

# Thirty Meter Telescope

## Science-Based Requirements Document (SRD)

### v15.0 Instrument RFP release

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## Executive Summary

This document describes the science-driven requirements for the Thirty-Meter Telescope (TMT) project. TMT will be the first of the next-generation giant optical/infrared ground-based telescopes and will be a flagship facility for addressing the most compelling areas in astrophysics: the nature of Dark Matter and Dark Energy, the assembly of galaxies, the growth of structure in the Universe, the physical processes involved in star and planet formation and the characterization of extra-solar planets. In the current era, 8m and 10m telescopes have often provided the spectra that are required for physical interpretation of the imaging discoveries of the Hubble Space Telescope, Chandra X-ray Observatory, Compton Gamma-ray Observatory, Spitzer Space Telescope, and other forefront facilities. In addition to being a very powerful standalone facility, TMT will provide similar crucial complementarities for future space-based missions. A facility such as TMT was identified in the 2001 National Academy of Sciences report “Astronomy and Astrophysics in the New Millennium” as the highest priority ground-based new facility for the first decade of this century.

TMT is envisioned as a 30-meter facility with broad capabilities operating over the wavelength range 0.3-30  $\mu\text{m}$ . In addition to providing 9 times the collecting area of the current largest optical/IR telescopes, the 10m Keck Telescopes, TMT will be used with adaptive optics systems to allow diffraction-limited performance. This will provide unparalleled high-sensitivity spatial resolution 12.5 times sharper than is achieved by the Hubble Space Telescope. For many applications, diffraction-limited observations give gains in sensitivity that scale like  $D^4$  (where  $D$  is the primary-mirror diameter).

TMT will provide new science opportunities in essentially every field of astronomy and astrophysics. Furthermore, as has been the case for every previous increase in capability of this magnitude, it is very likely that the scientific impact of TMT will go far beyond what we envision today and TMT will enable discoveries that we cannot anticipate. Nevertheless, there are some key science goals that have been used to define the technical capabilities of TMT.

These key areas include:

- Spectroscopic exploration of the “dark ages” when the first sources of light and the first heavy elements in the universe formed and when the universe, which had recombined at  $z \sim 1000$ , becomes re-ionized by these sources of light. The nature of “first-light” objects and their effects on the young Universe are among the outstanding open questions in astrophysics. Here TMT and JWST will work hand-in-hand, with JWST providing the targets for detailed study with TMT’s spectrometers.
- Exploration of galaxies and large-scale structure in the young universe, including the era in which most of the stars and heavy elements were formed and the galaxies in today’s universe were assembled. TMT will allow detailed

spectroscopic analysis of galaxies and subgalactic fragments during the epoch of galaxy assembly. Issues ranging from the early production and dispersal of the chemical elements, to the distribution of baryons within dark matter halos and the processes of hierarchical merging will be directly addressable. The early epoch of the formation and development of the large-scale structures that dominate the universe today will also be observable with the TMT assuming the  $\sim 10$ -arcmin field specified in the SRD. Studies of the matter power spectrum on small spatial scales, using direct observations of distant galaxies and the IGM, provide information on the physics of the early universe and the nature of dark matter that are inaccessible using any other techniques.

- Investigations of massive black holes throughout cosmic time. The recently-discovered tight correlation between central black hole mass and stellar bulge velocity dispersion strongly implies that black hole formation and growth is closely tied to the processes that form galaxies. This result also suggests that super massive black holes are at the centers of most or all large galaxies. The TMT combination of high spatial resolution and moderate-to-high spectral resolution will provide unprecedented capability for extending the detection and investigation of central black holes to cosmological redshifts. In addition to investigations designed to understand the black hole-galaxy growth issue, nearby supermassive black holes can be analyzed with very high physical resolution. This will allow us to measure general relativistic effects at the center of the Galaxy and to spatially resolve the accretion disks for active black holes in the centers of galaxies to the distance of the Virgo cluster.
- Exploration of planet-formation processes and the characterization of extra-solar planets. Two of the most exciting challenges to astrophysics in the next decades are to understand the physical processes that lead to star and planet formation and to characterize the properties of extra-solar planets. TMT will have a very important role to play in many aspects of this endeavor. Spectroscopic discovery observations that push into the terrestrial-planet regime, the kinematics of proto-planetary disks, spectroscopic detection and analysis of extra-solar planet atmospheres and the direct detection of extra-solar planets in reflected and emitted light are all goals that are driving the TMT design requirements.

These, and other, science goals have led to a set of TMT science-driven capabilities requirements that are described in the body of this document. Not all of the capabilities listed below are envisioned for first-light of the facility and some will depend on continued progress in technical areas. Because of the long lifetime of TMT and the often-rapid advancement of astronomy into new areas, broadly useful capabilities have been emphasized, while maintaining specific capabilities needed to address the key programs in the TMT science case. TMT will be a fundamental tool for investigating a very wide range of topics. An over-arching consideration has been to maintain the aperture advantage of TMT over its predecessor facilities, in both seeing-limited and diffraction-limited regimes.

The proposed TMT capabilities for the first decade of its operation are divided into “1<sup>st</sup> generation capabilities” and 2<sup>nd</sup> generation capabilities:

**1<sup>st</sup> generation instrument capabilities:**

- InfraRed Imaging Spectrometer (IRIS): Diffraction-limited,  $R \sim 4000$  spectral resolution,  $1\mu\text{m}$  to  $2.5\mu\text{m}$  spectroscopy (utilizing a slit or integral field unit (IFU)) over a small field. This capability will also include direct imaging (in addition to direct images generated from IFU spectra).
- Wide-field Optical Spectrometer (WFOS): Seeing-limited multiplexed  $150 < R < 6000$  spectral resolution,  $0.31\text{-}1\mu\text{m}$  spectroscopy over a wide (8-20 arc-min) field.
- InfraRed Multi-Object Spectrometer (IRMOS): near-diffraction limited,  $R \sim 2000 - 10000$  IFU-based spectrometer operating over a wavelength range  $0.8\text{-}2.5\mu\text{m}$ . Will use multiple IFUs and access a 5 arcmin diameter field. This capability may share the IRIS AO system and have other significant IRIS shared technologies.
- Mid-IR High-resolution Echelle Spectrometer (MIREs): Diffraction-limited,  $5000 < R < 100,000$  spectral resolution,  $5\text{-}28\mu\text{m}$  spectroscopy.
- Planet Formation Instrument (PFI): Very high-contrast imaging along with low-resolution spectroscopy for direct planet detection, on scales near the diffraction limit in the  $1 - 2.5\mu\text{m}$  region. Contrast ratio  $\sim 10^6$  at angular distances greater than  $4\lambda/D$  from bright stars is the first-generation capability, contrast of  $10^8$  is the second-generation goal.

**2<sup>nd</sup> generation instrument capabilities:**

- Near-IR High-resolution Echelle Spectrometer (NIREs): Diffraction-limited, high-spectral-resolution ( $20000 < R < 100,000$ ) spectroscopy in the  $1\text{-}5\mu\text{m}$  range.
- High-resolution Optical Spectrometer (HROS): Optical spectroscopy 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. This capability will likely be achieved via a large, echelle spectrometer.
- Wide-field Infrared Camera (WIRC): Diffraction-limited imaging in the  $0.8\text{-}2.5\mu\text{m}$  wavelength range over a  $\sim 30$  arcsec contiguous field.

# 1 Introduction

## 1.1 Background and Motivation

A 30m-class “Giant Segmented Mirror Telescope” was the top priority recommendation of the 2001 Astronomy and Astrophysics Decadal Survey of the U.S. National Research Council. The Survey also recommended that such a telescope be a public-private partnership. Such a telescope, operating from the UV to the mid-IR, is seen as an essential tool for science ranging from understanding star and planet formation to unraveling the history of galaxies and the development of structure in the universe. Because of the extremely high angular resolution achievable at the diffraction limit of a 30m aperture, and because of the ten-fold increase in collecting area over existing optical/IR telescopes, such a facility will mark gains in sensitivity over existing facilities ranging from a factor of 10 to a factor of 100, depending on the application. The “GSMT” is also envisioned to play an essential complementary role to the James Webb Space Telescope (JWST), an infrared optimized 6.5m aperture space telescope to be launched early in the next decade, and the Atacama Large Millimeter Array (ALMA), an array of 64 antennae that will revolutionize astrophysics at sub-mm and mm wavelengths. Many of the key scientific questions to be addressed by the next generation giant ground-based telescope are in common with those of JWST and ALMA; the complementary power of state-of-the art telescopes on the ground is largely based on the ability to obtain spectra of extremely faint sources in the optical and near-IR, and to achieve unprecedented angular resolution when operating at the diffraction limit at wavelengths between 1 and 30  $\mu\text{m}$ .

The Thirty Meter Telescope (TMT) project is a public-private partnership that fulfills all of the goals for the GSMT articulated by the decadal review committee. It has as its goal the design and construction of a 30m segmented-mirror telescope, the adaptive optics (AO) systems required to achieve diffraction-limited performance and the instruments required to use this facility to address the most compelling questions in astronomy and astrophysics in the coming decades.

## 1.2 Basis for Science Requirements

This document describes the science-driven capabilities required of the TMT as agreed to by the TMT Science Advisory Committee (SAC) representing the four partners in the project. To accommodate the science-based goals, the SRD describes the requirements on the TMT site characteristics, the telescope performance, the adaptive optics (AO) performance and the instrument suite and performance. Specific science drivers and the flow down from science case to requirements and goals are described in depth in TMT Report 53, the “Detailed Science Case”. In identifying the highest priority capabilities of the TMT, the potential to carry out the programs described in the science case document is one important driver. It has always been the case that significant improvements in capability in astronomical facilities have led to unanticipated major discoveries. For example, many of the most important discoveries of the Keck 10m telescopes (e.g. extra-solar planets, the accelerating Universe, the nature of gamma-ray bursts sources) were not part of the original science case on which the observatory design was based. A second

important driver for the TMT is accordingly that the capabilities be broadly based enough to open a large “discovery” space.

A final major consideration in the SAC deliberations has been complementarity to planned and anticipated future forefront astronomical facilities in space and at other wavelengths, most importantly JWST and ALMA. At present there is a powerful scientific synergy combining discovery images taken with the 2.5m Hubble Space Telescope and spectra from the largest ground-based telescopes. However, the current generation of 8 and 10m telescope will be unable to provide spectra of faint sources discovered with a 6m O/IR space telescope. We will require the capabilities of TMT to take full advantage of the discoveries made by JWST (and other future missions).

### 1.3 Priorities:

The capabilities and AO/instrument concepts described in the SRD have been prioritized into two groups, ordered by when the SAC feels the capabilities should be realized. The SAC recommends that all the capabilities described here should be implemented in the first decade of TMT operation. The subset of first-generation instruments reflects a strategic desire to deliver within a few years of first-light a powerful suite of complementary capabilities with broad scientific application that can take advantage of seeing- and diffraction-limited science opportunities. These first-generation capabilities will allow many of the programs described in the TMT Detailed Science Case to be addressed in the first few years of TMT operations. It is anticipated (based on current assessments of technical risk) that initially, 50% or more of the time the telescope will be used for seeing-limited observations, giving a significant gain needed for seeing limited science. As AO technology matures, we also anticipate that TMT will operate a larger fraction of the time in the diffraction-limited regime where sensitivity gains over smaller telescopes can grow as fast as  $D^4$  and there will be unparalleled gains in angular resolution. The capabilities are specified in detail in the body of the SRD; we list here the first and second-generation designation.

#### 1.3.1 1<sup>st</sup> generation capabilities:

- InfraRed Imaging Spectrometer (IRIS): Diffraction-limited,  $R \sim 4000$  spectral resolution,  $1\mu\text{m}$  to  $2.5\mu\text{m}$  spectroscopy (utilizing a slit or IFU) over a small field. This capability should will also include direct imaging (in addition to direct images generated from IFU spectra).
- Wide-field Optical Spectrometer (WFOS): Seeing-limited multiplexed  $150 < R < 6000$  spectral resolution,  $0.31\text{-}1\mu\text{m}$  spectroscopy over a wide (8-20 arc-min) field.
- InfraRed Multi-Object Spectrometer (IRMOS): near-diffraction limited,  $R \sim 2000 - 10000$  IFU-based spectrometer operating over a wavelength range  $0.8\text{-}2.5\mu\text{m}$ . Will use multiple IFUs and access a 5 arcmin diameter field. This capability may share the IRIS AO system and have other significant IRIS shared technologies.
- Mid-IR High-resolution Echelle Spectrometer (MIREs): Diffraction-limited,  $5000 < R < 100,000$  spectral resolution,  $5\text{-}28\mu\text{m}$  spectroscopy.

- Planet Formation Instrument (PFI): Very high-contrast imaging along with low-resolution spectroscopy for direct planet detection, on scales near the diffraction limit in the 1 – 2.5 $\mu$ m region. Contrast ratio  $\sim 10^6$  at angular distances greater than  $4\lambda/D$  from bright stars is the first-generation capability, contrast of  $10^8$  is the second-generation goal.

### 1.3.2 2<sup>nd</sup> generation instrument capabilities:

- Near-IR High-resolution Echelle Spectrometer (NIREs): Diffraction-limited, high-spectral-resolution ( $20000 < R < 100,000$ ) spectroscopy in the 1-5 $\mu$ m range.
- High-resolution Optical Spectrometer (HROS): Optical spectroscopy with  $20,000 < R < 100,000$  for wavelengths ranging from the atmospheric cutoff at 0.31 $\mu$ m to 1 $\mu$ m (or longer if detectors exist that will allow it) with wide spectral coverage in a single exposure. This capability will likely be achieved via a large, echelle spectrometer.
- Wide-field Infrared Camera (WIRC): Diffraction-limited imaging in the 0.8-2.5 $\mu$ m wavelength range over a  $\sim 30$  arcsec contiguous field.

## 1.4 General Comments Regarding Large-telescope Capabilities

Much of the power of a 30-m ground-based telescope lies in its ability to perform spectroscopy of unprecedented sensitivity over a very wide wavelength range, and to take advantage of the ability to continue developing instrumental capabilities as the technological and scientific landscape changes with time.

A 30-m class ground-based telescope operating from the UV to the mid-IR will contribute in unique ways to astrophysical discovery, and the nature of these contributions is largely a function of wavelength. In the UV and optical part of the electromagnetic spectrum (0.31-1 $\mu$ m), achieving diffraction limited images with a 30-m aperture is challenging; however, because the terrestrial background is very low (comparable to that in space), TMT will achieve spectral sensitivity at flux levels of ten nano-Janskys (nJy), even with image quality that is limited by atmospheric turbulence (“seeing”) at the level of a few tenths of an arc second. Generally, the gain in sensitivity for UV/optical observations will be a factor of 10-20 compared to the present-day state of the art, and will allow for qualitatively new science and discoveries, particularly in the distant universe.

At wavelengths 1-2.5 $\mu$ m, the atmosphere is relatively transparent, but the terrestrial background is dominated by a “forest” of extremely bright night sky lines produced in the upper atmosphere. For broad-band observations (e.g., imaging), the night sky is approximately 600 times brighter per unit solid angle at 1-2.5 $\mu$ m as compared to 0.4 $\mu$ m. However, using adaptive optics, the typical image quality for a point source can be improved from  $\sim 0.4$  arc seconds in “seeing limited” mode, to  $\sim 0.01$  arc seconds. From a sensitivity standpoint, for unresolved sources in a background-limited regime, this is equivalent to reducing the effective background by a factor of  $\sim 1600$ , or increasing the

signal-to-noise ratio in a given integration time by a factor of 40 (assuming a high Strehl ratio is achieved). Because the sensitivity is enhanced relative to a smaller telescope both by the increase in the aperture *and* the decrease in the relevant background, sensitivity scales roughly proportional to  $D^4$ , where D is the telescope primary diameter. Thus, moving from present-day 6.5-10m telescopes to a 30m aperture will increase the sensitivity by a factor of 80-400 for some types of observations.

More specifically, needed integration time to reach a desired signal-to-noise ratio on a faint point source varies as

$$t \propto \frac{\text{background} / \text{arcsec}^2}{(\text{throughput}) D^4 S^2}$$

where background/arcsec<sup>2</sup> includes sky, telescope, optics, and detector dark current

throughput is the fractional throughput from the primary to the detected photons

S is the Strehl ratio (~fraction of light in the diffraction-limited core of the image).

## 1.5 Summary Table of Capabilities

FUNCTION/NAME	MODE	FIELD OF VIEW	SPECTRAL RESOLUTION	WAVELENGTH RANGE ( $\mu\text{M}$ )	SRD PRIORITY	COMMENTS
InfraRed Imager and Spectrometer (IRIS)	DL	2" IFU 10" imaging	4000 2-50(imaging)	0.8 – 2.5 0.6 – 5(goal)	1	NFIRAOS
Wide-field Optical spectrometer and imager (WFOS)	SL	75 arcmin <sup>2</sup> 300 arcmin <sup>2</sup> (goal) Slitlength>500"	500- 5000@0.75" slit 150- 6000@0.75" (goal)	0.31-1.0 0.3-1.3(goal)	2	
Multi-IFU imaging spectrometer (IRMOS)	n-DL	2" over 5' diameter field	2000-10000	0.8-2.5	1	MOAO
Mid-IR AO-fed echelle spectrometer (MIRES)	DL	3" slit 10" imaging	5000-100000	8.0-18.0 5.0-28.0(goal)	3	MIRAO
Planet Formation Instrument (PFI)	DL	1" outer working angle, 0.03" inner working angle	$R \leq 100$	1.0-2.5 1.0-5.0 (goal)	4	$10^6$ contrast for 1 <sup>st</sup> gen. $10^8$ for 2 <sup>nd</sup> generation
Near-IR AO-fed echelle spectrometer (NIRES)	DL	2" slit	20000-100000	1.0-5.0	5	NFIRAOS
High-Resolution Optical Spectrometer (HROS)	SL	5" slit	50000	0.31-1.1 0.31-1.3(goal)	6	
"wide"-field AO imager (WIRC)	DL	30" imaging field	5-100	0.8-5.0 0.6-5.0(goal)	7	MCAO

## 2 Science-Based Requirements

### 2.1 Telescope

#### 2.1.1 General Description

Expected science covers a wide range of wavelengths, generally needing the highest sensitivities or angular resolution. Wavelength limitations due to the atmosphere are given in Appendix 1.

The TMT will be the largest ground-based telescope in the world. It will carry out a variety of forefront science over a wide range of wavelengths. The telescope requirements are designed to support these expected and potential future uses.

Based on current scientific interest and technology limitations, initially the telescope is expected to be used roughly 50% of time for seeing-limited observations and 50% of the time with diffraction-limited observations (using AO). AO with laser beacons is also likely to be compromised by cirrus clouds, so otherwise useful nights may not be available for AO. As AO capabilities come to fruition, this percentage may change.

#### 2.1.2 Optical

##### 2.1.2.1 Optical Configuration

Segmented mirror primary, entrance pupil equivalent to 30m diameter

Aplanatic configuration with 20 arcmin field of view

Discussion: The secondary provides aplanatic correction (removes coma) to provide 20 arcmin field of view. This can be done with either a Ritchey-Chretien or an Aplanatic-Gregorian (AG) configuration.

Prime focus: not needed

Discussion: We have found no strong science cases in support of a prime focus. Because of the simplification to the telescope we are comfortable omitting this focus.

Cassegrain focus: TBD

Nasmyth focus: Two large Nasmyth platforms needed with expected sizes each of  $\sim 450\text{m}^2$  and ability to place multiple instruments per platform

##### 2.1.2.2 Image and Wavefront Quality

The telescope image quality specification encompasses many effects, including those from guiding, autofocus, collimation, wavefront sensing, wind, mirror and dome seeing, and instrument rotators. This specification should be met for all wind speeds below the median. The ADC has a separate specification and is not included here.

The telescope should deliver image quality that is defined by the seeing-limited images caused by the atmosphere. The intent is to degrade the best 10 percentile images by no more than 10%. The resulting specification is that the telescope should blur images no more than an atmosphere with  $r_0 = 0.8\text{m}$  at a wavelength of

500nm, according to the Kolmogorov model of the atmosphere described in Appendix 10. Specific enclosed energy curves for such a system are shown in Appendix 10.

When AO is used, wavefront errors are more suitable to describe the requirements, but we can use basically the same specification. The structure function of telescope wavefront errors entering the AO system should be no worse than those of an atmosphere with an  $r_0$  of 0.8m at all spatial scales longer than 0.1m, and no worse than those at a scale of 0.1m, on smaller scales.

These specifications are allowed to degrade with zenith angle at the same rate as the atmosphere. Thus specifications degrade as  $(\sec z)^{3/5}$ .

#### **2.1.2.3 Atmospheric dispersion compensation (ADC)**

Dispersion in the index of refraction of the atmosphere causes image blur for observations made away from the zenith. ADC compensation will be needed and applied either by the telescope, AO system, or instrument as agreed. Atmospheric dispersion requiring dispersion compensation is described in Appendix 9. Specific ADC requirements will vary with instruments.

#### **2.1.2.4 Throughput**

Mirror reflectivity as good as any broadband coatings available.

Discussion: From  $0.31\mu\text{m}$  to  $1\mu\text{m}$  the reflectivity should exceed 95% (this is met by the LLNL coating for the Keck-LRIS collimator). Beyond  $1.5\mu\text{m}$  the reflectivity should exceed 99% (met by silver). Details of existing coatings and the impact on system throughput are given in Appendix 3.

Telescope night-time lost to servicing mirrors should be minimized.

Discussion: The concern is that replacing mirror segments will require night-time for realignment of the new segments. Durable, cleanable mirror coatings will reduce the frequency that mirrors are removed from the telescope and thus will be useful in meeting this requirement.

Blockage of the full aperture by structure should be  $\leq 1\%$

Discussion: Thin members will block light and also diffract an equal amount of light into large angles where it is useless, hence the blockage is effectively twice the cross sectional area. Blockages of order 1% are historically achievable.

#### **2.1.2.5 Backgrounds and stray light**

Stray light is a potential problem for science observations. This may be mitigated by telescope baffles or by instrument baffles. Determining the optimal solution will require detailed trade studies. Emissivity issues and wind buffeting both suggest it is better to resolve this within the instrument. We assume the telescope is unbaffled.

Background from thermal radiation from the telescope and its optics should be minimized and including primary, secondary and tertiary (M1+ M2+ M3) should be  $\leq 5\%$  of a 273° blackbody.

Discussion: In the infrared region, at wavelengths longer than about 2 $\mu\text{m}$ , the thermal emission of the telescope optics can dominate the natural sky background. In order to minimize this the reflectivity of the mirrors should be as high as possible. The secondary support structure also adds thermal backgrounds and its optical cross section should be minimized. Beyond these measures, it may be necessary to cool all optics beyond M1, M2, and M3, which must be in an ambient environment. The brightness of the night sky and black body radiation curves are shown in Appendix 4.

Provisions should be made for frequent cleaning of the mirrors to preserve their low emissivity and high reflectivity. Actual cleaning frequency will depend on site characteristics, but is likely to exceed 1/month.

### **2.1.3 Motion**

#### **2.1.3.1 Slewing and acquiring**

The telescope shall be able to move from any point in the sky to any other in less than 5 minutes, and be ready to begin observing. This time includes time needed to rotate the instrument, rotate the dome, acquire a guide star, and set up the ADC and AO system.

Requirements on small motions are TBD.

#### **2.1.3.2 Pointing**

Point to 1 arcsec rms with a goal of 0.5 arcsec rms over the whole accessible sky.

Offset to 0.5 arcsec rms over distances up to 5 arcmin.

Offset to 0.05 arcsec rms over distances up to 10 arcsec (goal 0.01 arcsec rms)

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.

#### **2.1.3.3 Guiding**

Guide/track on non-sidereal rate objects, as well as sidereal rate objects is possible up to 10x sidereal rates and with an error  $\leq 0.05$  arcsec rms.

#### **2.1.3.4 Zenith angle range**

The telescope is required to operate within specifications from within 1° of zenith to at 65° zenith angle

Discussion: As a goal, the telescope should be able to move to the horizon.

This configuration might be useful for servicing the secondary mirror or cleaning the optics.

#### **2.1.3.5 Nodding and Chopping**

Telescope nodding is needed to reduce systematic drifts in backgrounds.

Secondary mirror chopping is needed to reduce systematic drifts in sensitivity.

Detailed requirements are TBD.

## **2.1.4 Instrument Support**

### **2.1.4.1 Space**

Require sufficient space at the telescope foci for large ( $\sim 125\text{m}^3$ ) instruments, with masses  $\sim 50\text{t}$

### **2.1.4.2 Support facilities**

Require power, cooling, signal lines, servicing equipment at instrument locations

### **2.1.4.3 Rapid access**

Require ability to observe with any instrument, at night, in  $<10$  minutes

Discussion: With queue scheduled instruments, ready availability is essential for the virtues of the scheduling to be gained.

### **2.1.4.4 Field rotation**

Observatory must make suitable plans to correct for field rotation for all instruments. Field rotation rates are larger near the zenith.

## **2.2 Site**

### **2.2.1 General Description**

The site is not known at this time. The principal parameters to be measured for use in the final site analysis are identified and are being incorporated into a signal-to-noise based merit function. Final choice will also require weights for each of the parameters. These are currently being developed.

A draft metric for site selection has been developed; when more information on the possible sites becomes available, we will develop this in collaboration with the Site Working Group.

### **2.2.2 Key Astronomical Features**

Excellent image quality (large  $r_0$ , easier to achieve AO performance)

Large isoplanatic angle (larger field of view for AO)

Long coherence time of atmosphere (easier for AO)

Smaller outer scale ( $L_0$ , improved image quality, easier AO)

High fraction of clear nights

High fraction of spectroscopic nights

Low precipitable water vapor distribution (lower IR absorption)

Low typical temperatures (lower thermal background)

High altitude (transparency, low water vapor, low temperature, smaller atmosphere dispersion)

### **2.2.3 Other performance related features**

Low wind speed distribution

Minimal change of temperature during the night (telescope and instrument athermalization)

Minimal seasonal temperature variations

Minimal day-night temperature variations

Latitude (maximize overlap with key observatories such as ALMA)

### **2.2.4 Cost related features**

Easy physical access for minimizing construction costs  
Good human access for minimizing operating costs  
Availability of site

### **2.2.5 Other engineering/safety features**

High mechanical integrity of soil  
Low seismicity

### **2.2.6 Assumed model atmosphere**

For much of what follows, quantitative analysis requires some assumed atmosphere characteristics. Even though atmospheric conditions are widely variable, we will define a “standard atmosphere” for ease of analysis. This is particularly important for assessing AO requirements. The standard atmosphere is described in Appendix 5.

## **2.3 Enclosure**

### **2.3.1 Opening size and Tracking**

Opening should be sufficiently large to avoid vignetting of light from the science field or from laser guide stars.

Enclosure motion should follow motion of the telescope precisely enough that vignetting of the science field and or laser guide stars by the dome is avoided.

Discussion: stray (IR) radiation from the edge of the shutter should be well separated from the field of the telescope.

### **2.3.2 Slewing**

Enclosure motions should never be a cause of delays in beginning scientific observations.

### **2.3.3 Wind protection**

Protect the telescope from wind buffeting

Discussion: during periods of high wind, wind buffeting of the top end of the telescope as well as at the primary are potential concerns. The telescope specification (2.1.2.2) must be met in median winds. The enclosure design should minimize the amplitude and temporal frequency of these forces.

### **2.3.4 Thermal control and locally induced seeing**

Thermally induced seeing degradation caused by temperature differences should be minimized by a suitable combination of natural ventilation, insulation, daytime air conditioning, limiting daytime air leakage, and minimizing thermal inertia of the enclosure interior. The goal is to allow the interior to follow the night-time ambient air temperature as closely as practical.

### **2.3.5 Weather protection**

Protect the telescope against storms, other weather, and daytime air leakage.

Discussion: Water and ice should not be allowed into the enclosure interior. Condensation on the optics should be prevented at all times. Liquid drips on the primary should be avoided. At night, the enclosure should be operable at all times in good weather. The design of the enclosure should minimize the buildup of snow and ice and provide for easy removal of snow and ice to allow for observing after storms.

### 2.3.6 Dust protection

To avoid problems of stray light and emissivity caused by accumulation of dust on the telescope optics, the design of the enclosure should minimize the accumulation of dust on the telescope, for example, by not allowing free infiltration of outside air during the day and by minimizing horizontal surfaces on which dust can accumulate above the level of the telescope.

### 2.3.7 Opening and Closing

The enclosure must open or close in under 2 minutes to protect against sudden changes in weather.

### 2.3.8 Servicing

Provide suitable servicing facilities for telescope, optics, AO, and instruments

## 2.4 Adaptive Optics (AO)

There are a number of different science observational modes requiring adaptive optics to achieve diffraction-limited performance in the  $0.65\mu\text{m}$ - $28\mu\text{m}$  wavelength range. Here we summarize these modes; more detailed requirements are presented below

- Narrow Field, Diffraction-Limited, Near-IR, or Narrow Field IR Adaptive Optics System (NFIRAOS): We expect this mode will be used for NIR spectroscopy with an on-axis IFU or slit *sampled at the diffraction limit*. The delivered field need only be 10 arcsec for this application (but with nearly 100% sky coverage), but ideally this system could work over the whole range  $0.6$ - $5\mu\text{m}$  with high Strehl. All spectroscopic applications require that the system emissivity is kept low for high sensitivity at wavelengths  $> 1.6\mu\text{m}$ .
- Wide Field, Near-Diffraction-Limited, or Multiple Object Adaptive Optics (MOAO): This mode involves correction of a number of small discrete angular regions ( $1$ - $5''$ ) distributed throughout a  $5'$  field. This capability is envisioned to provide diffraction-limited images to deployable IFU's for multiplexed spectroscopy of  $\sim 10$ - $20$  objects. This is the system to be used for the most sensitive observations of extremely faint objects in the  $0.6$ - $2.5\mu\text{m}$  range, and should be optimized for throughput and low emissivity.
- Moderate Field, Diffraction-Limited, or Multi-conjugate Adaptive Optics (MCAO): This mode requires a contiguous  $30''$  field that delivers near-IR images of high Strehl to an imager. The primary scientific drivers of this system are precision photometry of point sources in crowded fields, and precision astrometry.

This system must work over the wavelength range 0.6-2.5 $\mu\text{m}$ , and as a goal should also work in the 3-5 $\mu\text{m}$  range if it does not compromise the performance in the required range. At this time, we envision this system to be an MCAO system, but any system architecture that satisfies the requirements would be acceptable

- Small Field, Diffraction-Limited Mid-IR (MIRAO): the highest priority mid-IR science (5-28 $\mu\text{m}$ ) requires only a small field of view, since it is feeding an echelle spectrometer. However, high sky coverage is required and near-IR wavefront sensing may be required for some science applications.

#### **2.4.1 Overall efficiency of AO modes**

The AO systems should be available on 10-minute notice.

Down time should be under 1%.

Night-time calibration should need no more than 1% of the observing time.

Overhead or duty cycle goal is TBD

#### **2.4.2 Small Field, Diffraction-Limited, Near-IR (NFIRAOS)**

##### **2.4.2.1 General description**

This AO system is intended to deliver diffraction-limited images over a small field, sufficient for either an IFU or a slit. The instruments might be a near-IR echelle spectrometer or a near-IR moderate resolution spectrometer.

##### **2.4.2.2 Wavelength range**

Over 1-5 $\mu\text{m}$  the throughput should exceed 95%, goal is 0.6 $\mu\text{m}$  to 5 $\mu\text{m}$

Discussion: the throughput requirement applies to the AO system alone.

##### **2.4.2.3 Field of view**

The diameter of the field of view should be 5 arcsec, goal 10 arcsec

Discussion: this small field of view is intended to service a long slit, an echelle slit or a fully-sampled, diffraction-limited IFU.

##### **2.4.2.4 Image/wavefront quality**

RMS wavefront error less than 120 nm on axis. Over the 10-arcsec field, anisoplanatic errors are allowed to increase this.

Discussion: For the standard atmosphere, anisoplanatic errors at 5 arcsec off axis will add about 140 nm rms. RMS tip-tilt errors should be as small as natural guide star density will allow. Appendix 7 provides guidance on sky coverage and tip-tilt errors. All wavefront errors except tip-tilt are included, down to the instrument detector. The intent is to achieve Strehl ratios of better than 0.5 at 1 $\mu\text{m}$  for feeding a diffraction-limited slit or IFU.

##### **2.4.2.5 Sky coverage**

Sky coverage should be > 50% at the galactic poles, and as large as natural tip-tilt guide stars will allow. Appendix 7 provides details.

Discussion: sky coverage is limited by the density of natural guide stars for tip/tilt correction. In order to achieve high sky coverage near the galactic poles ( $\geq 50\%$ ) at or near the diffraction limit, diffraction limited guide stars

will probably be needed. This in turn suggests low-noise IR tip-tilt wavefront sensors are needed. See appendix 7 for a discussion.

#### **2.4.2.6 Background**

The AO system should not increase the (inter-OH) background by more than 15% over natural sky (see Appendix 4) + telescope background (assume 5% emissivity at 273K).

Discussion: If the inter-OH brightness is 0.01 of the K mag sky, then a 273° black body has an equal flux at 1.8 $\mu$ m. A three-mirror telescope with net emissivity of 0.05 matches this sky at 2.0 $\mu$ m. Black body emission at 2 $\mu$ m is reduced a factor of 10 by cooling 22°. Thus an AO system with an emissivity of 0.05 must be cooled about 20° below ambient to meet this requirement.

#### **2.4.2.7 Operational Modes:**

##### **2.4.2.7.1 *Multiple lasers***

##### **2.4.2.7.2 *Single Natural Guide Star, no Lasers.***

The system should be operable with a single bright natural star producing rms wavefront errors of <133 nm on axis. The natural angular limits imposed by the isoplanatic angle are acceptable.

### **2.4.3 Wide Field, Near-Diffraction-Limited (0.6-2.5 $\mu$ m) (MOAO)**

#### **2.4.3.1 General description**

This AO system is intended to deliver Na-laser-based tomographic knowledge over a large field of view (~ 5 arcmin) and apply that knowledge to making excellent wavefront correction over small selected subfields within the larger field. Notionally, IFU's could then be distributed over this field could be fed diffraction-limited images for analysis.

#### **2.4.3.2 Wavelength range**

From 0.6 $\mu$ m to 2.5 $\mu$ m the throughput should exceed 85%

Discussion: due to high backgrounds, the number of objects detectable in the 3-5 $\mu$ m window is greatly reduced relative to the object density at shorter wavelengths. Thus the long wavelength cutoff is set to 2.5 $\mu$ m. Single object work is discussed in 2.4.1.

#### **2.4.3.3 Field of View**

Each AO-corrected "patch" needs to be 1-5 arcsec, with as many as 10-20 such patches at adjustable positions over a 20 arcmin<sup>2</sup> region.

Minimum separation between AO patches: goal should be as small as 20 arcsec

Discussion: A 5-arcmin field matches the size of the JWST imaging field. The typical sizes of objects of interest will be 0.1-2 arcsec; the surface density of potential targets will range from a few over the 5-arcmin field to tens per square arc minute. A reasonable IFU sampling and field size would be 0.05 arcsec samples over a 2 arcsec field, or roughly 40 x 40 spatial sampling per IFU head. Note that this is roughly 3 times the diffraction limit @2 $\mu$ m. Coarser sampling over the 5 arcsec field may also occur.

**2.4.3.4 Image/wavefront quality**

At least 50% of the flux from a point source at 1 $\mu$ m wavelength should go into a 0.05 arcsec square.

Discussion: Much of the anticipated use of MOAO will be to study extended objects where sampling of 0.05 arcsec is sufficient. Thus a figure of merit on enclosed energy is appropriate. The given specification is likely similar to a wavefront error requirement of 130 nm, excluding tip and tilt.

**2.4.3.5 Sky coverage**

Sky coverage should be at least 90% at the galactic poles. Appendix 7 provides details.

Discussion: the density of natural guide stars for tip/tilt correction limits sky coverage. Because the image quality tip-tilt requirements here are somewhat relaxed, seeing limited guide star image quality should be sufficient. See appendix 7 for a discussion.

**2.4.3.6 Background**

The AO system should not increase the (inter-OH) background by more than 15% over natural sky (see Appendix 4) + telescope background (assume 5% emissivity at 273K).

Discussion: If the inter-OH brightness is 0.01 of the K mag sky, then a 273 $^{\circ}$  black body has an equal flux at 1.8 $\mu$ m. A three-mirror telescope with net emissivity of 0.05 matches this sky at 2.0 $\mu$ m. Black body emission at 2 $\mu$ m is reduced a factor of 10 by cooling 22 $^{\circ}$ . Thus an AO system with an emissivity of 0.05 must be cooled about 20 $^{\circ}$  below ambient to meet this requirement.

**2.4.3.7 Laser Asterism and Flexibility**

Lasers must be deployable in a flexible way over the 5-arcmin-diameter field to maximize the effectiveness of the AO correction depending on the geometry of the field being observed and the distribution of targets within it.

**2.4.4 Moderate Field, Diffraction-Limited (0.6-2.5 $\mu$ m) (MCAO)****2.4.4.1 General description**

This mode requires a contiguous 30 arcsec field that delivers near-IR images of high Strehl to an imager. The primary scientific drivers of this system are precision photometry of point sources in crowded fields, and precision astrometry. This system must work over the wavelength range 0.6-2.5 $\mu$ m, and as a goal should also work in the 3-5 $\mu$ m range if it does not compromise the performance in the required range. At this time, we envision this system to be an MCAO system, but any system architecture that satisfies the requirements would be acceptable

**2.4.4.2 Wavelength range**

0.6-2.5 $\mu$ m the throughput should exceed 85%, goal 0.6-5 $\mu$ m throughput  $\geq$ 85%

**2.4.4.3 Field of view**

Diffraction limited images over 30x30 arcsec<sup>2</sup> at the stated image quality. This field of view is only acceptable if the MOAO system exists.

**2.4.4.4 Image/wavefront quality**

$\leq 133$  nm rms over the stated field of view under “standard conditions”

Specifications should be met over individual standard photometric band passes R, I, J, H, K, L.

Discussion: These requirements include the telescope wavefront errors and the instrument wavefront errors. This rms wavefront error will achieve 50% Strehl at  $1\mu\text{m}$ . Achieving the stated photometric and astrometric accuracy is critical. An ADC will be needed and should be in the AO system or instrument.

**2.4.4.5 Sky coverage**

Sky coverage should be  $> 50\%$  at the galactic poles, and as large as natural tip-tilt guide stars will allow. Appendix 7 provides details..

Discussion: the density of natural guide stars for tip/tilt correction limits sky coverage. In order to achieve high sky coverage near the galactic poles ( $\geq 50\%$ ) at or near the diffraction limit, diffraction limited guide stars will probably be needed. See appendix 7 for a discussion. Such infrared tip-tilt guide stars will be particularly useful for imaging of obscured regions where visible tip-tilt stars may be absent.

**2.4.4.6 Background**

The AO system should not increase the (inter-OH) background by more than 15% over natural sky (see Appendix 4) + telescope background (assume 5% emissivity at 273K)..

**2.4.4.7 Differential Photometric Precision**

Systematic errors in differential photometry due to PSF residual spatial variability should be under 2% for 10-minute integrations, at  $1\mu\text{m}$ , over the 30 arc-sec FOV. A single standard star is assumed for each image.

**2.4.4.8 Absolute Photometric Accuracy**

With suitable observations of photometric standards, photometry on an absolute scale should be possible to  $<10\%$  with a goal of 5%.

**2.4.4.9 Differential Astrometry**

Residual time-dependent rms distortions (after a fit to physically allowed distortion with field stars) should be no larger than image FWHM/SNR or 1% of the FWHM, whichever is worse, for a 100s integration time. Errors should fall as  $t^{-1/2}$ . These are one-dimensional position uncertainties. This should be achieved over a 30 arcsec FOV.

Discussion: we assume that there will be modest static field distortions, but these will be removed by initial calibration and the use of field stars within the image that can remove residual “static” errors that the AO system might introduced, dependent on the exact tip-tilt guide star configuration.

**2.4.4.10 Operational Modes**

#### **2.4.4.11 Operational Efficiency-Dithering**

Dither pattern losses should be under 1 second for up to 5 arc-sec and 5 sec for up to 30 arc-sec

Dither patterns may have moves from 1-30 arc-sec

Discussion: we want the MCAO setup to be fully automated, and have as a goal the setup time is 1 minute. The dither spec needs to go into the telescope motion specs as well. The dither specs relate to moving the tip-tilt guider mechanisms.

### **2.4.5 Small Field, Diffraction-Limited Mid-IR (MIRAO)**

#### **2.4.5.1 General description**

The highest priority mid-IR science (4.5-28 $\mu$ m) requires only a small field of view, since it is feeding an echelle spectrometer. However, high sky coverage is required and near-IR wavefront sensing may be required for some science applications, both for improved tip-tilt errors and for working in obscured regions.

#### **2.4.5.2 Wavelength range**

From 4.5 $\mu$ m to 28 $\mu$ m the throughput should exceed 85%

#### **2.4.5.3 Field of view**

10 arcsec, goal 1 arcmin

Discussion: goal field of view will allow future imaging modes.

#### **2.4.5.4 Image/wavefront quality**

Wavefront error <750 nm rms, goal < 350 nm rms

Discussion: We understand that this implies poor performance at L band (3.8 $\mu$ m); we envision that L band imaging could be accomplished with MOAO and L-band spectroscopy with NFIRAOS/IRIS.

#### **2.4.5.5 Sky coverage**

all sky, limited only by availability of natural tip-tilt stars

Discussion: system should be operable with natural guide stars. Natural guide stars will probably not provide all sky coverage for the AO correction and need to be supplemented with laser beacons. Here the coverage will be limited by the availability of natural tip-tilt stars. See Appendix 7 for details.

#### **2.4.5.6 Background**

The AO system should not increase the N band background by more than 15% over natural sky (see Appendix 4) + telescope background (assume 5% emissivity at 273K).

Discussion: in order to reduce black body flux at 10 $\mu$ m a factor of 10, the body must be cooled 85°.

#### **2.4.5.7 Photometry**

Systematic, uncalibrated errors in photometry due to PSF residual spatial variability < 5% in the N (10 $\mu$ m) band over 1 arcmin field.

### 2.4.5.8 Astrometry

Differential astrometry is important, and the AO system should provide sufficient calibration information to not degrade the astrometric capabilities beyond the limits set by the atmosphere.

## 2.5 1<sup>st</sup> Generation Instruments

We describe 4 instruments that will be available in the early years of the Observatory. The instrument choice is influenced by several factors. Unique scientific advantage comes from diffraction-limited imaging (AO based). Many important optical spectroscopic problems exist that greatly benefit from the increased collecting area, along with multi-object capability, and should be done in dark time. We expect that roughly 50% of the time we will use the telescope for seeing limited observations. Many cosmological problems benefit from collecting IR spectra from many objects, but do not require diffraction-limited images, since the objects are small, but extended ( $\geq 0.1$  arcsec).

Background light can influence the sensitivity of all instruments. For observations short of about  $1.8\mu\text{m}$ , the brightness of the sky is a more important background than thermal radiation from the optics and telescope. For these observations, optical baffles are often used on telescopes to shield the focal plane from any light outside of the designed field of view. However, these same shields can add thermal background to longer wavelength observations. One solution to this issue is to require the instruments provide suitable baffles, rather than the telescope. This issue is still under discussion.

Atmospheric dispersion can adversely effect many observations. Atmospheric dispersion compensators need to be design in built into the telescope, the AO system or the science instruments. Design options and locations are complex and still under discussion. The basic dispersion facts are given in Appendix 9.

### 2.5.1 InfraRed Imaging Spectrometer (IRIS)

#### 2.5.1.1 General description

This instrument is intended to provide diffraction-limited moderate spectral resolution ( $\sim R=4000$ ) spectra and images over a small field of view, using an integral field unit (IFU). It is also desirable to obtain diffraction-limited images over a 10-arcsec field. This instrument relies on AO and uses the unique diffraction-limited resolution of TMT.

This instrument can use the small field diffraction-limited, near-IR AO system, NFIRAOS (2.4.2) or possibly the wide field, near-diffraction-limited AO system, MOAO (2.4.3). These AO systems might be identical.

Science cases for this instrument include studies of very small crowded fields and detailed astrophysical dissections of individual objects.

#### 2.5.1.2 Wavelength range

0.8-2.5 $\mu\text{m}$ , goal 0.6-5 $\mu\text{m}$

### **2.5.1.3 Field of view**

Up to 2 arcsec for IFU  
Imaging mode 10x10 arcsec

### **2.5.1.4 Image quality**

Wavefront quality delivered by the AO system should be preserved

### **2.5.1.5 Spatial sampling**

0.004 arcsec per pixel (Nyquist sampled ( $\lambda/2D$ )) over 4096 pixels for IFU  
(at 0.004 arcsec/pixel this is a  $(0.26 \text{ arcsec})^2$  field)  
Nyquist sampled ( $\lambda/2D$ ) (0.004 arcsec) over 10x10 arcsec for imaging  
Plate scale adjustable 0.004, 0.009, 0.022, 0.050 arcsec/pixel  
128x128 with small wavelength coverage ( $\Delta\lambda/\lambda \leq 0.05$ )

### **2.5.1.6 Spectral resolution**

R=4000 over entire J, H, K, L bands, one band at a time  
R=2-50 for imaging mode

### **2.5.1.7 Background**

The instrument should not increase the (inter-OH) background by more than 15% over natural sky (see Appendix 4) + telescope background (assume 5% emissivity at 273K).

### **2.5.1.8 Detector**

Detector dark current and read noise shall not increase the effective background by more than 5% for an integration time of 2000 s.

Discussion: In the 1-2.5 $\mu\text{m}$  region, dark current  $\leq 0.002$  e/s and read noise  $\leq 2e$  after multiple reads should be sufficient.

### **2.5.1.9 Throughput**

High throughput is important for this instrument

## **2.5.2 Wide Field Optical Imaging Spectrometer (WFOS)**

### **2.5.2.1 General Description**

This is a seeing-limited, multi-object spectrometer and imager with a large field. This instrument fills a broad capability for optical and near-UV observations of very faint sources. An ADC will be required. If partial AO image correction proves feasible, a detailed review of its capabilities and these requirements will be required.

### **2.5.2.2 Wavelength range**

0.31 – 1.0 $\mu\text{m}$  (required) 0.3 – 1.5 $\mu\text{m}$  (goal);

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

### **2.5.2.3 Field of view**

75 arcmin<sup>2</sup>, goal 300 arcmin<sup>2</sup>

Discussion: The field need not be contiguous. Imaging is required over the same field of view.

#### **2.5.2.4 Total slit length**

$\geq 500$  arcsec

#### **2.5.2.5 Image quality**

$\leq 0.2$  arcsec FWHM over any  $0.1\mu\text{m}$  wavelength interval

Discussion: This includes the contribution from the telescope and the ADC at  $z=60^\circ$

Spectroscopy: Less than  $0.2$  arcsec FWHM at every wavelength

#### **2.5.2.6 Spatial sampling**

$< 0.15$  arc-sec per pixel, goal  $< 0.1$  arc-sec

#### **2.5.2.7 Spectral resolution**

$R = 500-5000$  for a  $0.75$  arc-sec slit, goal  $150-6000$

#### **2.5.2.8 Throughput**

$\geq 30\%$  from  $0.31 - 1.0\mu\text{m}$

Discussion: for seeing limited instruments, high throughput is essential in order to maintain the collecting area advantage over other telescopes.

Throughput should be as good as that of the best existing spectrometers. This includes everything from the telescope focal plane to the detected photons.

Mask setup time should also be short,  $\leq 5$  minutes.

#### **2.5.2.9 Sensitivity**

Requirement: maintain aperture advantage compared to  $8 - 10\text{m}$  wide-field spectrometers

Spectra should be photon noise limited in a one hour exposure.

Discussion: in order to remove detector variations, nod and shuffle capability in the detectors may be needed.

#### **2.5.2.10 Desirable features**

Cross-dispersed mode for smaller sampling density and higher  $R$ .

Imaging through narrowband filters.

IFU option

AO based image quality improvements

### **2.5.3 near-InfraRed, Multi-Object Spectrometer (IRMOS)**

#### **2.5.3.1 General Description**

This instrument is envisioned to work behind the wide field AO system (MOAO) that delivers individually corrected small fields of view over a large ( $5$  arcmin) field of view. Each deployable AO corrector will then connect to its deployable IFU that will sample the field of view ( $\leq 2$  arcsec) and feed the spatially divided information into a spectrometer. Each spectrometer may process information from multiple IFU's depending on the actual instrument design.

This instrument is intended to study multiple extended objects. Because they are extended, spatial resolution  $\sim 0.05$  arcsec is anticipated to be typical, depending on the size of the objects, the spatial channels available, and the sampling density desired.

With such coarse sampling, it is expected that the required tip-tilt stability can be relaxed for the AO system.

### **2.5.3.2 Wavelength Range**

0.8 – 2.5 $\mu$ m

Discussion: the low density of sources beyond 2.5 $\mu$ m makes coverage beyond 2.5 $\mu$ m unnecessary.

### **2.5.3.3 Field of View**

IFU heads deployable over 5 arcmin diameter field

### **2.5.3.4 Image quality**

Should not degrade the image quality delivered by the AO system (50% of energy in 0.050 arcsec)

### **2.5.3.5 Spatial sampling**

Sampling: 0.05x0.05 arcsec

IFU head size: 2.0" IFU heads

Number of IFU units:  $\geq 10$

Smallest head separation: as small as practical, no worse than 20 arcsec

### **2.5.3.6 Spectral Resolution**

R= 2000-10000

Complete atmospheric band covered in a single exposure at R=4000

### **2.5.3.7 Throughput**

High throughput is important for this instrument

### **2.5.3.8 Background**

The instrument should not increase the (inter-OH) background by more than 15% over natural sky (see Appendix 4) + telescope background (assume 5% emissivity at 273K).

### **2.5.3.9 Detector**

Detector dark current and read noise shall not increase the effective background by more than 5% for an integration time of 2000 s.

Discussion: In the 1-2.5 $\mu$ m region, dark current  $\leq 0.002$  e/s and read noise  $\leq 2e$  after multiple reads should be sufficient.

## **2.5.4 Mid-IR Echelle Spectrometer (MIREs)**

### **2.5.4.1 General description**

This instrument will be fed by the MIRAo system. Large sky coverage is desired, so the AO system will probably be fed either by natural guide stars (NGS) or lasers. The AO correction location (deformable mirror) is unknown at this time. It could be with an adaptive secondary, or with a deformable mirror

downstream. In order to keep thermal backgrounds to a minimum, a downstream deformable mirror should be cold.

The guider for this instrument might be associated with the AO system.

This instrument might be a slit instrument or could be an IFU fed spectrometer.

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

#### **2.5.4.2 Wavelength range**

8 $\mu$ m- 18 $\mu$ m, goal 4.5-28 $\mu$ m

#### **2.5.4.3 Field of view of field acquisition camera**

10 arcsec, Nyquist sampled at 5 $\mu$ m (0.017 arcsec pixels)

Discussion: A field acquisition camera is 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.

#### **2.5.4.4 Field of view of science camera**

A science camera with the same field of view and same sampling is desirable (goal).

Discussion: This camera should work in N band at least, and be able to image through narrow band filters

#### **2.5.4.5 Slit Length**

3 arcsec, sampled at 0.04 arcsec/pixel

Discussion: this slit length should accommodate nodding along the slit

#### **2.5.4.6 Spectral Resolution**

$5000 \leq R \leq 100,000$  (diffraction-limited slit)

single exposures at  $R=100,000$  should give continuous coverage over the orders imaged, 8 - 14 $\mu$ m

Discussion:  $R=50-100K$  is the prime scientific region, and 100,000 is deemed valuable. Maximum detector size is likely to be bounded by 2Kx2K.

#### **2.5.4.7 Background**

The instrument should not increase the N band background by more than 15% over natural sky (see Appendix 4) + telescope background (assume 5% emissivity at 273K).

Discussion: integration time to reach a given SNR will be proportional to the total background

#### **2.5.4.8 Throughput**

High throughput is a priority for this instrument

#### **2.5.4.9 Sensitivity**

Sensitivity should be limited by photon statistics in the background, and not limited by any systematic errors, up to an 8 hr integration.

#### **2.5.4.10 Nodding**

This is a requirement on the telescope

Range should cover length of slit at an accuracy of  $\lambda/10D$  at  $8\mu\text{m}$

Frequency-amplitude constraints are TBD

Discussion: Nodding is viewed as the process by which we move the telescope optical axis (moving the telescope). We expect to nod along the slit, distances of many  $\lambda/D$ . Actual nodding requirements should be based on a careful study of the time variability of the telescope backgrounds. Goal is to reach the theoretical sensitivity limited by photon statistics.

#### **2.5.4.11 Chopping**

Discussion: chopping is probably not needed for high-resolution spectroscopy. Broad band imaging may require chopping to reach theoretical sensitivity. Actual requirements should be based on a careful study of the time variability of the detectors.

#### **2.5.4.12 Duty cycle**

At least 80%

Discussion: this is the fractional integration time, limited by nodding and chopping.

### **2.5.5 Planet Formation Instrument (PFI)**

#### **2.5.5.1 General description**

This instrument seeks to directly image and take low-resolution spectra of extra-solar planets. This requires a sophisticated AO system with high accuracy and stability, as well as a coronagraph or similar instrument to block the starlight. We envision that initially the PFI system will be capable of imaging planets with contrast ratios of  $10^6 - 10^7$ . A later and more sophisticated instrument will have a capability of detecting planets at contrast ratios of  $10^7 - 10^8$ .

#### **2.5.5.2 Wavelength range**

1- $2.5\mu\text{m}$ , goal 1- $5\mu\text{m}$

#### **2.5.5.3 Field of view**

0.03-1 arcsec radius

#### **2.5.5.4 Image quality**

See 2.5.5.7

#### **2.5.5.5 Spatial sampling**

Critically sampled at  $1\mu\text{m}$

#### **2.5.5.6 Spectral resolution**

$R \leq 100$

Discussion: slit or IFU

#### **2.5.5.7 Achievable contrast with coronagraph**

Errors in the optical system should not prevent reaching contrast ratios of  $10^8$  before systematic errors dominate. This should be achieved in H band on stars with  $R < 8$  mag.

The first-generation system should be capable of detecting a planet at  $10^{-6}$  (requirement) or  $10^{-7}$  (goal) of the brightness of the central star. This should be achieved at 7x rms noise with a 2 hr integration. This requirement should be achieved for  $H \leq 11$ .

The second-generation system should be capable of detecting a planet at  $10^{-8}$  (requirement) or  $10^{-9}$  (goal) of the brightness of the central star. This should be achieved at 7x rms noise with a 2 hr integration.

#### **2.5.5.8 Polarization**

Polarization measurements of these systems should be able to detect polarization levels of TBD%.

## **2.6 2<sup>nd</sup> Generation Instruments**

### **2.6.1 Near-IR Echelle Spectrometer (NIREs)**

#### **2.6.1.1 General Description**

This high-resolution spectrometer will generally be used with a diffraction-limited slit. It will be placed behind the small field AO system (NFIRAOS) that delivers a high quality image over a small field of view. We assume an 8kx8k detector will be available. Note: see TMT Science Note XXX, Cohen & Najita

#### **2.6.1.2 Wavelength range**

1 $\mu$ m- 5 $\mu$ m

Simultaneous from 1.0 $\mu$ m–2.4 $\mu$ m or simultaneous from 3.5 $\mu$ m- 5.0 $\mu$ m at a resolution of 20,000

#### **2.6.1.3 Field of view of field acquisition camera**

An acquisition camera with field of view of 10 arcsec is needed, Nyquist sampled at 0.0035arcsec per pixel

#### **2.6.1.4 Length of slit**

A slit length of up to 2 arcsec is needed

#### **2.6.1.5 Image quality**

The spectrometer should deliver diffraction-limited images to the detector, as delivered by the AO system.

#### **2.6.1.6 Spatial sampling**

Nyquist sampled ( $\lambda/2D$ ) (0.004 arcsec)

#### **2.6.1.7 Spectral resolution**

$20000 \leq R \leq 100,000$

#### **2.6.1.8 Background**

The instrument should not increase the (inter-OH) background by more than 15% over natural sky (see Appendix 4) + telescope background (assume 5% emissivity at 273K).

### **2.6.1.9 Detector**

Detector dark current and read noise shall not increase the effective background by more than 5% for an integration time of 2000 s.

Discussion: In the 1-2.5 $\mu\text{m}$  region, dark current  $\leq 0.002$  e/s and read noise  $\leq 2e$  after multiple reads should be sufficient.

### **2.6.1.10 Throughput**

High throughput is a priority for this instrument

## **2.6.2 High-Resolution Optical Spectrometer (HROS)**

### **2.6.2.1 General description**

This instrument will provide high spectral resolution data in the optical range, suitable for detailed study of stars, quasars, and planet radial velocity programs.

### **2.6.2.2 Wavelength range**

0.31 $\mu\text{m}$ - 1.1 $\mu\text{m}$ , goal 0.31-1.3 $\mu\text{m}$

Discussion: working into the infrared is scientifically valuable, but CCD's cut off at 1.1 $\mu\text{m}$ . New detectors are needed to reach the long wavelength limit.

### **2.6.2.3 Field of view**

10 arcsec

### **2.6.2.4 Slit length**

A slit length of 5 arcsec is needed, with this separation between orders

### **2.6.2.5 Image quality**

Image quality in the detector should be no worse than 0.2 arcsec FWHM

### **2.6.2.6 Spatial sampling**

Sampling should be no coarser than 0.2 arcsec

### **2.6.2.7 Spectral resolution**

$R=50,000$  (1 arc-sec slit, image slicer for  $R \geq 90,000$ )

Options: single slit, fiber feed for multiplexing

### **2.6.2.8 Sensitivity**

Must maintain 30m aperture advantage over existing similar instruments.

## **2.6.3 Wide-field InfraRed Camera (WIRC)**

### **2.6.3.1 General description**

This near IR imager is envisioned to work behind the moderate field, diffraction-limited AO system (MCAO). It should provide superlative diffraction-limited images through a variety of filters, providing excellent photometric accuracy and high quality astrometric information.

### **2.6.3.2 Wavelength range**

0.8 $\mu\text{m}$ - 5 $\mu\text{m}$ , goal 0.6 $\mu\text{m}$ -5 $\mu\text{m}$

### **2.6.3.3 Field of view**

30 arcsec (contiguous, imaged at once)

#### **2.6.3.4 Image quality**

These are totally replaced by the MCAO image spec (make sure it is explicit about including the instrument wfe)

Uncorrectable wavefront errors should be TBD nm or some TBD fraction of total, or just say it's a fraction of the total and the AO system gets the complementary fraction. Or see AO

Comment: this needs to be coupled to the AO error budget

#### **2.6.3.5 Spatial sampling**

Nyquist sampled at the observing wavelength

Discussion: this need is clearly wavelength and field angle dependent

#### **2.6.3.6 Background**

The instrument should not increase the (inter-OH) background by more than 15% over natural sky (see Appendix 4) + telescope background (assume 5% emissivity at 273K).

#### **2.6.3.7 Spectral Resolution**

$R = 5-100$

Comment: the intent is to install narrow and broad band filters, that will be changed infrequently

#### **2.6.3.8 Throughput**

Keep it competitive- high throughput desirable, as high as possible, as good as best existing instruments, preserve the diameter advantage of telescope

#### **2.6.3.9 Repeatability, stability, flexure**

Allow mosaicing of multiple fields together with no more than TBD % image quality degradation

#### **2.6.3.10 Astrometry**

Over 30arcsec FoV degrade the theoretical astrometric precision by no more than 10% of the image size with a 100s integration. Multiple measurements should reduce the errors as  $t^{-1/2}$ .

### **2.7 Additional Instruments**

#### **2.7.1 GLAO Near-IR Multi-object Imaging Spectrometer**

##### **2.7.1.1 General description**

##### **2.7.1.2 Wavelength range**

0.7-2.5 $\mu$ m

##### **2.7.1.3 Field of view**

$\geq 5$  arcmin

##### **2.7.1.4 Image quality**

Really good

##### **2.7.1.5 Spatial sampling**

0.05-0.15 arcsec/pixel

**2.7.1.6 Spectral resolution**

R= 3000 – 6000

**2.7.2 Mid-IR Diffraction-limited Imaging Spectrometer**

**2.7.2.1 General description**

**2.7.2.2 Wavelength range**

5-28 $\mu$ m

**2.7.2.3 Field of view**

$\geq 2$  arcmin

**2.7.2.4 Image quality**

**2.7.2.5 Spatial sampling**

**2.7.2.6 Spectral resolution**

R= 5-100 (imager); 1000 (grism spectroscopy)

Special mode: coronagraphy with occulting disk and rotating Lyot stop

Emissivity limit?

**2.8 Data Handling**

**2.8.1 Data archiving**

**2.8.2 Data reduction pipelines**

**2.9 Nighttime operations models**

**2.9.1 Queue scheduling models**

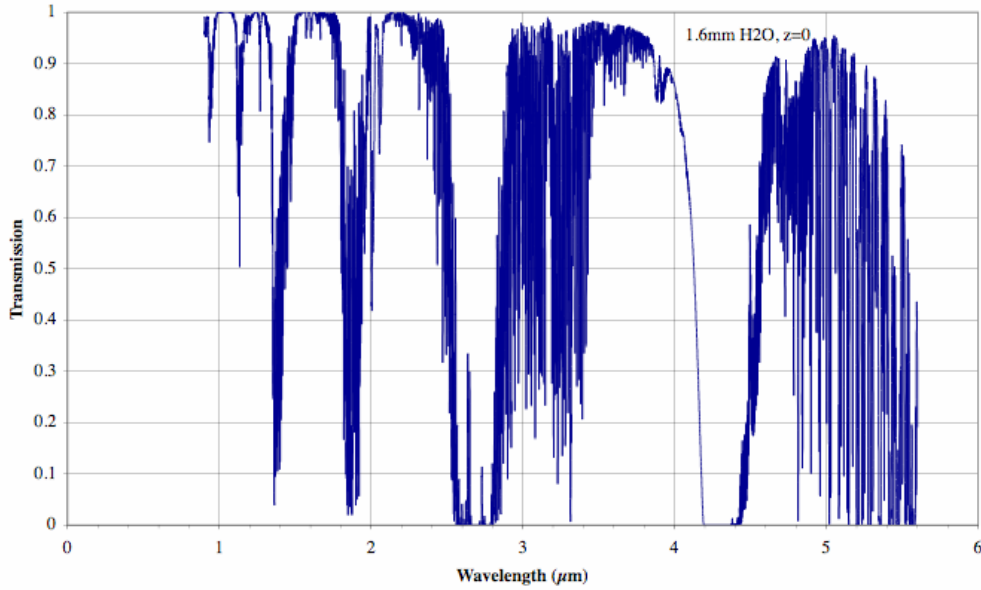
**2.9.2 Instrument Switching Requirement**

**2.9.3 PI mode observations**

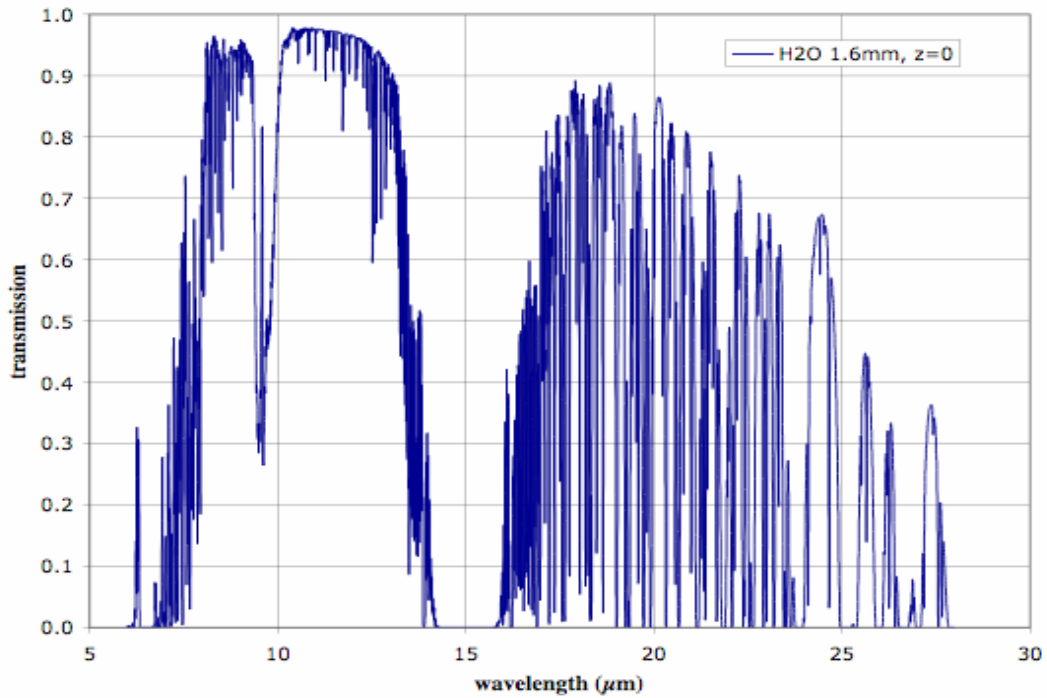
### 3 Appendices

#### Appendix 1: Atmospheric transmission for the summit of Mauna Kea

Atmospheric Transmission-MK



Atmospheric Transmission-MK

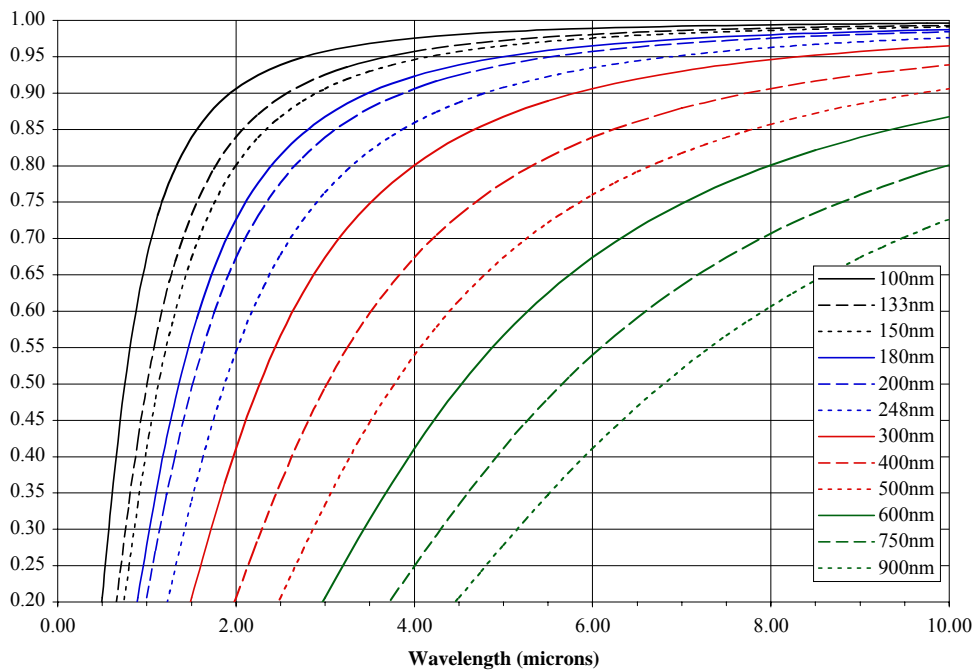


A ground-based telescope is limited in the wavelengths it can observe. This is set fundamentally by the transparency of the atmosphere, shown here. Different molecules cause the absorption features, and in the infrared, water is the dominant absorbing molecule. The amount of precipitable water is strongly dependent on site elevation; higher elevation sites will generally have better atmospheric transmission, particularly longward of  $10\mu\text{m}$ . We require that the telescope be functional with high throughput from  $0.31\mu\text{m}$  to  $30\mu\text{m}$ .

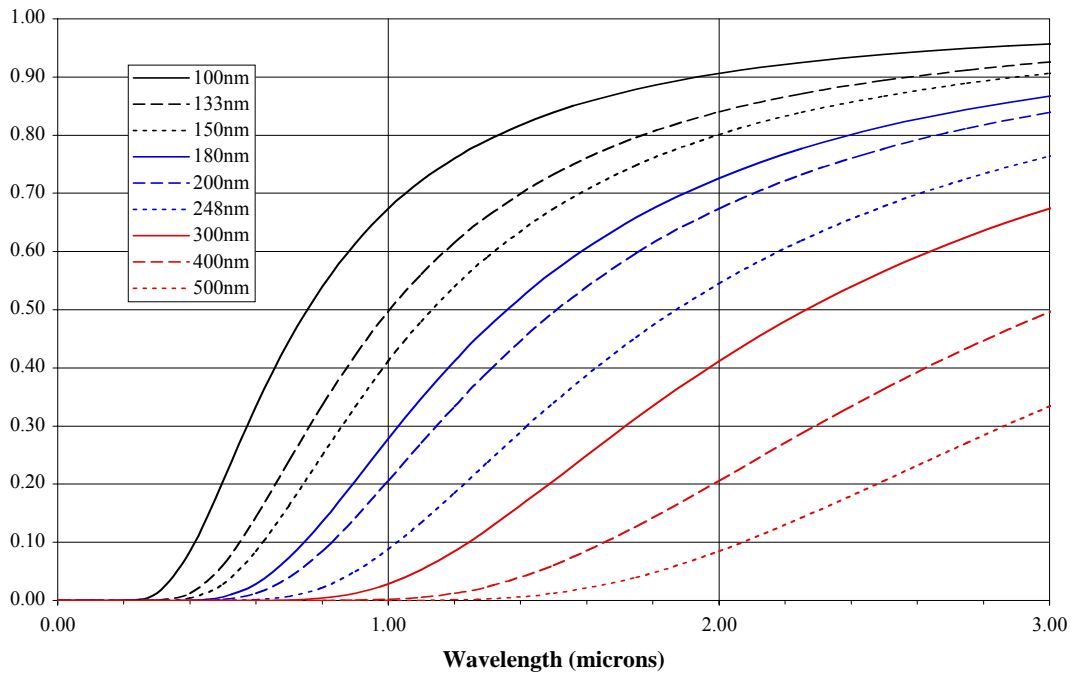
## Appendix 2: Strehl ratio for various wavelengths and wavefront errors

It is frequently useful to describe AO –achieved image quality by its Strehl ratio (S). The Strehl ratio is the image peak intensity divided by the maximum (diffraction-limited) peak intensity. For  $S > 0.2$  one can approximate S as  $\exp(-2\pi\sigma/\lambda)^2$  where  $\sigma$  is the rms wavefront error. Plots of this for a range of wavelengths and wavefront errors are shown below. For  $S > 0.2$  S is also an excellent approximation to the fraction of the PSF energy that is within the shape of a perfect diffraction-limited PSF.

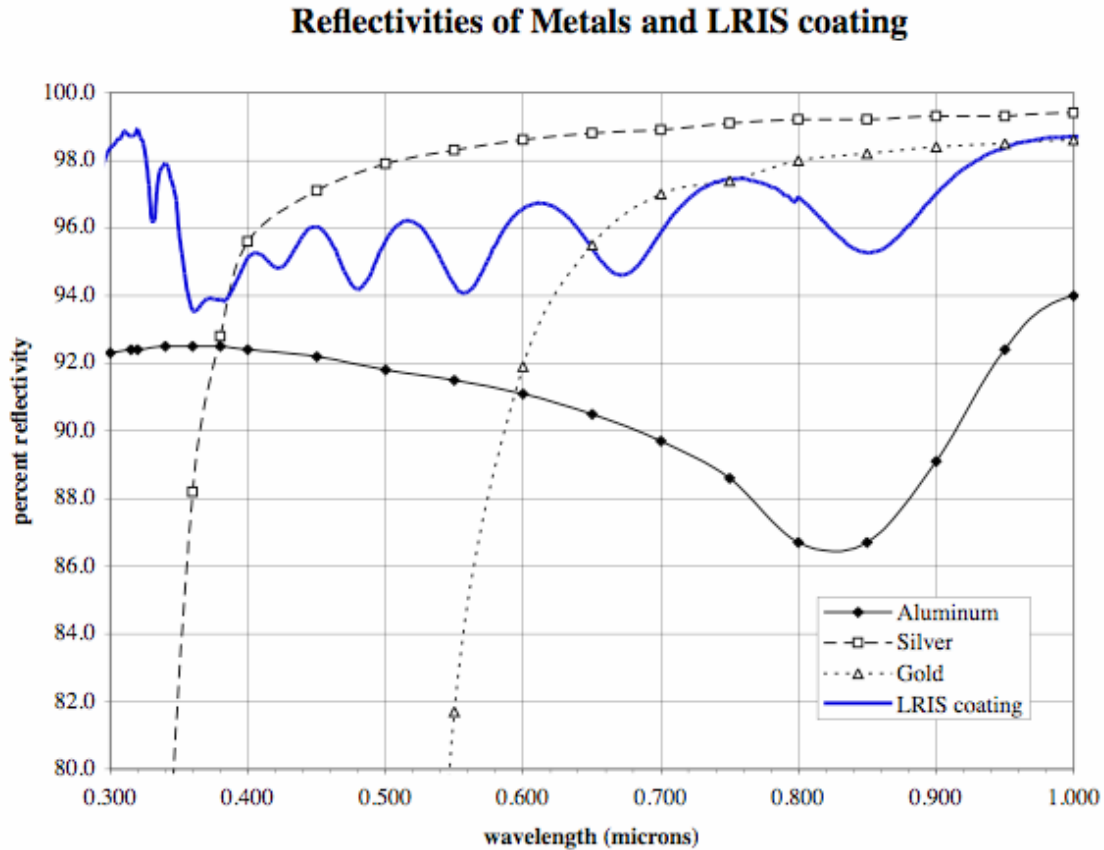
**Strehl ratio vs Wavelength**



### Strehl ratio vs Wavelength

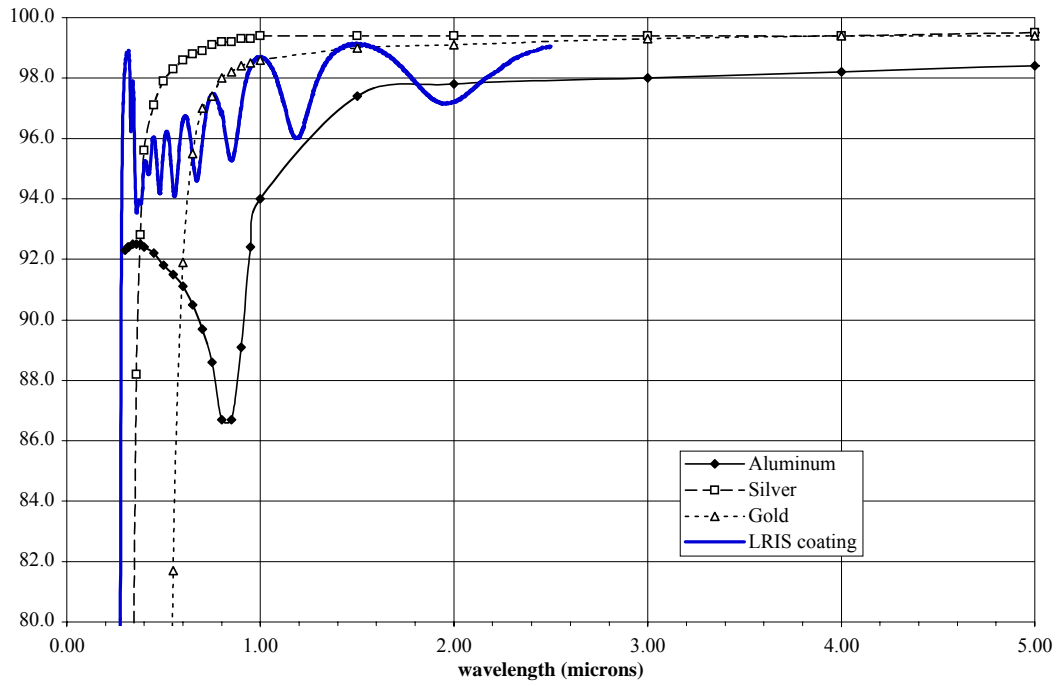


### Appendix 3: Reflectivities of Potential Mirror Coatings



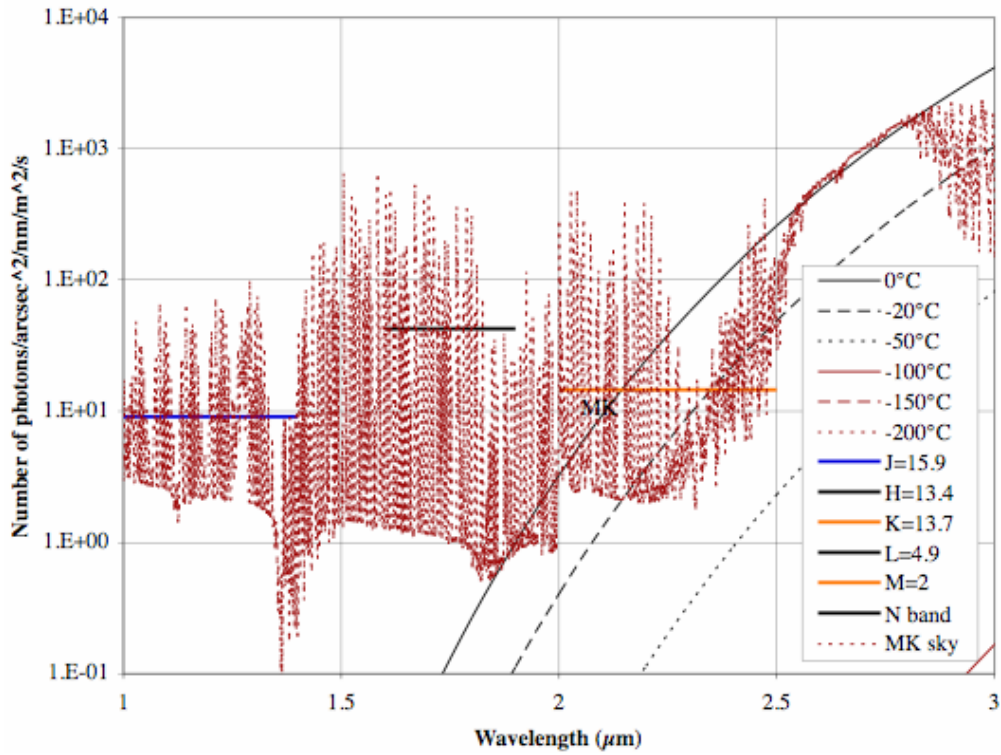
Mirror reflectivity is the most critical parameter limiting throughput. This figure shows the reflectivity of Aluminum, Silver, and Gold as a function of wavelength. Most large telescopes have their optics coated with Aluminum. Thus with a 3-mirror optical system, approximately 30% of the collected light is lost with Aluminum coatings. Recently developed multi-layer coatings have demonstrated >95% reflectivity from 300nm to 10  $\mu\text{m}$ . The Keck LRIS collimator coating developed by LLNL is shown in the figure. Coatings of this type will improve throughput by  $\sim 15\%$  and are essential for TMT.

### Reflectivities of Metals and LRIS coating



### Appendix 4: Sky and thermal backgrounds

Sky (MK) and Blackbody flux vs wavelength



## Appendix 5: Standard Atmosphere Assumptions

In order to define the AO performance requirements we define “Standard Conditions” under which the requirements should be met. When conditions differ from these, performance may be better or worse. The conditions are based on a Cerro Pachon profile believed to represent median conditions of the atmosphere at the selected site, and are given below (parameters are for a wavelength of 0.5 $\mu$ m)

$$T = 273^\circ$$

$$\text{Precipitable H}_2\text{O} = 1.5\text{mm}$$

$$r_0 = 0.15\text{m}$$

$L_0 = 25\text{m}$  (highly uncertain, will make image size  $\sim 15\%$  smaller than Kolmogorov atmosphere- see Tokovinin (2002))

$$\theta_0 = 2.46 \text{ arcsec}$$

$$\tau_0 = 3 \text{ ms}$$

$$\text{integrated } C_n^2 = 3.535\text{e-}13 \text{ m}^{1/3}$$

observations at the zenith

h(km)	% $C_n^2$
0	.646
1.8	.078
3.3	.119
5.8	.035
7.4	.025
13.1	.082
15.8	.015

$\theta_{\text{iso}} = 41 \text{ arcsec}$ . The isokinetic angle is the angular difference which produces an rms tip-tilt error of 7 milli-arcsec. The tip-tilt error grows approximately linearly with angular separation, depends on the  $C_n^2$  profile, the telescope diameter, and is wavelength independent.

$\tau_{\text{iso}} = 10\text{ms}$  The isokinetic time constant is the time it takes for the rms tip-tilt component to change by 7 milli-arcsec. This value is not well known and depends on details of the vertical wind profile as well as the diameter of the telescope. The rms tip-tilt error grows approximately linearly with delay time.

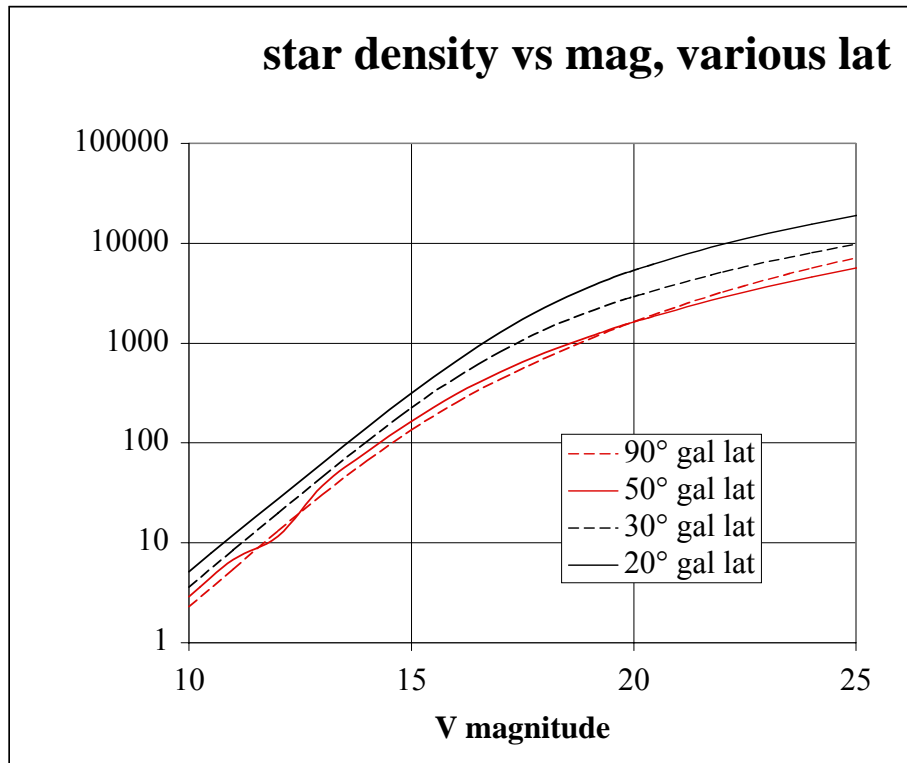
### Appendix 6: Star Densities for tip-tilt Stars

The use of laser beacons for measurements of atmospheric wavefront errors implies that any tip-tilt components in the atmosphere cannot be measured by the laser beacons and must be separately measured with natural stars (tip-tilt stars). Bahcall and Soniera (1981) give star densities in the V band and Spagna (2001) in J and K bands. They are given as a function of galactic latitude and longitude and as a function of magnitude.

Averaging over galactic longitude, the number of stars/deg<sup>2</sup> is tabulated below

V band star counts for several galactic latitudes (averaged over longitude)

magnitude	B=20	B= 30	B=50	B=90
12				1.31E+01
13				3.03E+01
14				6.67E+01
15				1.35E+02
16				2.53E+02
17				4.37E+02
18				7.09E+02
19				1.10E+03
20				1.64E+03
21				
22				3.26E+03



### **Appendix 7: Sky coverage with natural tip-tilt stars**

The use of laser beacons for measurements of atmospheric wavefront errors implies that any tip-tilt components in the atmosphere cannot be measured by the laser beacons and must be separately measured with natural stars (tip-tilt stars). Bahcall and Soniera (1981) give star densities in the V band and Spagna in J and K bands. They are given as a function of galactic latitude and longitude and as a function of magnitude.

## **Appendix 8: Astrometric Considerations**

Additional requirements on the architecture of an MCAO imager used for astrometry

An astrometric MCAO system must constrain Zernike modes 4-6 using either a single natural guide star (NGS) which is bright enough to sense defocus and astigmatism or provide two additional tip-tilt stars, making their total number 3. The differential tilts between the three tip-tilt stars constrain these modes. This requirement occurs because the tip and tilt of laser guide stars (LGS) are undetermined. As a consequence, the information brought by them is insufficient for a full solution of the tomographic problem. In addition to tip and tilt, differential astigmatism and defocus between the two DMs is unconstrained. These three unconstrained modes do not influence on-axis image quality, but produce differential tilt between the different parts of the field of view.

If multiple tip-tilt sensors are used, the MCAO system must provide for a facility to align them. If the tip-tilt sensors for the three NGSs are misplaced, the MCAO system will compensate these errors in the closed loop, hence the field will be distorted. For example, the plate scale will change if the upper DM has a static defocus. Calibration procedures must be applied to ensure that these errors do not compromise the astrometric performance of an MCAO system (e.g., flattening of the upper DM before closing the loop).

To ease the astrometric challenge, the static distortions in the field of view should be under 10% (goal 1%).

The limitations on astrometric accuracy imposed by the atmosphere are discussed in detail in TMT technical report #XX (Graham 2003).

## Appendix 9: Atmospheric Dispersion

The index of refraction of the atmosphere at Mauna Kea is well approximated by the formula

$$n(\lambda) = 1.0001702 + 9.32 \times 10^{-7} \lambda^{-2.102}$$

$$\frac{dn}{d\lambda} = -1.959 \times 10^{-6} \lambda^{-3.102}$$

where  $\lambda$  is the wavelength in units of  $\mu\text{m}$ . (Nelson, 1994, Atmospheric Refraction at Mauna Kea, Keck Technical Note 400)

At different sites the index of refraction ( $n-1$ ) will be proportional to the air density.

The atmosphere disperses light entering away from the zenith ( $z =$  zenith angle) and the length of this image blur is given by

$$\Delta\theta = \frac{dn}{d\lambda} \Delta\lambda \tan z$$

In the table, assuming Mauna Kea, we give the dispersive blur within various atmospheric windows of interest, evaluated for a zenith angle of  $45^\circ$ . We also list the diffraction limited image size ( $\lambda/D$ ) and compare them. When the dispersed image is larger than the diffraction limit, atmospheric dispersion compensation (ADC) will be useful. When this ratio is less than 1, it can probably be omitted, depending on the actual error budget of the system under consideration.

band	wavelength ( $\mu\text{m}$ )	full width ( $\mu\text{m}$ )	dispersive blur (arcsec)	diffraction $\lambda/D$ (arcsec)	blur/diff
U	0.365	0.068	-0.6262	0.0025	-249.54
B	0.440	0.098	-0.5055	0.0030	-167.09
V	0.550	0.090	-0.2323	0.0038	-61.44
R	0.700	0.220	-0.2688	0.0048	-55.85
I	0.900	0.240	-0.1345	0.0062	-21.73
J	1.250	0.380	-0.0768	0.0086	-8.94
H	1.680	0.300	-0.0242	0.0116	-2.10
K	2.200	0.480	-0.0168	0.0151	-1.11
L	3.400	0.700	-0.0064	0.0234	-0.27
M	4.770	0.460	-0.0015	0.0328	-0.04
N	10.470	5.200	-0.0014	0.0720	-0.02

## Appendix 10: Enclosed energy of images from a Kolmogorov Atmosphere

A Kolmogorov model of the atmosphere is often considered a useful approximation to the real complexities of the atmosphere. The basic imaging performance of such an atmosphere can be derived from a single parameter, the Fried parameter  $r_0$ . Excellent astronomical sites can have median atmospheric conditions with  $r_0 = 0.15$  m. We have set our overall observatory image quality requirement in this language, and specified it as  $r_0 = 0.8$ m.

In order to understand the implication of this specification, we calculate the PSF and the enclosed energy functions for this atmosphere.

The MTF is given by

$$MTF(f) = \exp[-(f / f_0)^{5/3}]$$

where  $f_0 = \frac{r_0}{2.1\lambda}$  and  $\lambda$  is the observing wavelength.

and the point spread function is given by

$$PSF(\theta) = K \int_0^{\infty} J_0(2\pi f\theta) MTF(f) f df$$

and the enclosed energy is given by

$$EE(\theta) = 2\pi \int_0^{\theta} PSF(u) u du$$

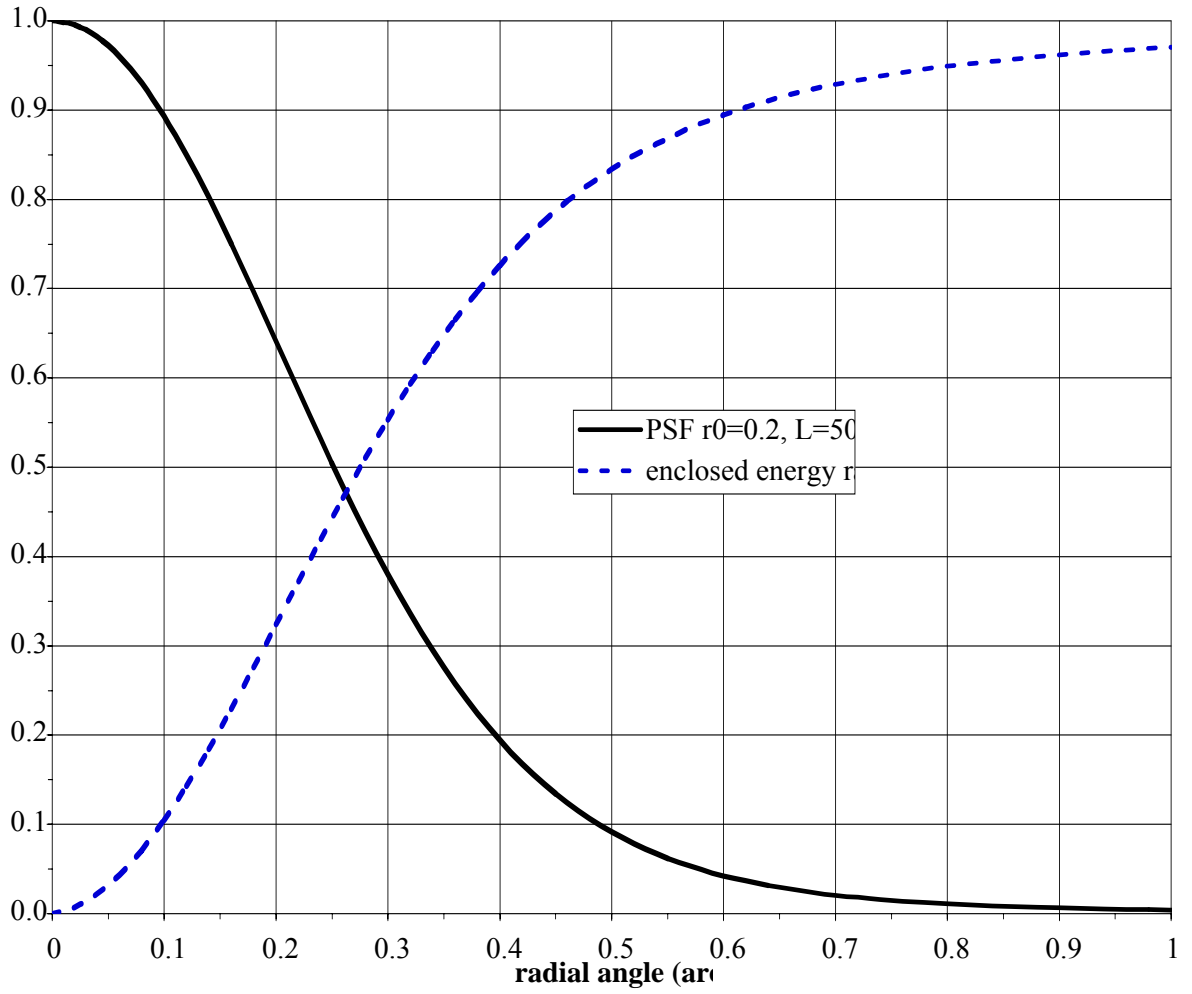
Furthermore, these functions will scale inversely with  $r_0$ . Doubling  $r_0$  will halve the image size. For a given  $r_0$  at a given wavelength, changing wavelength will change  $r_0$ , and thus the image size. The image size produced by a Kolmogorov atmosphere varies as

$$\frac{\theta}{\theta_0} = \left(\frac{\lambda}{\lambda_0}\right)^{-1/6}$$

In the figure we show the PSF and the radius of the circle that encloses a given fraction of the total energy in the image. These are generated for  $r_0 = 0.2$ m, and can be readily scaled to any other value of  $r_0$ .

More details about these equations and related ones can be found in Mast (1992, KOTN 331)

### Image PSF and EE for Kolmogorov $\epsilon$



## **References**

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