRMOS system shall provide the spectra by integral field unit (IFU) heads deployable over a 5 arcmin diameter field.

[REQ-1-ORD-4265] The system shall provide at least 10 IFU heads.

[REQ-1-ORD-4270] The IFU heads shall have a field of view of 2".

[REQ-1-ORD-4275] The IFU heads shall have a patrol area with a diameter of 5'.

[REQ-1-ORD-4280] The minimum IFU head separation shall be 20 arcsec. The goal is to make it as small as possible.

[REQ-1-ORD-4285] In IFU mode, IRMOS shall deliver spectral resolution of R=2000 to 10000 over entire J, H, K bands, one band at a time.

REQ-1-ORD-4288 Throughput shall exceed 50%

[REQ-1-ORD-4295] The instrument and AO system of this configuration shall not increase the inter-OH optical background by more than 15% over sky and telescope backgrounds.



[REQ-1-ORD-4300] The electronic background (detector dark current and read noise) of the system shall not increase the effective background by more than 5% for an integration time of 2,000 s.

[REQ-1-ORD-4305] IRMOS shall sample at 50 mas per IFU element.

[REQ-1-ORD-4310] The maximum allowable image jitter delivered from the MOAO system to the IRMOS IFUs shall be a maximum of 15 mas RMS.

[REQ-1-ORD-4315] The MOAO system shall be capable of improving the image quality of at least 10 2- to 5-arcsecond sized regions distributed within the IRMOS field.

[REQ-1-ORD-4318] The minimum separation of the MOAO corrected regions shall be 20 arcseconds

[REQ-1-ORD-4320] The MOAO system shall deliver 50% enclosed energy onto a 0.05 sec square pixel, in each of the corrected regions, at a wavelength of 1  $\mu\text{m}$ , under the reference atmospheric conditions, when bright natural guidestars (Magnitude TBD) are present for tip-tilt sensing.

#### 3.3.19.4 MIRES – Mid Infrared Echelle Spectrometer

[REQ-1-ORD-4350] MIRES is a small field of view mid-infrared high resolution spectrometer configuration including a dedicated AO (MIRAO) system operating at the diffraction limit.

[REQ-1-ORD-4355] This instrument shall be fed by, or incorporate, a mid-IR AO system (MIRAO) using both natural and laser guide stars to deliver diffraction limited images. Thus, incorporation of a deformable mirror, as cold as practicable, into MIRES may be required if an adaptive secondary will not be available on an appropriate timescale.

[REQ-1-ORD-4358] MIRAO shall provide full sky coverage, limited only by the availability of natural tip/tilt stars

[REQ-1-ORD-4360] MIRAO shall provide an RMS wavefront error of less than 500 nm (goal 300 nm) over the full field of the MIRES science camera under the reference atmospheric conditions, when bright natural guidestars (Magnitude TBD) are present for tip-tilt sensing.

[REQ-1-ORD-4365] It is desirable (goal) that this instrument can also serve as a mid IR imager.

[REQ-1-ORD-4370] The system shall provide images in the K band (2.2  $\mu\text{m}$  wavelength) for acquisition. The goal is to provide images also in the N band (10  $\mu\text{m}$  wavelength) for science, possibly with narrow band filters.

[REQ-1-ORD-4375] The system shall offset to a target not more than 10 arcsec away with an accuracy of 0.0055 arcsec (one tenth of the diffraction limit at 8  $\mu\text{m}$ ).

[REQ-1-ORD-4380] The instrument shall provide acquisition, guiding and field rotation, as well as any calibration functions.

[REQ-1-ORD-4385] The maximum allowable image jitter delivered from the MIRAO system to the MIRES instrument shall be a maximum of 5.5 mas RMS.

*Additional requirements for MIRES are presented in Table 10.*

Table 10 MIRES Requirements

Requirement Number	Description	Requirement
[REQ-1-ORD-4400]	Wavelength Range	8 $\mu$ m- 18 $\mu$ , goal 4.5-28 $\mu$ m
[REQ-1-ORD-4405]	Field of View of acquisition camera	10 arcsec, Nyquist sampled at 5 $\mu$ m (0.017 arcsec pixels) This camera is assumed to be needed for accurate positioning of the science object onto the diffraction-limited slit. The images should be of scientific quality (low distortion, good uniformity, etc). This camera can work in K band.
[REQ-1-ORD-4410]	Field of view of science camera	A goal is to incorporate a science camera with the same sampling and field as above, operating in the N band, at least, to be used with narrow band filters. As an additional goal, this camera shall be used as the acquisition camera.
[REQ-1-ORD-4415]	Slit Length	3 arcsec, sampled at 0.04 arcsec/pixel. Slit or IFU
[REQ-1-ORD-4420]	Spectral Resolution	5000 $\leq$ R $\leq$ 100,000 (with diffraction-limited slit). R=50-100K is the prime scientific region Single exposures at R=100,000 should give continuous coverage over the orders imaged, 8 - 14 $\mu$ m
[REQ-1-ORD-4425]	High Throughput	High priority
[REQ-1-ORD-4430]	Instrument background	The instrument and AO system should not increase the N band background by more than 15% over natural sky + telescope background (assume 5% emissivity at 273K).
[REQ-1-ORD-4440]	Sampling	17 mas / pixel <i>Discussion: Maximum detector size is likely to be bounded by 2Kx2K</i>
[REQ-1-ORD-4445]	Sensitivity	Sensitivity should be limited by photon statistics in the background, and not limited by any systematic errors, in observations up to an 8 hr long integration

### 3.3.19.5 PFI – Planet Formation Imager

[REQ-1-ORD-4500] PFI is a high contrast imager configuration including an Extreme AO system with high accuracy and stability, and a coronagraph or similar instrument.

[REQ-1-ORD-4505] The PFI science case requires that it take advantage of the diffraction limited performance of a 30m telescope to directly image and take low-resolution spectra of extra-solar planets.

Additional requirements for PFI are presented in Table 11.

Table 11 PFI Requirements

Requirement Number	Description	Requirement
[REQ-1-ORD-4510]	Wavelength Range	1-2.5 $\mu$ m, one band at a time. Goal is 1 - 4 $\mu$ m.
[REQ-1-ORD-4515]	Field of View	0.7 arcsec radius, goal 2 arcsec radius (applies to all requirements for PFI)
[REQ-1-ORD-4520]	Planet Detection Contrast (I<8) @ Inner Working Angle with 5x rms noise, for a two hour integration	10 <sup>-8</sup> @ 50 mas, goal 10 <sup>-9</sup> @ 100 mas
[REQ-1-ORD-4525]	Planet Detection Contrast (H<10) @ Inner Working Angle with 5x rms noise, for a two hour integration	10 <sup>-6</sup> @ 30 mas, goal 2x10 <sup>-7</sup> @ 30 mas
[REQ-1-ORD-4530]	Spatial Sampling	Nyquist sampled at H band, goal J band.
[REQ-1-ORD-4535]	Spectral Resolution, full FOV, IFU	R = 50, goal 100
[REQ-1-ORD-4540]	Spectral Resolution, partial FOV, IFU	R = 500, goal 1000
[REQ-1-ORD-4545]	Polarimetry	Simultaneous dual channel to detect polarized light (e.g. from scattering off circumstellar dust) at a level of 1% of the residual stellar halo, and measure absolute polarization to an accuracy of 10%

[REQ-1-ORD-4570] Errors in the optical system, including the telescope, should not prevent reaching contrast ratios of 10<sup>8</sup> before systematic errors dominate. This should be achieved in H band on stars with I < 8 mag.

*Discussion: This is expected to require an instrument with three major components: a sophisticated adaptive optics system with high accuracy and stability, a coronagraph or similar instrument to block the starlight, plus a "scientific instrument" to analyze the light.*

### 3.3.19.6 NIRES-B – Near Infrared Echelle Spectrometer (Blue)

[REQ-1-ORD-4600] NIRES-B is a small field of view near infrared (1 – 2.5 micron) high spectral resolution spectrometer configuration utilizing diffraction limited images from NFIRAOS.

[REQ-1-ORD-4605] NIRES-B shall be fed MCAO corrected light from the NFIRAOS adaptive optics system.

[REQ-1-ORD-4610] NIRES-B shall provide both field derotation and pupil derotation.

[REQ-1-ORD-4615] NIRES-B shall include three NGS wavefront sensors to provide guide star position feedback to maintain plate scale.

[REQ-1-ORD-4620] NIRES-B shall use identical NGS wavefront sensors as those IRIS, providing pixel intensities to NFIRAOS.

[REQ-1-ORD-4625] The system shall provide 10 arcsec FOV images of the sky around the spectroscopic slit. It is understood that this image is needed for accurate positioning of the science object onto the spectroscopic slit.

[REQ-1-ORD-4630] The instrument shall provide acquisition, guiding and field rotation, as well as any calibration functions.

*Additional requirements for NIRES-B are presented in Table 12.*

*Table 12 NIRES-B Requirements*

Requirement Number	Description	Requirement
[REQ-1-ORD-4650]	Wavelength Range	1µm- 2.5µm
[REQ-1-ORD-4655]	Image quality	Aberrations uncorrectable by an order 60x60 AO system should not add wavefront errors larger than 30 nm RMS
[REQ-1-ORD-4660]	Length of slit	Up to 2 arcsec, and/or IFU
[REQ-1-ORD-4665]	Field of View of acquisition camera	10 arcsec, Nyquist sampled at 0.004 arcsec
[REQ-1-ORD-4670]	Spatial Sampling	Nyquist sampled ( $\lambda/2D$ ) (0.004 arcsec)
[REQ-1-ORD-4675]	Spectral Resolution	$20000 \leq R \leq 100,000$
[REQ-1-ORD-4680]	High Throughput	High priority
[REQ-1-ORD-4685]	Stability	Stability sufficient to enable, e.g., Doppler searches for planets
[REQ-1-ORD-4690]	Instrument background	The instrument shall not increase the background by more than 5% (TBC) over the sum of: inter-OH sky, telescope and NFIRAOS background.
[REQ-1-ORD-4695]	Detector	Detector dark current and read noise should not increase the effective background by more than 5% for an integration time of 2000 s.

**3.3.19.7 NIRES-R – Near Infrared Echelle Spectrometer (Red)**

[REQ-1-ORD-4900] NIRES-R is a small field of view near infrared high spectral resolution spectrometer configuration utilizing diffraction limited images from MIRAO.

[REQ-1-ORD-4905] NIRES-R shall be fed corrected light from the MIRAO adaptive optics system.

[REQ-1-ORD-4910] NIRES-R shall provide both field derotation and pupil derotation.

[REQ-1-ORD-4915] NIRES-R shall include three NGS wavefront sensors to provide guide star position feedback to maintain plate scale.

[REQ-1-ORD-4930] The instrument shall provide acquisition, guiding and field rotation, as well as any calibration functions.

*Additional requirements for NIRES-R are presented in Table 13.*

Table 13 NIRES-R Requirements

Requirement Number	Description	Requirement
[REQ-1-ORD-4950]	Wavelength Range	2.9 $\mu$ m- 5.0 $\mu$ m
[REQ-1-ORD-4955]	Image quality	The spectrometer shall deliver diffraction limited images to the detector, as delivered by the AO system
[REQ-1-ORD-4960]	Length of slit	Up to 2 arcsec, and/or IFU
[REQ-1-ORD-4965]	Field of View of acquisition camera	10 arcsec, Nyquist sampled
[REQ-1-ORD-4970]	Spatial Sampling	Nyquist sampled ( $\lambda/2D$ )
[REQ-1-ORD-4975]	Spectral Resolution	$20000 \leq R \leq 100,000$
[REQ-1-ORD-4980]	Throughput	TBD (High throughput required)
[REQ-1-ORD-4985]	Stability	Stability sufficient to enable, e.g., Doppler searches for planets
[REQ-1-ORD-4990]	Instrument background	The instrument shall not increase the background by more than 5% (TBC) over the sum of: inter-OH sky, telescope and MIRA0 background.
[REQ-1-ORD-4995]	Detector	Detector dark current and read noise should not increase the effective background by more than 5% for an integration time of 2000 s.

*Discussion: The system shall provide 10 arcsec FOV images of the sky around the spectroscopic slit. It is understood that this image is needed for accurate positioning of the science object onto the spectroscopic slit.*

### 3.3.19.8 HROS – High Resolution Optical Spectrometer

[REQ-1-ORD-4700] HROS is a seeing limited optical spectrometer configuration with high spectral resolution.

[REQ-1-ORD-4705] The HROS science case requires HROS to obtain spectra with  $20,000 < R < 100,000$  for wavelengths ranging from the atmospheric cutoff at 0.31 $\mu$ m to 1 $\mu$ m (or longer if detectors exist that will allow it) with wide spectral coverage in a single exposure.

*Discussion: This is envisaged as a “seeing-limited instrument” (although image quality enhancement should be considered).*

[REQ-1-ORD-4710] HROS sensitivity requirement is to maintain the 30m aperture advantage over the best existing similar capabilities on 8-10m telescopes.

[REQ-1-ORD-4715] The system shall provide 10 arcsec FOV images of the sky around the spectroscopic slit. It is understood that this image is needed for accurate positioning of the science object onto the spectroscopic slit.

[REQ-1-ORD-4720] HROS shall provide an atmospheric dispersion corrector.

[REQ-1-ORD-4725] HROS shall provide a tip-tilt-focus WFS/guider.

[REQ-1-ORD-4730] HROS shall provide a 6x6 (TBC) WFS to supply active optics feedback signals.

*Additional requirements for HROS are presented in Table 14.*

Table 14 HROS Requirements

Requirement Number	Description	Requirement
[REQ-1-ORD-4740]	Wavelength Range	0.31 – 1.0 $\mu$ m (required) 0.3 – 1.3 $\mu$ m (goal).
[REQ-1-ORD-4745]	Field of View	10 arcseconds
[REQ-1-ORD-4750]	Length of slit	5 arcseconds, with this separation between orders
[REQ-1-ORD-4755]	Image Quality	$\leq$ 0.2 arcsec FWHM at detector
[REQ-1-ORD-4760]	Spatial Sampling	< 0.2 arcsec per pixel
[REQ-1-ORD-4765]	Spectral Resolution (slit)	R=50,000 (1 arc-sec slit)
[REQ-1-ORD-4770]	Spectral Resolution (image slicer)	R $\geq$ 90,000
[REQ-1-ORD-4775]	Sensitivity	Must maintain 30m aperture advantage over existing similar instruments.
[REQ-1-ORD-4780]	Stability	Long term stability required to achieve radial velocity measurement repeatability and accuracy of 1 m/s over time spans of 10 years.

### 3.3.19.9 WIRC - Wide Field Infrared Camera

[REQ-1-ORD-4800] WIRC is a moderate field (30 arcsec) near infrared imager configuration fed by NFIRAOS to provide near diffraction limited images through a variety of filters with high photometric and astrometric accuracy.

[REQ-1-ORD-4805] WIRC is a moderate field near infrared imager configuration including an MCAO system to provide near diffraction limited images through a variety of filters with high photometric and astrometric accuracy.

[REQ-1-ORD-4810] The instrument and AO system of this configuration shall not increase the inter-OH optical background by more than 15% over sky and telescope background.

[REQ-1-ORD-4815] WIRC shall include three NGS wavefront sensors to provide guide star position feedback to maintain plate scale.

[REQ-1-ORD-4820] The NGS WFS sensors shall provide pixel intensities to NFIRAOS.

*Discussion: From these pixel intensities, the NFIRAOS RTC will compute: - the tip-tilt modes necessary to perform fast guiding - the focus mode necessary to calibrate the focus biases in the LGS WFS induced by the variations in the range to the sodium layer - the DM Tilt anisoplanatism modes, which compensates for tilt anisoplanatism over the extended FOV without introducing higher order wavefront errors. Additional requirements for IRIS are presented in Table 7.*

*Additional requirements for WIRC are presented in Table 15.*

*Table 15 WIRC Requirements*

Requirement Number	Description	Requirement
[REQ-1-ORD-4835]	Wavelength Range	0.8 – 2.5 $\mu\text{m}$ , goal 0.6-5 $\mu\text{m}$
[REQ-1-ORD-4840]	Image Quality	Aberrations uncorrectable by an order 60x60 AO system should not add wavefront errors larger than 30 nm RMS
[REQ-1-ORD-4845]	Field of View	30 arcsec diameter (contiguous, imaged all at once)
[REQ-1-ORD-4850]	Spatial Sampling	Nyquist sampled ( $\lambda/2D$ ) (0.004 arcsec)
[REQ-1-ORD-4855]	Spectral Resolution	R= 5-100 (narrow and broad band filters)
[REQ-1-ORD-4860]	Throughput	High; must preserve telescope aperture advantage compared to similar instruments on smaller telescopes
[REQ-1-ORD-4865]	Astrometry	Over the 30arcsec field of view, WIRC shall deliver precise astrometric measurements with at most a 10% degradation of the achievable performance on NFIRAOS feeding an idealized perfect instrument.
[REQ-1-ORD-4870]	Stability, Flexure	Must allow mosaicing of multiple fields together with no significant loss of image quality or precision.
[REQ-1-ORD-4875]	Background	The instrument and AO system of this configuration shall not increase the inter-OH optical background by more than 15% over sky and telescope background.

### 3.4 FACILITY REQUIREMENTS

*Note: TMT Science Center, and TMT Data Archive facilities are not part of the current baseline TMT construction project and early operations plans.*

#### 3.4.1 Operations Support

[REQ-1-ORD-5000] The Observatory shall provide adequate infrastructure for operations, including utilities and operational environment.

#### 3.4.2 Summit Facility

*Note: The TMT Summit Facility is a deliverable for the TMT construction project.*

##### 3.4.2.1 General

[REQ-1-ORD-5100] The summit facility shall provide facilities to enable operations, servicing and maintenance of the observatory, including mirror maintenance and recoating, operations spaces, lab and shop spaces, people spaces, shipping and receiving areas, mechanical and electrical plants, roads and parking.

##### 3.4.2.2 Enclosure

[REQ-1-ORD-5200] The enclosure shall protect the telescope, instruments, and associated equipment from adverse environmental conditions during non-observing time.

[REQ-1-ORD-5205] The enclosure shall have an aperture opening and shutter of sufficient size to not vignette the 20 arcminute diameter field of the telescope during observations, plus additional clearance of 1 degree radius outside the field of view in all directions.

*Discussion: The telescope must be able to quickly reposition over small distances without requiring the enclosure to move at the same rate. With the enclosure stationary, the telescope shall be able to move 1° in any direction from the center of the enclosure aperture without vignetting the 20 arcminute diameter optical field. Note that for moves close to 1 degree, margin can be gained by pre-biasing the enclosure pointing in the direction of the planned telescope move.*

[REQ-1-ORD-5210] The enclosure shall be capable of opening or closing the aperture shutter and any other openings to the outside environment in 2 minutes.

*Discussion: This is to ensure timely sealing of the enclosure during adverse weather conditions.*

[REQ-1-ORD-5215] The enclosure aperture opening shall be capable of a continuous and unlimited range of azimuth motion (no cable wraps) and zenith motion range from 0 to 65 degrees zenith angle.

[REQ-1-ORD-5220] The enclosure shall provide azimuth and zenith motion of the aperture opening in concert with the telescope to track the astronomical sky during observations.

[REQ-1-ORD-5225] The enclosure design shall minimize dome seeing, mirror seeing, and wind buffeting during observations.

[REQ-1-ORD-5230] The enclosure shall utilize a passive ventilation schema to manage the enclosure thermal environment during observation.

[REQ-1-ORD-5235] The enclosure design shall minimize the daytime thermal load inside the enclosure from solar absorption, power dissipation, and air infiltration.



[REQ-1-ORD-5240] The design of the enclosure should minimize the buildup of snow and ice and provide for easy removal of snow and ice to allow for observing after storms.

#### **3.4.2.3 Lightning Protection**

[REQ-1-ORD-5250] The enclosure and summit buildings shall be designed with provisions to protect personnel and equipment from the effects of lightning strikes.

*Discussion: The applicable standard for lightning protection is contained in Table 2*

#### **3.4.3 Road**

[REQ-1-ORD-5520] There shall be an access road between an existing public road and the summit facilities.

## 3.5 SYSTEM ATTRIBUTES

### 3.5.1 Reliability and Maintainability

#### 3.5.1.1 *Maintenance Driven System Attributes*

#### 3.5.1.2 *Maintenance Plan*

[REQ-1-ORD-6100] An observatory maintenance plan shall be established by the end of construction, which describes the schedule and technical details of preventive maintenance, component and assembly replacement, and alignment procedures.

[REQ-1-ORD-6105] Subsystem maintenance plans shall be delivered with the subsystems.

[REQ-1-ORD-6110] Based on the maintenance plan, a spare parts depository shall be established to ensure the continuous operations of the observatory.

#### 3.5.1.3 *Engineering Databases*

[REQ-1-ORD-6200] A maintenance database shall be established by the end of construction which logs all the scheduled maintenance and unexpected repairs.

[REQ-1-ORD-6205] A failure database shall be established by the end of construction and maintained throughout the operations, which logs the errors of the system and its subsystems, including the corrective actions taken.

[REQ-1-ORD-6210] The system shall extract information about the current condition of the system from the science and calibration data streams, and log this information along with other relevant system and environmental status information. Based on this information, it shall be possible to monitor, save, and analyze the technical performance of the system.

#### 3.5.1.4 *Reliability*

*Discussion: The OCD (AD2), specifies the operational requirements on technical downtime for the observatory. The following requirements support the implementation of the OCD maintenance and reliability requirements.*

[REQ-1-ORD-6300] Reliability and time to repair budgets shall be allocated at the system decomposition level, and shall be consistent with the level 1 requirements for reliability and maintainability of the system.

[REQ-1-ORD-6310] Definitions of the conditions that determine a subsystem failure shall be defined at level 1 for all sub-systems.

*Discussion: In many cases the definition of system failure will be straightforward. However, in some cases a loss of some functionality or performance can be tolerated and not considered unscheduled technical downtime. For example, some loss of laser power, a loss of a single actuator on M1, or a loss of some subset of functionality in an instrument, may not result in unscheduled technical downtime.*

### 3.5.2 Operational Efficiency

[REQ-1-ORD-6400] The Observatory shall be efficient in the use of energy.

*Discussion: Energy will be a major component of the observatory operations costs. Designs should be assessed for energy efficiency.*

[REQ-1-ORD-6410] The Observatory shall be designed to be efficiently maintained.

*Discussion: Maintenance will be a major component of the observatory operations costs. Designs should be assessed for reliability and maintainability.*

## 3.6 ENVIRONMENTAL, HEALTH, AND SAFETY REQUIREMENTS

### 3.6.1 Safety

#### 3.6.1.1 General

[REQ-1-ORD-7003] The safety priorities of the system shall be: (i) protection of persons, (ii) guarding the technical integrity of the observatory and other equipment potentially affected by the operation of the observatory, and (iii) protection of scientific data, in this order.

[REQ-1-ORD-7005] TMT hazard analysis and safety practices will be governed by an order of precedence as follows:

1. Design for Minimum Risk: The primary means for mitigation of risk shall be to eliminate the hazard through design.
2. Incorporate Safety Devices: Fixed, automatic or other protective devices shall be used in conjunction with the design features to attain an acceptable level of risk. Provisions shall be made for periodic functional checks as applicable.
3. Provide Warning Devices: When neither design nor safety items can effectively eliminate or reduce hazards, devices shall be used to detect the condition, and to produce an adequate warning to alert personnel of a hazard. Devices may include audible or visual alarms, permanent signs or movable placards.
4. Procedures and Training: Where it is impractical to substantially eliminate or reduce the hazard or where the condition of the hazard indicates additional emphasis, special operating procedures and training shall be used.

[REQ-1-ORD-7010] A comprehensive safety plan shall be established and implemented before the construction starts at the observatory site.

[REQ-1-ORD-7015] An operational safety plan shall be established before Early Operations starts.

### 3.6.2 Health

[REQ-1-ORD-7200] The observatory shall comply with all applicable local and national environmental and occupational health regulations and standards.

### 3.6.3 Environment

[REQ-1-ORD-7400] The observatory shall comply with all local environmental regulation and international environmental standards applicable to the observatory site, appearance, and operations.

[REQ-1-ORD-7405] During night time, the observatory shall not generate detectable light pollution.

*Discussion: To both prevent loss of TMT science, but also in consideration of other observatories that may be located nearby.*

[REQ-1-ORD-7410] The observatory shall not emit electromagnetic radiation at any frequency that significantly interferes with itself or the operation of any other current astronomical facility.

*Discussion: this requirement applies to both summit and support facilities.*

### 3.6.4 Security

[REQ-1-ORD-7600] The observatory shall provide a secure and safe environment for personnel.

[REQ-1-ORD-7605] The observatory shall provide a secure environment for equipment

[REQ-1-ORD-7610] The observatory shall provide an independent system to communicate with outside locations in emergencies.

### 3.7 HIGH LEVEL SOFTWARE REQUIREMENTS

#### 3.7.1 General requirements

[REQ-1-ORD-9000] The TMT software system shall not be the source of degradation of any system performance metrics established in the *TMT Observatory Requirements Document (ORD)* or *TMT Observatory Operations Concept Definition Document (OCD)*.

#### 3.7.2 Communications network requirements

*Discussion: the requirements in this section flow from a combination of the OCD requirements and common practice.*

[REQ-1-ORD-9150] The TMT Observatory shall support the following general communication services within the Observatory as well as between the Observatory and the general Internet:

- Video conferencing
- Voice over IP (VoIP)
- General Web access

[REQ-1-ORD-9155] The TMT Observatory 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-ORD-9160] Internet connection bandwidth requirements are shown in Table 16.

*Table 16: ISP Bandwidth Requirements*

Category	Required bandwidth (Mbits)
General communications	TBD
Remote observing	TBD
Remote diagnostics	TBD
Data transfer	TBD
<b>Total</b>	<b>TBD</b>

[REQ-1-ORD-9165] Within the Observatory local area network (LAN), IT 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
- Technical data traffic
- AO data traffic

[REQ-1-ORD-9170] A backup telephone communications system independent of other observatory systems shall be available in case of emergencies.

## 4. APPENDIX

### 4.1 REFERENCE ATMOSPHERIC PARAMETERS

#### 4.1.1 Meteorological Parameters

Ground level median nighttime temperature  $T = 2.3^{\circ}\text{C}$

Precipitable H<sub>2</sub>O = 1.9mm

#### 4.1.2 Turbulence Parameters

In order to define AO performance requirements we specify “Standard Conditions” under which the requirements should be met. These conditions are based upon the TMT site testing results taken at Mauna Kea 13N from 29<sup>th</sup> June 2005 to 1<sup>st</sup> June 2008. Three sets of standard conditions are given, identified as the 25<sup>th</sup> and 75<sup>th</sup> percentile and median conditions. These three sets were established from the 3 years of recorded profiles as follows, using a ‘NFIRAOS like’ AO system to compute residual DM fitting and servo lag errors:

- 1) Compute the residual DM fitting error and servo lag for each profile
- 2) Sort the profiles based on the results of step 1
- 3) Compute the mean value of the 10% range around each profile (i.e. for 25% profile, calculate mean of the profiles between 20<sup>th</sup> and 30<sup>th</sup> percentile)

Table A1 summarizes the standard values for 4 fundamental atmospheric turbulence parameters for each condition, specified at a wavelength of 0.5  $\mu\text{m}$  and a zenith angle of 0 degrees. We have no measurements of  $L_0$  so we use a generally accepted median value of 30m.

**Table A1: Atmospheric turbulence parameters**

Parameter	25 <sup>th</sup> Percentile Conditions	Median	75 <sup>th</sup> Percentile Conditions
Effective coherence diameter ( $r_0$ ), m	0.27	0.20	0.13
Integrated $C_n^2$ , $\text{m}^{1/3}$	1.30E-13	2.21E-13	4.64E-13
Isoplanatic angle ( $\theta_0$ ), arc sec	2.70	2.23	1.71
Greenwood frequency ( $f_g$ ), Hz	15.9	21.7	32.2
Outer scale ( $L_0$ ), m	30	30	30

The values for  $\theta_0$  and  $f_g$  have been derived using the 7-layer turbulence and wind profiles from table A2. These are also the standard profiles to be used for more detailed AO analysis and simulation.

**Table A2: Standard atmospheric  $C_n^2dh$  and windspeed profiles**

h, km	$C_n^2dh$ ( $m^{1/3}$ )			Median windspeed, m/s
	25 <sup>th</sup> Percentile Conditions	Median	75 <sup>th</sup> Percentile Conditions	
0	4.20E-14	6.39E-14	1.07E-13	5.6
0.5	1.93E-14	3.94E-14	1.11E-13	5.8
1	6.07E-15	1.46E-14	5.72E-14	6.3
2	5.32E-15	1.73E-14	4.45E-14	7.6
4	2.03E-14	3.11E-14	5.09E-14	13.3
8	1.38E-14	2.69E-14	5.49E-14	19.1
16	2.29E-14	2.81E-14	3.83E-14	12.1

Note: The above  $C_n^2$  values are based on results taken at a height of 7m above the ground, but have been adjusted to remove turbulence between 7m and 60m to account for the height of the enclosure. Table 2 consequently does not include conditions inside the enclosure.

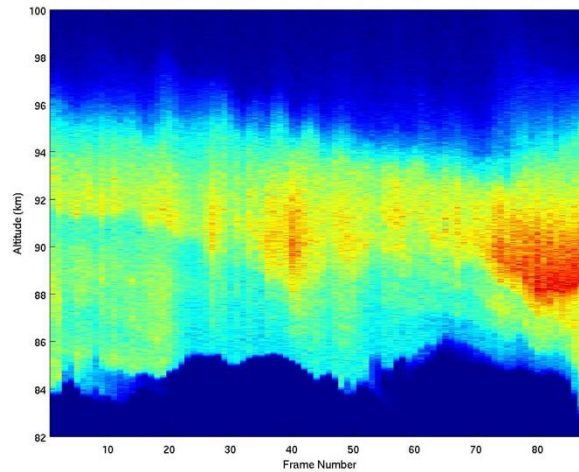
### 4.1.3 Mesospheric Sodium Layer

The following parameters for the mesospheric sodium layer shall be used in the design of LGS AO systems for TMT:

- Mean sodium layer altitude: 85 to 105 km above sea level (instantaneously)
- Maximum layer thickness: 10 km
- Column density:  $3e13$  ions/m<sup>2</sup>
- Sodium ion cross section: 130 photons-m<sup>2</sup>/s/W/ion
- Sodium D2 line width: 3 GHz

The column density is in fact highly variable; the value given above is conservative but not worst-case. The sodium ion cross section corresponds to a CW laser tuned to the peak of the sodium D2 line, and better or worse efficiencies will be obtained with other laser pulse formats. Sodium layer saturation is not expected to be a significant issue at the LGS intensities anticipated for TMT.

Figure 1 illustrates a sample time history of the sodium layer profile which has been used for AO modeling and analysis. Document number TMT.AOS.TEC.07.005.DRF01 at the TMT DCC contains the data set as a Matlab \*.mat file.



**Figure 1:** Sample sodium layer profiles versus time and altitude. Each column of pixels shows a single 1-minute Lidar profile taken with the Purple Crow Lidar at the University of Western Ontario. The vertical axis ranges from 82 to 100 km and the horizontal axis spans a total of 88 contiguous profiles.

The temporal variability of the sodium layer is not yet understood on the time scales of interest to TMT LGS AO systems. Based upon temporal PSDs extrapolated from existing sodium layer time histories sampled at rates of approximately 0.01 Hz, it is believed that focus measurements from a natural guide star must be obtained at rates of about 100 Hz to track the variations in the range to the sodium layer to the level of accuracy required for the NFIRAOS error budget. Furthermore, higher-order wavefront measurements from a natural guidestar must be obtained at rates of 0.01 to 0.1 Hz to calibrate for wavefront reconstruction errors associated with changes in the shape of the sodium layer profile. These values should be considered tentative until further sodium layer measurements are obtained.



**4.2 WAVELENGTH BANDS**

**4.2.1 Astronomical Filters**

Band	Center wavelength	Bandwidth
U	0.3663 $\mu\text{m}$	0.0650 $\mu\text{m}$
B	0.4361 $\mu\text{m}$	0.0890 $\mu\text{m}$
V	0.5448 $\mu\text{m}$	0.0840 $\mu\text{m}$
R	0.6407 $\mu\text{m}$	0.1580 $\mu\text{m}$
I	0.7980 $\mu\text{m}$	0.1540 $\mu\text{m}$
Y	1.03 $\mu\text{m}$	0.13 $\mu\text{m}$
J	1.250 $\mu\text{m}$	0.16 $\mu\text{m}$
H	1.635 $\mu\text{m}$	0.29 $\mu\text{m}$
K'	2.12 $\mu\text{m}$	0.34 $\mu\text{m}$
K <sub>s</sub>	2.15 $\mu\text{m}$	0.32 $\mu\text{m}$
K	2.2 $\mu\text{m}$	0.34 $\mu\text{m}$
L	3.77 $\mu\text{m}$	0.7 $\mu\text{m}$
M	4.68 $\mu\text{m}$	0.22 $\mu\text{m}$
N	10.47 $\mu\text{m}$	5.2 $\mu\text{m}$
Q	20.13 $\mu\text{m}$	7.8 $\mu\text{m}$

Data in the table is from [RD6].

### 4.2.2 Atmospheric Transmission Windows

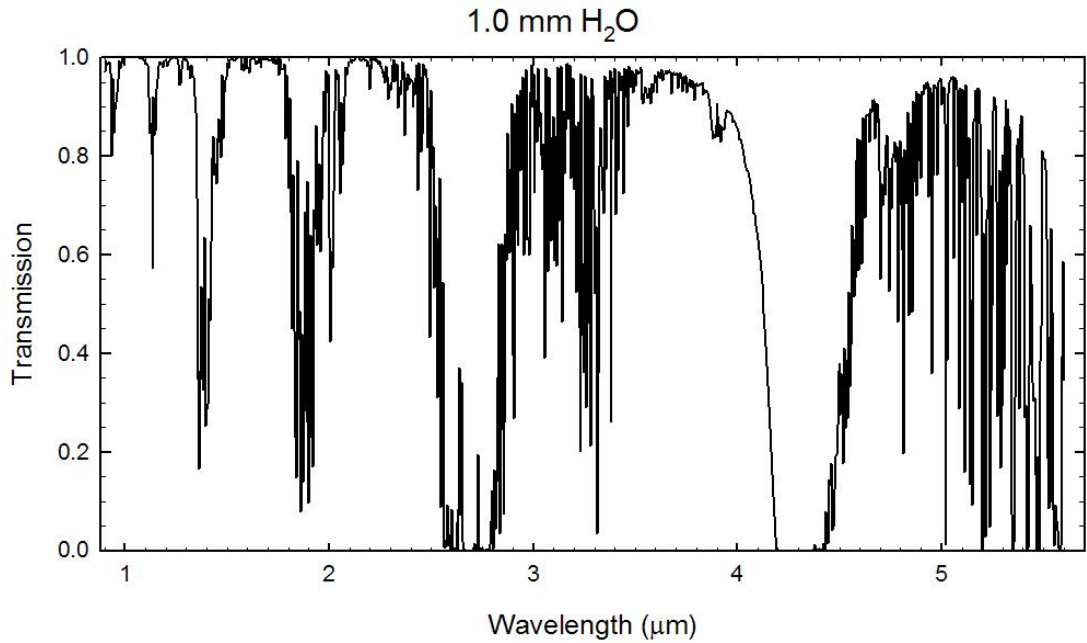


Figure 6 Near and mid infrared atmospheric transmission windows for 1 mm precipitable water vapor [RD7]

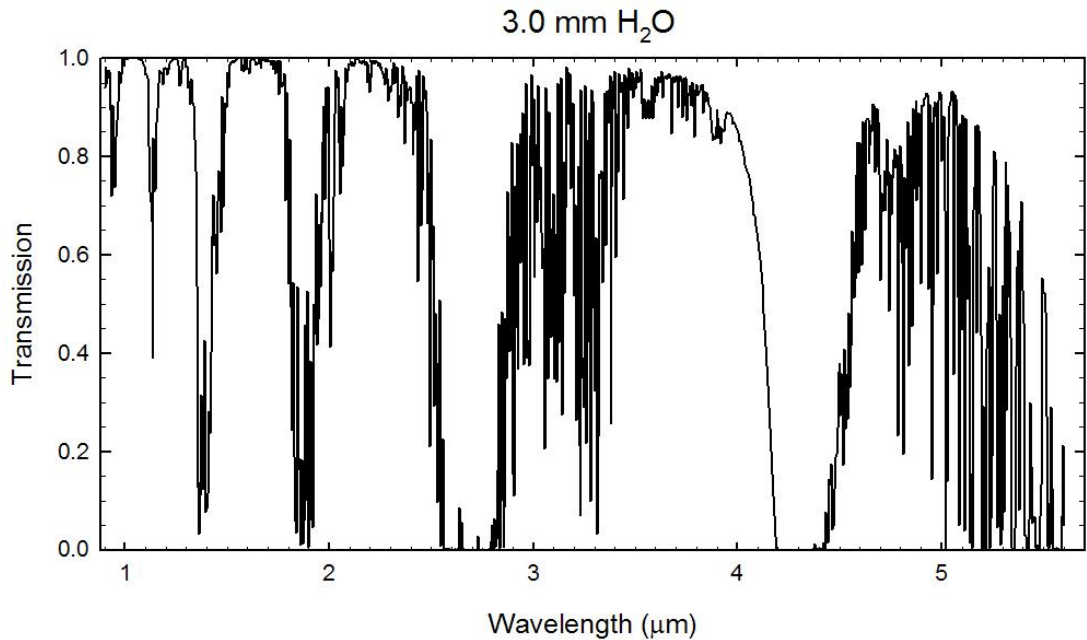


Figure 7 Near and mid infrared atmospheric transmission windows for 3 mm precipitable water vapor [RD7]

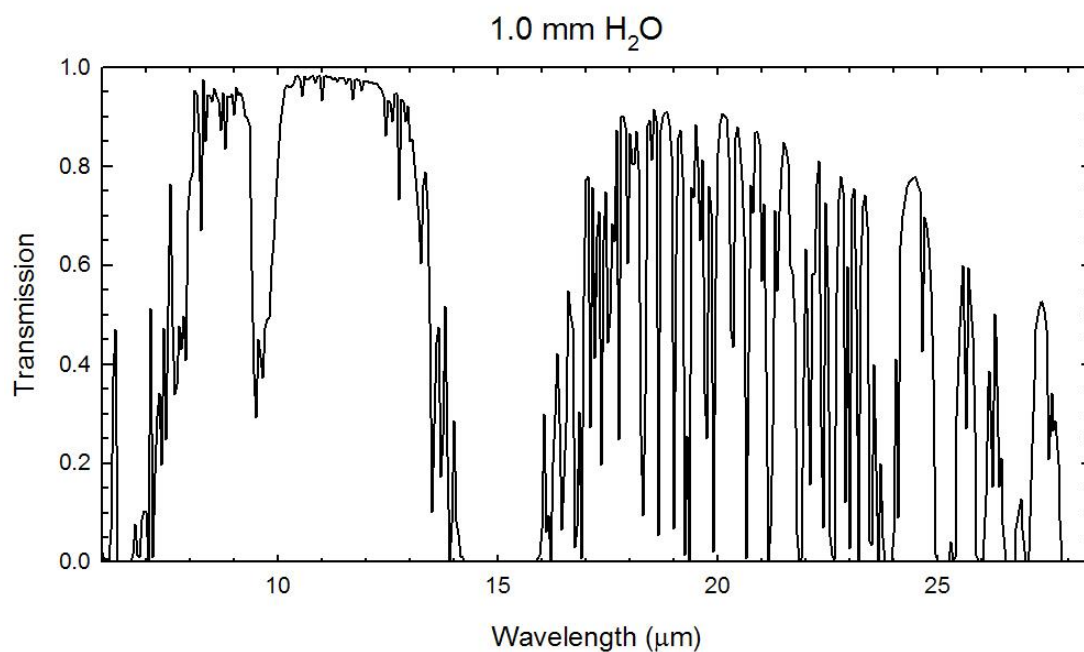


Figure 8 Infrared atmospheric transmission windows for 1 mm precipitable water vapor [RD7]

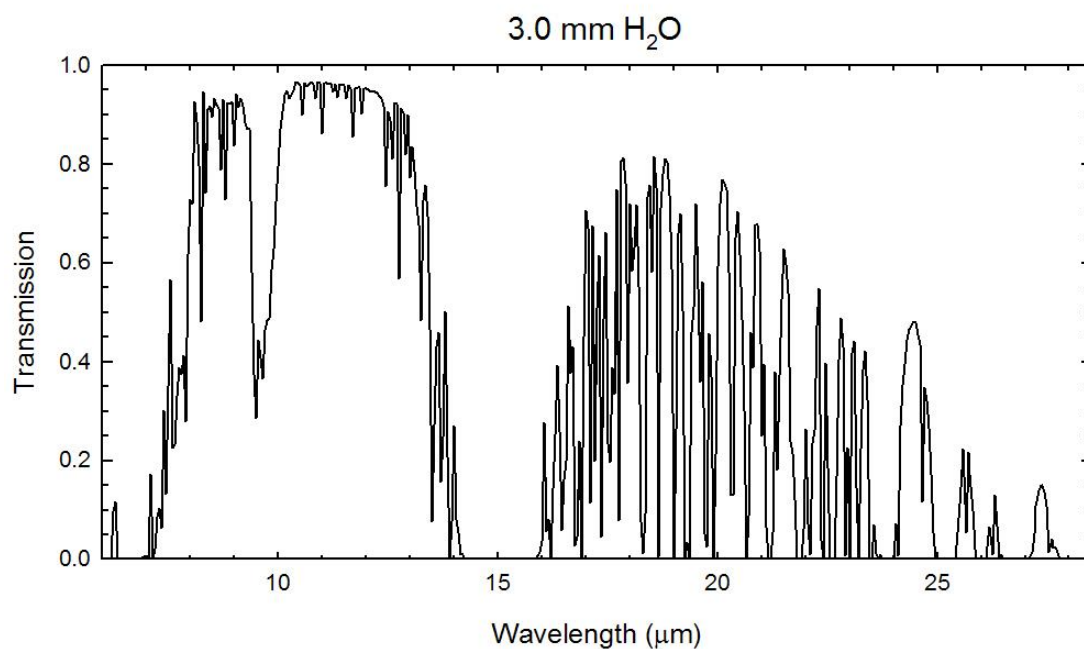


Figure 9 Infrared atmospheric transmission windows for 3 mm water vapor [RD7]

### 4.3 TEMPORAL TEMPERATURE GRADIENTS

Table 17 summarizes the night time temporal temperature gradients measured during the TMT site testing at Mauna Kea 13N from 29<sup>th</sup> June 2005 to 1<sup>st</sup> June 2008. The temperature gradients quoted are based on temperature values measured at 2m above ground level.

Integration time (minutes)	min (°C/h)	2.5% (°C/h)	97.5% (°C/h)	max (°C/h)
1	-54.1	-9.4	9.4	57.0
4	-32.0	-5.5	5.3	30.9
8	-16.9	-3.4	3.2	13.5
16	-9.8	-2.2	2.0	7.2
32	-5.8	-1.5	1.2	3.7
60	-3.7	-1.1	0.7	2.1

*Table 17: Night time temporal temperature gradients*