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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 Requirements Document (OpsRD, RD12) and the Observatory Architecture Document (OAD, RD11).

This document is the project's response to the science requirements encapsulated in the Science Requirements Document (SRD, RD1).

As necessary, new requirements implied by the current document flow into the OAD (RD11). The requirements in the OAD will flow down to requirements for the observatory subsystems.

The requirements in this document are numbered in the form [REQ-1-ORD-XXXX], where "1" denotes the level of this document, and "XXXX" is the 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 ORD and the OpsRD are intended to fully describe the top-level engineering and operational requirements that satisfy the criteria of the Science Requirements Document and Operations Plan, respectively.

By this definition, the ORD will change in response to changes in the SRD, but will not require modification when changes are made to the OpsRD and OAD, or to the subsystem requirements documents.

1.3 SCOPE

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

- General and 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 Standard for the Installation of Lightning Protection Systems
NFPA 780 Edition 2004

https://global.ihs.com/doc_detail.cfm?&rid=Z06&mid=5280&input_search_filter=NFPA&item_s_k ey=00140693&item_key_date=950316&input_doc_number=780&input_doc_title=&org_code=NFPA &origin=HISC

1.5 REFERENCE DOCUMENTS

RD1 Science-Based Requirements Document

TMT.PSC.DRD.05.001

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

RD2 DELETED

RD3 DELETED

RD4 The Tertiary Mirror Equations of Motion for an "off-altitude-axis" Nasmyth Focus

TMT.SEN.TEC.07.022

<https://docushare.tmt.org/docushare/dsweb/Get/Document-8345>

RD5 Systems Engineering for the Preliminary Design of the Thirty Meter Telescope

TMT.SEN.JOU.07.004

SPIE Conference 10.1117/12.787220 (Volume 7017)

<https://docushare.tmt.org/docushare/dsweb/Get/Document-22254>

RD6

Standard Photometric Systems by Michael S. Bessell (Annual Review Astronomy and Astrophysics, Volume 43:293-336)

<http://www.annualreviews.org/doi/abs/10.1146/annurev.astro.41.082801.100251>

RD7

A New Software Tool for Computing Earth's Atmospheric Transmission of Near- and Far-Infrared Radiation by Steven D. Lord

<http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19930010877.pdf>

RD8

Establishing Environmental Requirements

TMT.SEN.TEC.09.031

<https://docushare.tmt.org/docushare/dsweb/Get/Document-15650>

RD9

Accuracy Definition

TMT.SEN.TEC.05.029

<https://docushare.tmt.org/docushare/dsweb/Get/Document-4126>

RD10 Deleted

RD11 Observatory Architecture Document

TMT.SEN.DRD.05.002

<https://docushare.tmt.org/docushare/dsweb/Get/Document-2689>

RD12 Operations Requirement Document (OpsRD)

TMT.OPS.MGT.07.002

<https://docushare.tmt.org/docushare/dsweb/Get/Document-7842>

RD13 TMT Observatory NFIRAOS LGS MCAO, NGS AO and IRIS Imager Wavefront Error Budget and Current Best Estimate

TMT.AOS.COR.16.062

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

1.6 ABBREVIATIONS

Acronym	Definition
ADC	Atmospheric Dispersion Compensation
AM2	Adaptive Secondary Mirror
AO	Adaptive Optics
AOS	AO System
CCD	Charge Coupled Device
CW	Continuous Wave
DCC	Document Control Center
DM	Deformable Mirror
DRD	Design Requirements Document
ENC	Enclosure
ExAO	Extreme AO system
FOV	Field of View
FWHM	Full Width at Half Maximum
GHz	Gigahertz
GLAO	Ground-layer adaptive optics
H ₂ O	Water
HROS	High Resolution Optical Spectrometer
IFU	integral field unit
IP	Internet Protocol
IR	InfraRed
IRIS	InfraRed Imaging Spectrometer
IRMOS	Near Infrared Multi-Object Spectrometer
IRMS	Infrared Multi-Object Spectrometer
ISP	Internet Service Provider
IT	Information Technology
LAN	Local Area Network
LGS	Laser Guide Stars
LOWFS	Low Order Wavefront Sensor
LUT	Look-Up-Table
MCAO	Multi Conjugate AO System
MCE	Maximum Considered Earthquake
MEMS	Micro Electro-Mechanical Systems
MIRAO	Mid-IR AO system
MIRES	Mid InfraRed Echelle Spectrometer
MOAO	Multiple Object Adaptive Optics
MOSFIRE	Multi-Object Spectrometer for Infra-Red Exploration
NFIRAOS	Narrow Field Infrared Adaptive Optics System
NFPA	National Fire Protection Association
NGS	Natural Guide Stars
NIR	Near InfraRed
NIRES	Near InfraRed Echelle Spectrometer
OAD	Observatory Architecture Document
OH	Oxygen-Hydrogen Radical
OIWFS	On instrument wavefront sensors
OpsRD	Operations Requirements Document
ORD	Observatory Requirements Document
PFI	Planet Formation Instrument
PI	Principal Investigator
PSD	Power Spectral Density??

Acronym	Definition
PSF	Point Spread Function
PWFS	Pyramid WFS
RMS	Root Mean Square
RTC	Real Time Computer
SAC	Science Advisory Committee
SPIE	International Society for Optical Engineering
SPM	Science Productivity Metric
SRD	Science Requirements Document
TBC	To Be Confirmed
TBD	To Be Defined or To Be Determined or To Be Done
TMT	Thirty Meter Telescope
UV	Ultraviolet
VoIP	Voice over IP
WBS	Work Breakdown Structure
WFOS	Wide Field Optical Spectrograph
WFS	Wavefront Sensor
WIRC	Wide Field Infrared Camera
WRMS	residual on-axis wavefront error

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 2-1: The observatory system with its inputs and outputs' below.

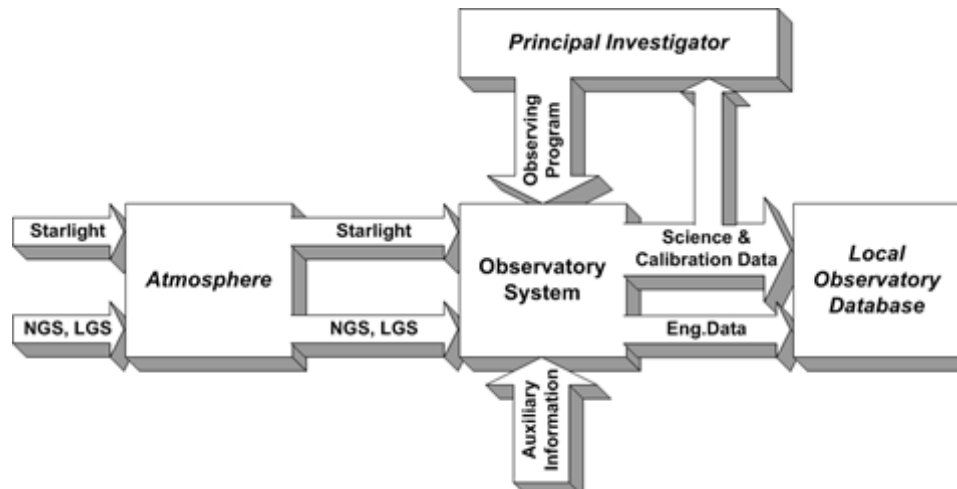


Figure 2-1: The observatory system with its inputs and outputs

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 to 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. Laser Guide Star Multi Conjugate AO System (MCAO) or Natural Guide Star AO (NGSAO) with the Infra-Red Imaging Spectrometer (IRIS);
- b. Laser Guide Star Multi Conjugate AO System (MCAO) or NFIRAOS Seeing Limited with the Infra-Red Multi-Object Spectrometer (IRMS);
- c. The seeing limited or Ground Layer AO (GLAO) Wide Field Optical Imaging Spectrometer (WFOS)
- d. Laser Guide Star Multi Conjugate AO System (MCAO) or Natural Guide Star AO (NGSAO) with the Near Infra-Red Echelle Spectrometer (NIREs);
- e. Multi-object AO System (MOAO) with the Near Infra-Red Multi-Object Spectrometer (IRMOS);
- f. Mid-IR AO system (MIRAO) with the Mid Infra-Red Echelle Spectrometer (MIREs), including a small field, low emissivity;
- g. The seeing limited High Resolution Optical Spectrometer (HROS);
- h. The extreme AO system (ExAO) with the Planet Formation Instrument, including a coronagraph enabling very high contrast imaging (PFI).

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 (M1, M2 and M3). 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 different for each class of TMT configuration, and different AO system concepts are most suitable for each case:
 - i. **NFIRAOS LGS MCAO Mode:** TMT 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 NFIRAOS LGS MCAO Mode is developed for IR instruments like IRIS and IRMS.
 - ii. **NFIRAOS NGSAO Mode:** The NGS mode makes use of a single, bright star to feed a single high order visible NGS WFS. The bandpass of the NGS WFS is set by the light passed by both the science and LGS beamsplitters. This mode will be used throughout the lifetime of the instrument, as the NGS mode will be capable of delivering somewhat higher Strehl ratios for bright NGS, albeit with an extremely limited sky coverage and a smaller corrected field-of-view.
 - iii. **NFIRAOS Seeing Limited Mode:** NFIRAOS includes a seeing limited enhanced mode in which fast guiding is performed via the NFIRAOS tip/tilt stage using measurements from a science instrument on-instrument wavefront sensor (OIWFS),

- together with sending slow speed pyramid wavefront sensor (PWFS) measurements of telescope aberrations to the telescope control system and to the DM.
- iv. **MIRAO Mode:** 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 system in support of MIREs system configuration
 - v. **GLAO Mode:** 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.
 - vi. **MOAO Mode:** 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.
 - vii. **ExAO Mode:** 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).
- c. **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
 - d. 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 TMT Observatory shall operate and meet all the requirements herein for at least 50 years with preventive maintenance.

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

[REQ-1-ORD-1005] The TMT Observatory shall comply with all local and national standards and regulations relevant to the construction and operation of the observatory.

Discussion: 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 TMT 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 TMT 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.

3.1.2.2 Observing Performance Conditions

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

[REQ-1-ORD-1200] The TMT Observatory, in seeing limited and adaptive optics operating modes, shall be able to carry out astronomical observations under the conditions listed in 'Table 3-1: Observing Performance Conditions'.

Table 3-1: Observing Performance Conditions

Ambient air temperature range	-5°C to +9°C
Ambient air pressure range	600 hPa to 618 hPa
Temporal air temperature gradient	+2.1 C/hr, -3.7 C/hr (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 99th 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 4.2.3 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-1210] The TMT Observatory shall meet all requirements herein, unless otherwise stated, over the range of the Observing Performance Conditions listed in Table 3-1.

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

[REQ-1-ORD-1255] The TMT Observatory 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/m² 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] TMT Observatory systems necessary to support servicing and maintenance shall operate over the range of conditions listed in 'Table 3-2: Facility Performance Conditions'.

Table 3-2: Facility Performance Conditions

Ambient air temperature range	-10°C to +13°C
Ambient air pressure range	600 hPa to 618 hPa
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 [AD1]

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 will be 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/m² snow and ice load (vertical projection).

3.1.2.4 Component Functional Conditions

[REQ-1-ORD-1375] All TMT Observatory mechanical and electrical components shall function over the range of conditions listed in 'Table 3-3: Component Functional Conditions'.

Table 3-3: Component Functional Conditions

Ambient air temperature range	-13°C to +25°C
Ambient air pressure range	600 hPa to 1015 hPa
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 see level air pressure in a laboratory.

3.1.2.5 Survival Conditions

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

[REQ-1-ORD-1400] Under any state, the system shall be designed to survive repeated exposure to the Survival conditions shown in 'Table 3-4: Survival Conditions' without damage.

Table 3-4: Survival Conditions

Ambient temperature range	-16°C to +30°C
Ambient air pressure range	590 hPa to 1025 hPa
Temporal temperature gradient	+2.1 C/hr, -3.7 C/hr
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 [AD1]

Discussion: Survival Conditions occur when any of the conditions in Table 3-4 arise and they exceed the Facility Performance conditions listed in 'Table 3-2: Facility Performance Conditions'.

Discussion: No prior warning is available for this condition and subsystems cannot 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.

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: Transportation and storage conditions are not addressed by these requirements. It is quite likely that transportation and storage conditions will exceed this maximum temperature.

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-1410] The TMT Observatory Technical Operations staff shall, in less than 6 hours, be able to perform an inspection of the full system that ensures 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-1420] The TMT Observatory shall withstand the Survival Conditions listed in Table 3-4 when there is no power to the observatory.

[REQ-1-ORD-1425] The TMT Observatory 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/m².

[REQ-1-ORD-1435] The system shall be able to support ice loads up to 68kg/m². 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 TMT Observatory shall withstand earthquakes up to the levels of the 10-year return period earthquake with no damage.

Discussion: Inspection by the normal operations staff, as described in [REQ-1-ORD-1410] will be sufficient to ensure that the observatory can be returned to normal operations after such an earthquake.

Discussion: The TMT observatory will 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.

Discussion: 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] The TMT Observatory shall be designed such that it can resume normal operations within two weeks after the observatory staff has resumed regular duty after exposure to an earthquake up to the levels of the 200-year return period earthquake.

Discussion: This should be accomplished 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.

Discussion: 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 TMT Observatory subsystems shall 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:

Discussion: 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

Discussion: 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] The TMT Observatory subsystem components shall 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 earthquake.

Discussion: Any subsystems, 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 will be identified. The failure modes will be identified and where necessary measures will 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 TMT Observatory 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 TMT Observatory 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: To ensure the uninterrupted execution of the next observation, the telescope motion 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 TMT Observatory shall perform the complete target acquisition sequence in less than 5 minutes when an instrument change is not needed.

Discussion: The target acquisition sequence includes telescope configuration (including slew time), enclosure configuration, instrument configuration, AO system configuration, and guide star acquisition.

[REQ-1-ORD-1810] The TMT Observatory shall be able to change from one instrument to another instrument already installed on the telescope in less than 10 minutes, starting from the end of an observation in one instrument to the start of observation in the other.

[REQ-1-ORD-1815] The TMT Observatory shall be able to perform a major instrument reconfiguration in less than 10 minutes, starting from the end of an observation in one configuration to the start of observation in another.

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 INSTRUMENTS REQUIREMENTS

3.3.1 General

Discussion: The TMT Observatory telescope system will 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 TMT 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 TMT Observatory 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 TMT Observatory 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 TMT Observatory 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 TMT Observatory shall process the light collected in order to deliver specific spatial or spectral intensity distributions to the science detector.

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

[REQ-1-ORD-2545] The TMT Observatory shall generate enough calibration data to allow the removal of system signatures from the science data.

Discussion: Such calibration data are obtained via the observation of both celestial and observatory calibration sources and targets.

3.3.2 Wavelength Range

[REQ-1-ORD-2550] The TMT Observatory shall be designed to enable science over the wavelength range of 0.34 - 28 μm , with a goal of 0.31 to 28 μm .

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 will be assumed that it applies over wavelengths from 0.34 to 28 microns.

3.3.3 Light Collection Geometry

[REQ-1-ORD-2570] The TMT Observatory 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 TMT Observatory 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 TMT Observatory shall have an entrance pupil whose circumscribing circle is 30 m diameter.

[REQ-1-ORD-2585] The TMT Observatory 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 TMT Observatory primary mirror obscuration shall be capable of being masked by a cold stop in an instrument.

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

[REQ-1-ORD-2600] The TMT Observatory 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 TMT Observatory telescope system shall have a Nasmyth configuration, with several available foci on each side of the primary mirror.

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

[REQ-1-ORD-2615] The TMT Observatory 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 shall be 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 σ_{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 3-1: Illustrating the move time and settling band specification' below.

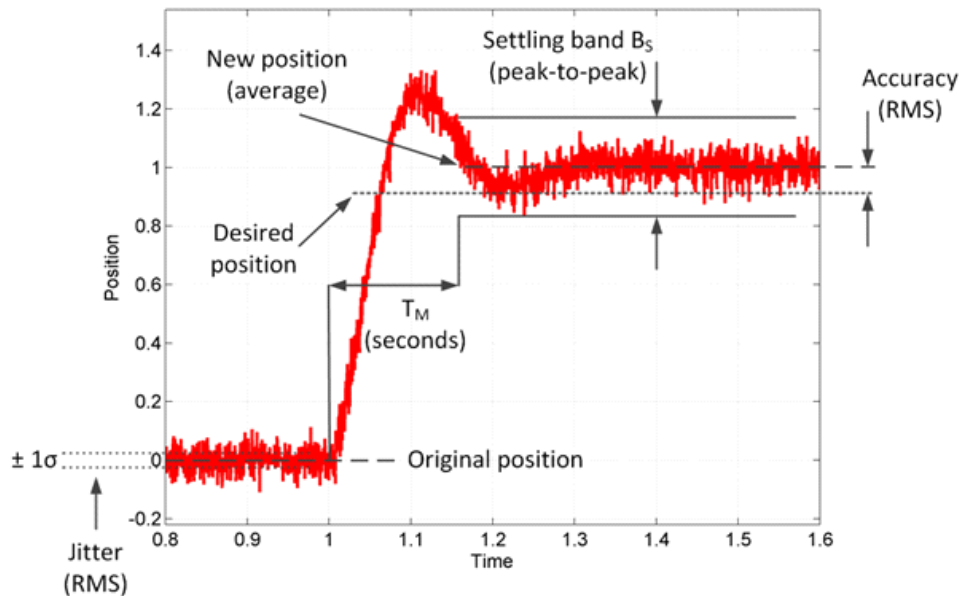


Figure 3-1: Illustrating the move time and settling band specification. T_M is the move time, B_S is the settling band.

[REQ-1-ORD-2625] The TMT Observatory 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 TMT Observatory shall be able to observe anywhere on the sky from 1° to 65° zenith angle.

[REQ-1-ORD-2635] The TMT Observatory 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 TMT Observatory shall be able to observe anywhere on the sky from 0° to 360° azimuth angle.

[REQ-1-ORD-2645] The TMT Observatory's range and mid-point of telescope azimuth motion shall be sufficient to continuously track any sidereal celestial object across the sky between elevation axis horizon limits.

[REQ-1-ORD-2650] The TMT Observatory 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-2656] The TMT Observatory average slew time between science targets shall be less than 60 seconds.

Discussion: This requirement applies to the 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] TMT Observatory instruments and adaptive optics systems shall implement hardware, including cameras or wavefront sensors, to support guide star acquisition.

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

[REQ-1-ORD-2685] The TMT Observatory 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 TMT observatory shall improve the alignment of the telescope relative to the sky by means of guiding, over the whole accessible sky.

[REQ-1-ORD-2705] TMT Observatory instruments or adaptive optics systems shall de-rotate the astronomical field as they require.

Discussion: The telescope will have no provision for de-rotating the science field. We assume this will be accomplished either by rotating the instrument or implementing a K mirror within the instrument.

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

Discussion: The TMT Observatory 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] TMT Observatory instruments and adaptive optics systems shall implement hardware, including 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-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] TMT Observatory shall open-loop track without the assistance of real time optical feedback to the following accuracies for no less than the respective durations.

Table 3-5: Open loop track accuracy

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

*Definition: **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-2753] The TMT Observatory shall be able to efficiently perform **Acquisition Offsets** of up to 1 degree on the sky.

[REQ-1-ORD-2755] The TMT Observatory shall be able to perform accurate and efficient **Guider Offsets** of up to 5 arcminutes on the sky.

[REQ-1-ORD-2760] The TMT Observatory shall be able to perform **AO Guider Offsetting**.

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.

[REQ-1-ORD-2765] The TMT Observatory shall be able to repetitively offset and settle between two or more given positions up to 30 arcsec apart on the sky.

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 3-3: illustration of extent of dither pattern' below.

[REQ-1-ORD-2775] The TMT Observatory 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 3-2.

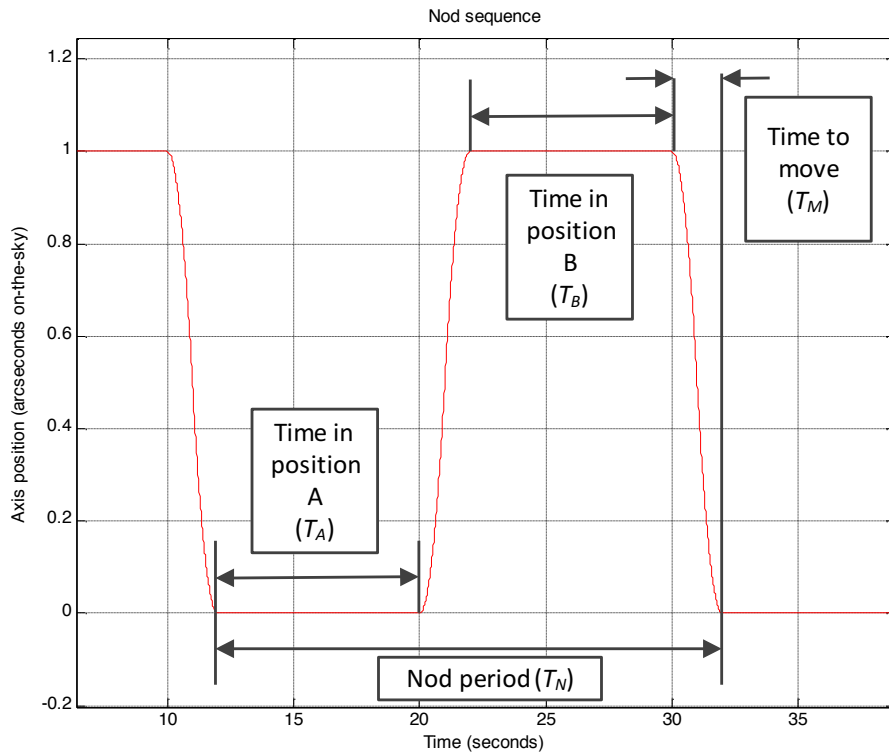


Figure 3-2: Example of nodding between two points 1 arcsecond apart.

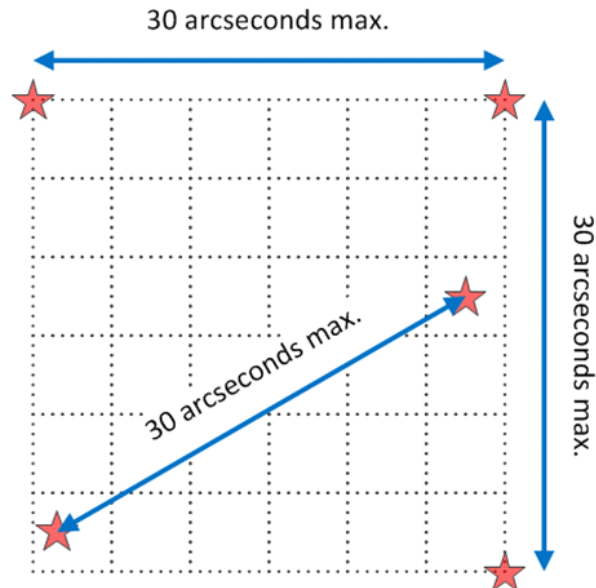


Figure 3-3: illustration of extent of dither pattern. Dimensions are defined on sky, square can be in any orientation on sky and tracks objects.

[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: Example of non-redundant dither' below 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: Example of non-redundant dither' below. 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: Summary of Accuracy and Timing Requirements for Motion during offsetting, nodding and dithering' above apply to the moves used in this dither pattern

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

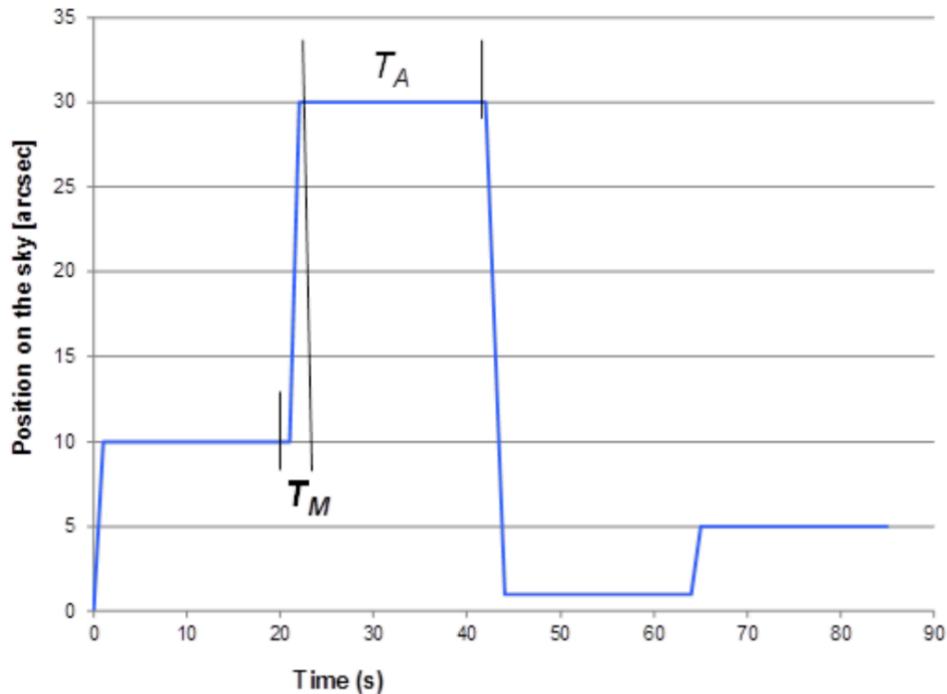


Figure 3-4: Example of non-redundant dither. T_A is the time between dither moves as per REQ-1-ORD-2774, i.e. the open shutter/dwell time ($T_A \geq 20s$), T_M is move time or dither loss.

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

3.3.8 Image Quality

3.3.8.1 Seeing Limited Mode

[REQ-1-ORD-2800] At 0.5 μm wavelength, the Science Productivity Metric (SPM) of the TMT 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 α 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] TMT Observatory 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 TMT observatory LGS MCAO and NGS AO WFE budgets are described in RD13.

[REQ-1-ORD-2830] TMT Observatory, for all AO modes, WFE degradation with zenith angle shall be less than or equal to $(\sec z)^{1/2}$ relative to the requirement at zenith.

[REQ-1-ORD-2730] TMT Observatory, in NFIRAOS LGS MCAO mode, shall deliver a Low Order RMS WFE less than or equal to 72 nm on axis, over 17, and 30 arcsec FOV under reference atmospheric seeing conditions (see Appendix 4.1) with 50% sky coverage at the galactic pole.

Discussion: Low Order WFE includes the following terms: Tip/Tilt, Focus, and Plate Scale

[REQ-1-ORD-3530] TMT Observatory, in NFIRAOS LGS MCAO mode, shall deliver a High Order RMS WFE less than or equal to 173 nm on axis and 188 nm over a 17 arcsec FOV under reference atmospheric seeing conditions (see Appendix 4.1).

Discussion: High Order WFE includes all terms except Low order terms as Tip/Tilt, Focus and Plate Scale.

[REQ-1-ORD-4225] TMT Observatory, in NFIRAOS upgraded LGS MCAO mode, shall deliver a High Order LGS RMS WFE of 120 nm on axis under reference atmospheric seeing conditions (see Appendix 4.1).

[REQ-1-ORD-3532] TMT Observatory, in NFIRAOS LGS MCAO mode, shall deliver a High Order LGS RMS WFE less than or equal to 190 nm over a 30 arcsec diameter FOV to early light science instruments focal plane under reference atmospheric seeing conditions (see Appendix 4.1).

[REQ-1-ORD-3531] TMT Observatory, in NFIRAOS upgraded LGS MCAO mode, shall deliver a High Order LGS RMS WFE less than or equal to 133 nm over a 30 arcsec diameter FOV to early light science instruments focal plane under reference atmospheric seeing conditions (see Appendix 4.1).

Discussion: Requirements [REQ-1-ORD-3530], [REQ-1-ORD-3531], [REQ-1-ORD-3532], and [REQ-1-ORD-4225] will be met one band at a time due to chromaticity of windows.

[REQ-1-ORD-2820] TMT Observatory Telescope and enclosure shall deliver to all AO systems, a RMS WFE of less than or equal to 25nm that is not correctable by an idealized 120 x 120 deformable mirror AO system with infinite temporal bandwidth.

Discussion: This requirement is intended to limit the high-spatial frequency errors for the TMT Telescope and Enclosure to enable high order adaptive optics system performance.

[REQ-1-ORD-2825] TMT Observatory Telescope and enclosure shall deliver to all AO systems, a RMS WFE of less than or equal to 45nm that is not correctable by an idealized 60 x 60 deformable mirror AO system with infinite temporal bandwidth.

Discussion: This requirement is intended to limit the high-spatial frequency errors for the TMT Telescope and Enclosure, to enable high order adaptive optics system performance.

3.3.8.2.1 NFIRAOS NGS AO Mode

[REQ-1-ORD-3669] TMT Observatory, in NFIRAOS NGS AO mode, shall deliver a Low Order RMS WFE of less than or equal to 30 nm on-axis, in median seeing, using an R < 12 magnitude star.

[REQ-1-ORD-3670] TMT Observatory, in NFIRAOS NGS AO mode, shall deliver a High Order RMS WFE of less than or equal to 146 nm on axis, in median seeing, using an R < 8 magnitude star.

[REQ-1-ORD-3671] TMT Observatory, in NFIRAOS NGS AO mode, shall deliver a High Order RMS WFE of less than or equal to 180 nm on axis, in median seeing, using an R < 12 magnitude star.

3.3.8.2.2 NFIRAOS Seeing Limited Mode

[REQ-1-ORD-3534] TMT Observatory, in NFIRAOS Seeing Limited mode, shall deliver a K Band enclosed energy of at least 50% for a 160mas slit, at the edge of the 2 arcmin unvignetted field of view under median conditions, using an R< (TBD).

[REQ-1-ORD-3533] TMT Observatory, in NFIRAOS Seeing Limited mode, shall deliver a J Band enclosed energy of at least 30% for a 160mas slit, at the edge of the 2 arcmin unvignetted field of view under median conditions, using an R< (TBD).

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 TMT Observatory telescope, not including instruments or AO systems, shall maintain the position of the exit pupil, centered within ± 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 3.6: Telescope Optical Throughput Requirements' below.

Table 3-6: Telescope Optical Throughput Requirements

Wavelength Range	Requirement	Goal
0.31 - 0.34 μm	N/A	0.50
0.34 - 0.36 μm	0.50	0.73
0.36 - 0.40 μm	0.50 \rightarrow 0.73	0.73 \rightarrow 0.86
0.4 - 0.5 μm	0.73 \rightarrow 0.86	0.86 \rightarrow 0.94
0.5 - 0.7 μm	0.86 \rightarrow 0.91	0.94
0.7 - 28 μm	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 TMT Observatory shall provide means for in-situ cleaning of the telescope optics to maintain throughput.

[REQ-1-ORD-2910] The TMT 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 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 TMT Observatory's facility AO system shall utilize laser guide stars to improve sky coverage.

[REQ-1-ORD-2965] The TMT Observatory shall be able to project several laser guide star asterisms, pre-defined and fixed to suit 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 m³.

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 NFIRAOS Baseline

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

[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 simultaneously meet its requirements for image quality, sky coverage, throughput, and background, one astronomical band at a time, over a wavelength range of 0.95 to 2.4 μ m.

Discussion: Simultaneous performance is limited to individually observing Y through K bands defined in section 4.2.1, due to chromaticity of windows. It is a strong goal to simultaneously meet these requirements down to 0.8 μ m. However, extending simultaneity shortward of 0.95 μ m stresses beamsplitter technology and may cost throughput and sky coverage, since a brighter natural guide star will be required for real-

time PWFS measurement of the LGS WFS measurement errors due to sodium layer variability and Rayleigh backscatter variability. Observations at 0.8 um 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 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-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 um 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 μ -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 μ 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 60% over 0.84 to 1.0 microns and 80% over the 1.0-2.4 micron wavelength range.

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-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.

3.3.19 Early Light Instruments

Discussion: At early light, the observatory will provide the following instrument capabilities:

3.3.19.1 InfraRed Imaging Spectrometer (IRIS)

3.3.19.1.1 General

[REQ-1-ORD-3700] IRIS shall provide diffraction-limited moderate spectral resolution ($\sim R=4000$) 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 IRIS OIWFS sensors shall provide pixel intensities to NFIRAOS.

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

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

[REQ-1-ORD-3740] IRIS shall have a wavelength range between $0.84\mu\text{m}$ - $2.4\mu\text{m}$ for all modes.

3.3.19.1.2 Imaging

[REQ-1-ORD-3755] The IRIS imager shall have a field of view greater than 15×15 arcsec.

[REQ-1-ORD-3760] IRIS shall sample 0.004 arcsec per pixel (Nyquist sampled ($\lambda/2D$) over 4096 pixels).

[REQ-1-ORD-3770] IRIS detector sampling, in Imaging Mode, shall be Nyquist sampled ($\lambda/2D$) (0.004 arcsec) over 10×10 arcsec.

[REQ-1-ORD-3735] The IRIS imager shall allow imager filters with a greater than 1% bandpass.

[REQ-1-ORD-3737] The IRIS imager shall have a throughput greater than 45%, not including telescope or NFIRAOS.

[REQ-1-ORD-3792] IRIS, in Imaging Mode, shall not increase the K-band background by more than 15% over natural sky.

3.3.19.1.3 Spectroscopy

[REQ-1-ORD-3750] The IRIS IFU shall have a field of view up to 3 arcsec.

[REQ-1-ORD-3745] IRIS shall preserve all wavefront quality delivered by the AO system for all modes in which the diffraction limit is critically sampled.

[REQ-1-ORD-3765] The IRIS spectrograph shall have adjustable spatial sampling to offer plate scales of 0.004, 0.009, 0.025 and 0.050 arcsec/spaxel for the IFU.

[REQ-1-ORD-3775] IRIS shall provide wavelength coverage ($\Delta\lambda/\lambda \leq 0.05$) for an area equivalent to 100×100 spatial pixels.

[REQ-1-ORD-3780] IRIS shall have a minimum spectral resolving power of $R=4000$ over entire Y, J, H, K bands, one band at a time.

[REQ-1-ORD-3785] The IRIS spectrograph shall have a throughput greater than 30%, excluding the AO system and telescope.

[REQ-1-ORD-3790] IRIS shall not increase the (inter-OH) background by more than 5% (TBC) over the sum of: inter-OH sky, telescope and NFIRAOS background.

[REQ-1-ORD-3795] IRIS detector dark current and read noise shall not increase the effective background by more than 5% for an integration time of 2000s.

3.3.19.2 Infrared Multi-Object Spectrometer (IRMS)

Discussion: IRMS is a near infrared multiple slit spectrometer.

[REQ-1-ORD-3800] IRMS shall be fed by an adaptive optics corrected beam from NFIRAOS.

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

[REQ-1-ORD-3803] The IRMS OIWFS sensors shall provide pixel intensities to NFIRAOS.

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

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

[REQ-1-ORD-3830] IRMS shall provide a pupil mask that can rotate to match the telescope pupil.

[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.

[REQ-1-ORD-3840] IRMS shall have a wavelength range of 0.95-2.40 μ m.

[REQ-1-ORD-3845] IRMS wavelength coverage shall cover an entire band at a time.

[REQ-1-ORD-3850] IRMS, in Spectroscopic Mode, shall have greater than 80% ensquared energy in a 0.12" by 0.16" box.

[REQ-1-ORD-3852] IRMS, in Direct Imaging Mode, shall have rms image diameters < 0.07" over full bandwidth without re-focus.

[REQ-1-ORD-3855] IRMS shall have a 2.0 arcmin diameter unvignetted field of view with AO correction by NFIRAOS.

[REQ-1-ORD-3856] IRMS spatial sampling shall be 0.060 arcsec/pixel in the spatial direction and 0.08 arcsec/pixel in the dispersion direction.

[REQ-1-ORD-3858] IRMS shall have a field of view of at least 2.05 arcmin x 2.05 arcmin at the sampling given in [REQ-1-ORD-3856].

[REQ-1-ORD-3860] IRMS shall have a spectral resolution of $R > 3270$ with a 3 pixel slit (0.24 arcsec).

[REQ-1-ORD-3861] IRMS shall have a spectral resolution of $R > 4660$ with a 2 pixel slit (0.16 arcsec).

[REQ-1-ORD-3865] IRMS throughput shall be >40% for imaging; >30% on order blaze in each band, not including telescope or NFIRAOS.

[REQ-1-ORD-3870] IRMS shall image the entire NFIRAOS 2 arcmin field of view with 0.06 arcsec sampling.

[REQ-1-ORD-3875] IRMS background shall not increase the inter-OH background by more than 10% over the natural sky+telescope+AO system background.

[REQ-1-ORD-3877] IRMS spectroscopic observations shall be background-limited for any exposure > 60 seconds.

[REQ-1-ORD-3880] IRMS shall have at least 46 adjustable cryogenic slits with a total slit length of up to 120 arcsec.

Discussion: Slits have discrete lengths of 2.43 arcsec and can be combined as desired in discrete steps. Gaps between slits are 0.17" when slits are not aligned into longer contiguous units. Slit widths are continuously variable. Slit mask remotely configurable in 3-5 minutes.

3.3.19.3 Wide Field Optical Imaging Spectrometer (WFOS)

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

[REQ-1-ORD-3905] WFOS shall be able to take an image of its spectrometric mode field of view.

[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-3940] WFOS shall provide internal baffling.

[REQ-1-ORD-3950] WFOS shall have a wavelength range of 0.31 - 1.0 μ m; 0.3 - 1.5 μ m (goal).

[REQ-1-ORD-3955] WFOS, in Imaging Mode, shall have an image quality \leq 0.2 arcsec FWHM over any 0.1 μ m wavelength interval, not including contributions from the telescope or the atmosphere.

[REQ-1-ORD-3960] WFOS, in Spectroscopy Mode, shall have an image quality less than 0.2 arcsec FWHM at every wavelength.

[REQ-1-ORD-3965] The WFOS field of view shall be > 40.5 arcmin².

Discussion: The field need not be contiguous.

[REQ-1-ORD-3970] The WFOS total slit length shall be \geq 500 arcsec.

[REQ-1-ORD-3975] WFOS shall have a spatial sampling < 0.15 arcsec per pixel, goal < 0.1 arcsec.

[REQ-1-ORD-3980] WFOS shall have a spectral resolution of $R = 500-5000$ a 0.75 arcsec slit. [Goal: $R = 150-7500$]

[REQ-1-ORD-3985] WFOS, in Spectroscopy Mode, shall have a throughput of \geq 30% from 0.31 - 1.0 μ m, not including the telescope.

[REQ-1-ORD-3990] WFOS spectra shall be photon noise limited for all exposure times > 60 sec.

[REQ-1-ORD-3992] WFOS background subtraction systematics shall be negligible (TBD) compared to photon noise for total exposure times as long as 100 Ksec.

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

[REQ-1-ORD-3995] WFOS shall have a gravity flexure due to instrument rotation at a level less than 0.15 arc-sec at the detector.

[REQ-1-ORD-3997] WFOS shall support short (< 3 minutes once telescope is in position) field acquisition for multi-slit masks.

[REQ-1-ORD-3999] WFOS shall support fast (< 1 min) acquisition of single targets onto a long slit.

3.3.19.3.1 WFOS Desirable Features

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

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

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

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

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

3.3.20 First Decade Instrumentation Requirements

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

3.3.20.1 General

[REQ-1-ORD-4200] The TMT Observatory shall be designed and built in a manner that supports the implementation of new instrumentation in the first decade of operation.

[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.

3.3.20.2 IRMOS - Near Infrared Multi Object Spectrometer

Discussion: 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 IRMOS and MOAO system shall have a wavelength range of 0.8 to 2.5 μm .

[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] IRMOS shall provide at least 10 IFU heads.

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

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

[REQ-1-ORD-4280] The IRMOS minimum IFU head separation shall be 20 arcsec.

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

[REQ-1-ORD-4288] IRMOS throughput shall be greater than 50%.

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

[REQ-1-ORD-4300] IRMOS electronic background (detector dark current and read noise) 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 μm , under the reference atmospheric conditions, when bright natural guidestars (Magnitude TBD) are present for tip-tilt sensing.

3.3.20.3 MIRES - Mid Infrared Echelle Spectrometer

Discussion: 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] MIRES shall be fed by, or incorporate, a mid-IR AO system (MIRAO) using both natural and laser guide stars to deliver diffraction limited images.

Discussion: The 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.

Discussion: It is desirable (goal) that this instrument can also serve as a mid IR imager.

[REQ-1-ORD-4370] MIRES shall provide images in the K band (2.2 μm wavelength) for acquisition.

Discussion: The goal is to provide images also in the N band (10 μm wavelength) for science, possibly with narrow band filters.

[REQ-1-ORD-4375] MIRES 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 μm).

[REQ-1-ORD-4380] MIRES 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.

REQ-1-ORD-4400] MIRES shall have a wavelength range of 8 μ m-18 μ m.

[REQ-1-ORD-4405] The MIRES acquisition camera field of view shall be 10 arcsec, Nyquist sampled at 5 μ m (0.017 arcsec pixels).

Discussion: 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] The MIRES science camera field of view shall be 10 arcsec.

Discussion: A goal is to incorporate a science camera with the same sampling and field as in REQ-1-ORD-4405, 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] MIRES shall have a slit length of 3 arcsec, sampled at 0.04 arcsec/pixel (slit or IFU).

[REQ-1-ORD-4420] MIRES shall have a Spectral Resolution of $5000 \leq R \leq 100,000$ (with diffraction-limited slit).

Discussion: R=50-100K is the prime scientific region.

[REQ-1-ORD-4422] MIRES single exposures at R=100,000 shall give continuous coverage over the orders imaged, 8 - 14 μ m.

[REQ-1-ORD-4425] MIRES shall have a high throughput (> 20%).

[REQ-1-ORD-4430] The MIRES and MIRAO system shall not increase the N band background by more than 15% over natural sky + telescope background (assume 5% emissivity at 273K).

[REQ-1-ORD-4440] MIRES shall have a sampling of 17 mas / pixel.

Discussion: Maximum detector size is likely to be bounded by 2Kx2K.

[REQ-1-ORD-4445] MIRES sensitivity shall be limited by photon statistics in the background, and not limited by any systematic errors, in observations up to an 8 hr long integration.

3.3.20.4 PFI - Planet Formation Imager

Discussion: 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: PFI Requirements' below.

Table 3-7: PFI Requirements

Requirement Number	Description	Requirement
[REQ-1-ORD-4510]	Wavelength Range	1-2.5 μ m, one band at a time. Goal is 1 - 4 μ 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^{-8} @ 50 mas, goal 10^{-9} @ 100 mas
[REQ-1-ORD-4525]	Planet Detection Contrast ($H < 10$) @ Inner Working Angle with 5x rms noise, for a two hour integration	10^{-6} @ 30 mas, goal 2×10^{-7} @ 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 10^8 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.

3.3.20.5 NIRES-B - Near Infrared Echelle Spectrometer (Blue)

Discussion: 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] NIRES-B shall provide 10 arcsec FOV images of the sky around the spectroscopic slit.

Discussion: It is understood that this image is needed for accurate positioning of the science object onto the spectroscopic slit.

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

Additional requirements for NIRES-B are presented in 'Table: NIRES-B Requirements' below.

Table 3-8: NIRES-B Requirements

Requirement Number	Description	Requirement
[REQ-1-ORD-4650]	Wavelength Range	1 μ m- 2.5 μ m
[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=R=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.

3.3.20.6 NIRES-R - Near Infrared Echelle Spectrometer

Discussion: NIRES-R is a small field of view near infrared high spectral resolution spectrometer configuration utilizing diffraction limited images from MIRA0.

[REQ-1-ORD-4905] NIRES-R shall be fed corrected light from the MIRA0 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] NIRES-R shall provide acquisition, guiding and field rotation, as well as any calibration functions.

Additional requirements for NIRES-R are presented in 'Table: NIRES-R Requirements' below.

Table 3-9: NIRES-R Requirements

Requirement Number	Description	Requirement
[REQ-1-ORD-4950]	Wavelength Range	2.9 μ m- 5.0 μ 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=R=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.

3.3.20.7 HROS - High Resolution Optical Spectrometer

Discussion: HROS is a seeing limited optical spectrometer configuration with high spectral resolution.

Discussion: The HROS science case requires HROS to obtain spectra with $20,000 < R < 100,000$ for wavelengths ranging from the atmospheric cutoff at $0.31\mu\text{m}$ to $1\mu\text{m}$ (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] HROS shall provide 10 arcsec FOV images of the sky around the spectroscopic slit.

Discussion: 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: HROS Requirements' below.

Table 3-10: HROS Requirements

Requirement Number	Description	Requirement
[REQ-1-ORD-4740]	Wavelength Range	0.31 – 1.0 μ m (required) 0.3 – 1.3 μ 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	= 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=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.

3.3.20.8 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: IRIS Requirements' below REQ-1-ORD-3725.

Additional requirements for WIRC are presented in 'Table: WIRC Requirements' below.

Table 3-11: WIRC Requirements

Requirement Number	Description	Requirement
[REQ-1-ORD-4835]	Wavelength Range	0.8 – 2.5 μm , goal 0.6-5 μm
[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 TMT Observatory shall provide adequate infrastructure and services for operations.

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 TMT Observatory 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 TMT Observatory shall protect the telescope, instruments, and associated equipment from adverse environmental conditions during non-observing time.

[REQ-1-ORD-5205] The TMT Observatory 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 TMT Observatory Enclosure shall be capable of opening or closing the aperture shutter and any other openings to the outside environment in less than 2 minutes.

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

[REQ-1-ORD-5215] The TMT Observatory 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 TMT Observatory 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 TMT Observatory Enclosure design shall minimize dome seeing, mirror seeing, and wind buffeting during observations.

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

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

[REQ-1-ORD-5240] The TMT Observatory Enclosure shall be designed to 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 TMT Observatory Enclosure and Summit Facilities 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: Facility Performance Conditions' below REQ-1-ORD-1300.

3.4.3 Road

[REQ-1-ORD-5520] The TMT Observatory shall be accessible via 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 enables the logging of all scheduled maintenance and unexpected repairs.

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

[REQ-1-ORD-6210] The TMT Observatory shall extract information about the systems' current condition from the science and calibration data streams, and log this information along with other relevant system and environmental status information such that it is possible to monitor, save, and analyze the technical performance of the observatory systems.

3.5.1.4 Reliability

Discussion: The OpsRD (RD12), specifies the operational requirements on technical downtime for the observatory.

[REQ-1-ORD-6300] The TMT Observatory shall not exceed a technical downtime of 3%, equivalent to 90 hours per year, during hours scheduled for science operations.

Discussion: Reliability and time to repair budgets are allocated at the system decomposition level to 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 TMT 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.

Discussion: A comprehensive safety plan, as addressed in the construction project WBS, will be established and implemented before the construction starts at the observatory site.

Discussion: An operational safety plan will be established before Early Operations starts.

3.6.2 Health

[REQ-1-ORD-7200] The TMT 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 TMT 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 TMT 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 TMT 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 Operations Requirements Document (OpsRD)*.

3.7.2 Communications Network Requirements

Discussion: the requirements in this section flow from a combination of the OpsRD 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: ISP Bandwidth Requirements' below.

Table 3-12: ISP Bandwidth Requirements

Category	Required bandwidth (Mbits)
General communications	TBD
Remote observing	TBD
Remote diagnostics	TBD
Data transfer	TBD
Total	TBD

[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 H₂O = 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 29th June 2005 to 1st June 2008. Three sets of standard conditions are given, identified as the 25th and 75th percentile and median conditions. These three sets were established from the 3 years of recorded profiles as follows, using a ‘NFIRAOS like’ AO system to compute residual DM fitting and servo lag errors:

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

'Table 4-1: Atmospheric Turbulence Parameters' summarizes the standard values for 4 fundamental atmospheric turbulence parameters for each condition, specified at a wavelength of 0.5 μm and a zenith angle of 0 degrees. We have no measurements of L_0 so we use a generally accepted median value of 30m.

Parameter	25 th Percentile Conditions	Median	75 th 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 (θ_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 θ_0 and f_g have been derived using the 7-layer turbulence and wind profiles from 'Table 4-2: Standard Atmospheric C_n^2 dh and Windspeed Profiles'. These are also the standard profiles to be used for more detailed AO analysis and simulation.

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

Note: The above Cn² values are based on results taken at a height of 7m above the ground, but have been adjusted to remove turbulence between 7m and 60m to account for the height of the enclosure. 'Table: Standard atmospheric Cn²dh and windspeed profiles' consequently does not include conditions inside the enclosure.

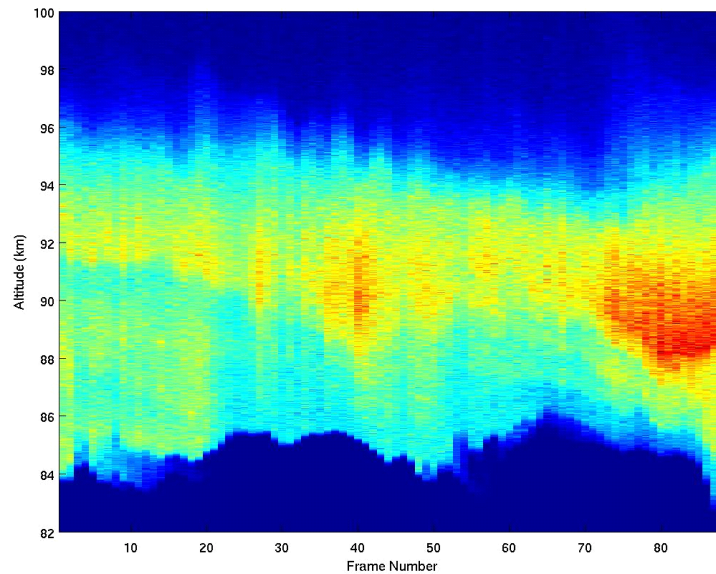
4.1.3 Mesospheric Sodium Layer

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/m²
- Sodium ion cross section: 130 photons-m²/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.

The figure below 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.



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.

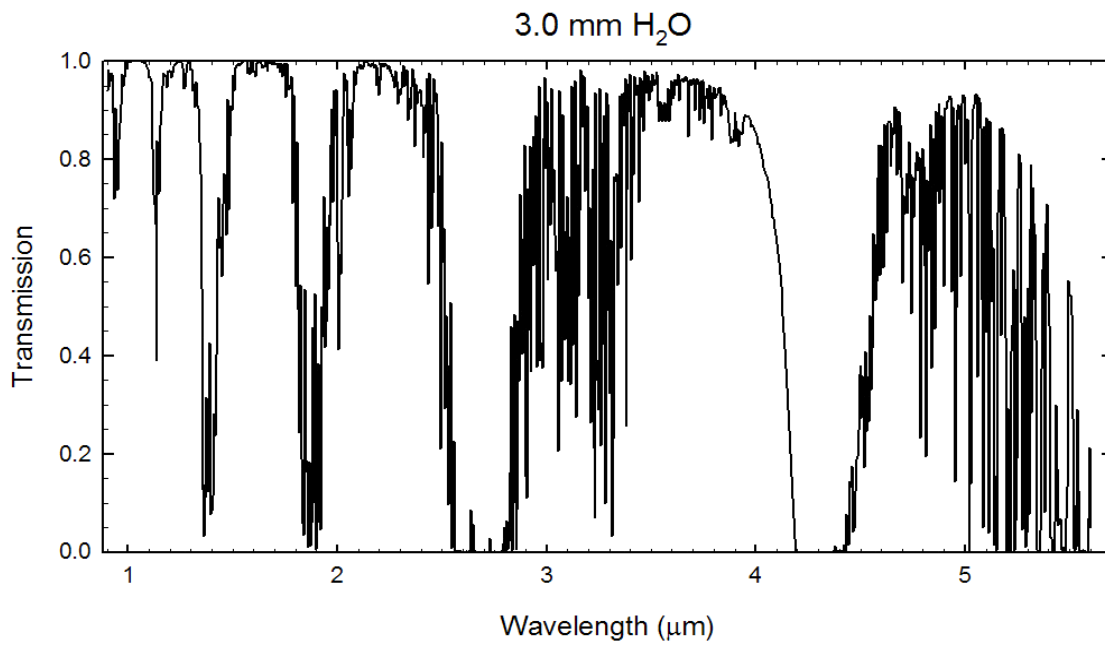
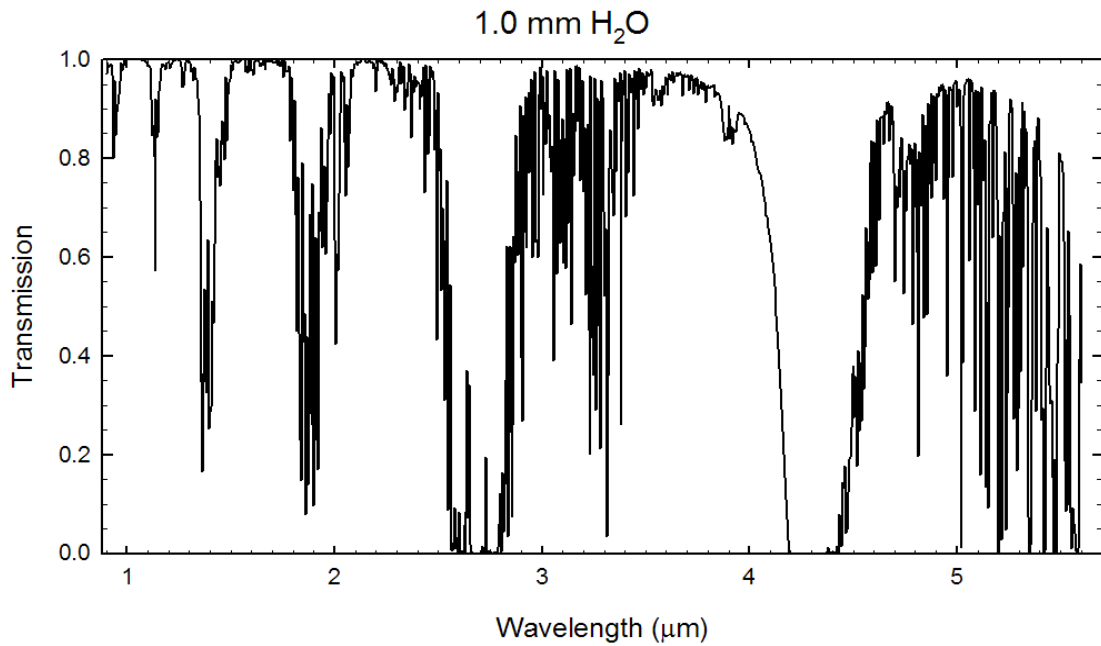
4.2 WAVELENGTH BANDS

4.2.1 Astronomical Filters

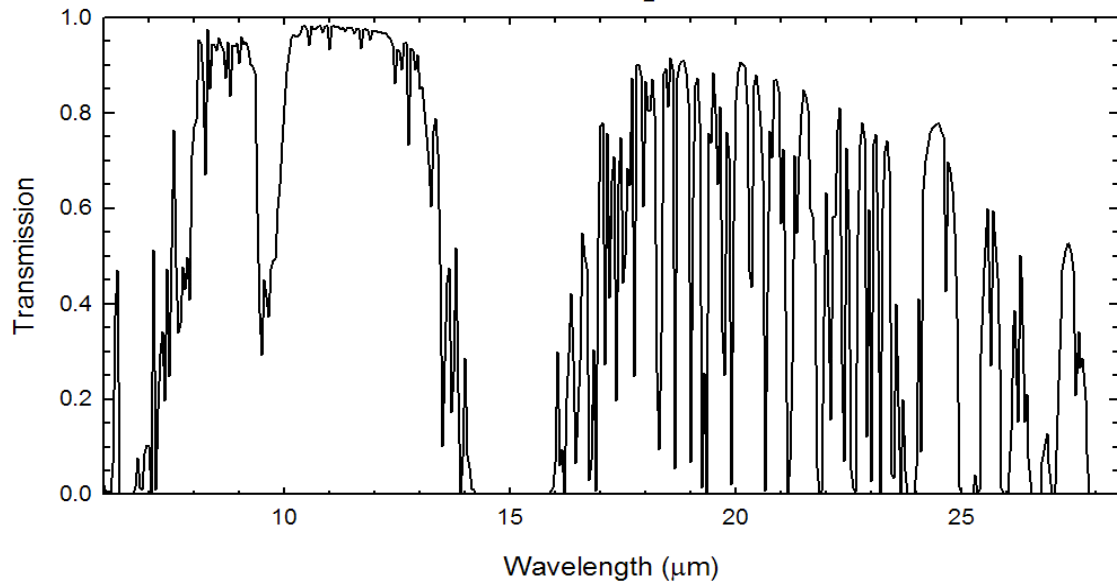
Band	Center wavelength	Bandwidth
U	0.3663 μm	0.0650 μm
B	0.4361 μm	0.0890 μm
V	0.5448 μm	0.0840 μm
R	0.6407 μm	0.1580 μm
I	0.7980 μm	0.1540 μm
Y	1.03 μm	0.13 μm
J	1.250 μm	0.16 μm
H	1.635 μm	0.29 μm
K'	2.12 μm	0.34 μm
K _s	2.15 μm	0.32 μm
K	2.2 μm	0.34 μm
L	3.77 μm	0.7 μm
M	4.68 μm	0.22 μm
N	10.47 μm	5.2 μm
Q	20.13 μm	7.8 μm

Data in the table is from [RD6].

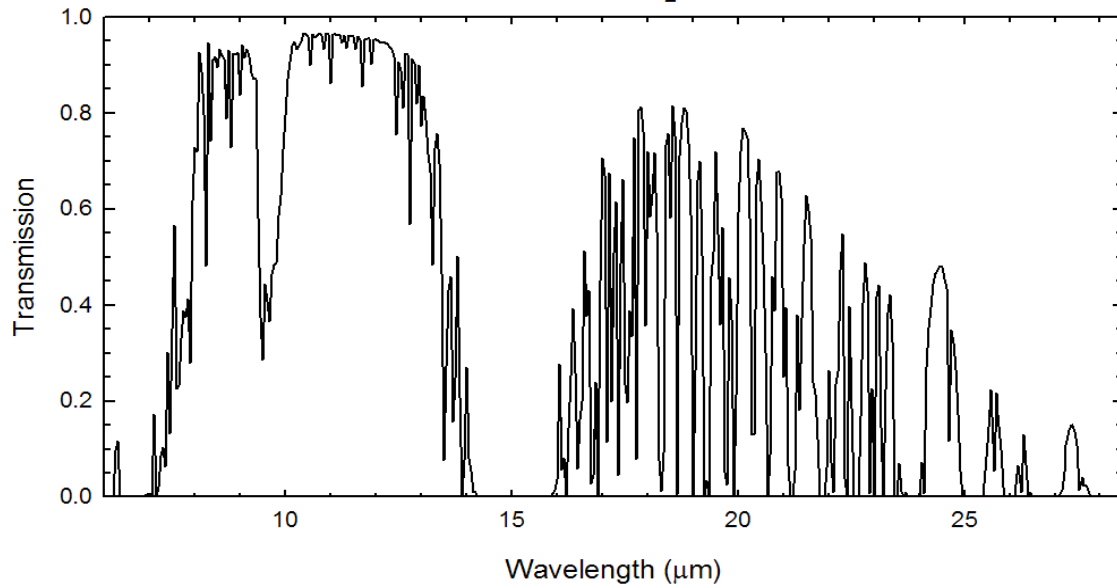
4.2.2 Atmospheric Transmission Windows



1.0 mm H₂O



3.0 mm H₂O



4.3 TEMPORAL TEMPERATURE GRADIENTS

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

Table 4-4: Night time temporal temperature gradients

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