SCIENCE REQUIREMENTS DOCUMENT

TMT.PSC.DRD.05.001.CCR25

April 27, 2021

SIGNATURE PAGE

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

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Document Change Record

Revision	Change Request Approval	Release Approval	Date Released
CCR25	Released per: CR355: Collection-28559 CR357: Collection-28650	G. Trancho, Routing #75605	April 27, 2021
CCR24	Released per: CR321: Collection-25545 CR296: Collection-22983 CR ADMIN	G. Trancho, Routing #62618	May 11, 2020
CCR23	Released per: CR243: Collection-19722	S. Roberts, Routing #44150	November 29, 2018
CCR22	Released per: CR198: Collection-12467 Admin Changes: AD/RD updates and Cover Page	S. Roberts , Routing #14755	March 28, 2017
CCR21	Released per: CR196: Collection-12344 (L1 Telescope Move Time Requirements)	see approval page in CCR21	May 20, 2016
CCR20	Released per: CR141: Collection-8422	see approval page in CCR20	December 11, 2014
CCR19	Released per: CR117: Collection-6630 **Summary of Changes to Previous Versions** (Scientist's Notes): see https://docushare.tmt.org/docushare/dsweb/Get/Document-32880/	see approval page in CCR19	July 5, 2013
CCR18	· Exec Summary, Section 1 & Table 1: Instrument capabilities now consistent with Section 2 · Section 2.1.3.1: Requirement on small motions being often required rewritten, moved to 2.1.3.5 named [REQ-0-SRD-0280	see approval page in CCR18	January 16, 2009

	· Section 2.6.2.10: [REQ-0-SRD-1445] rewritten · Section 2.6.3.4: [REQ-0-SRD-1510] rewritten · All: V17.5 will henceforth be known as CCR18 to comply with the TMT document numbering system. Future versions of the SRD will follow the RELXX numbering system. · Appendix 7: Revised version of Appendix 7 · All: Miscellaneous typos and formatting · Exec Summary: Clarified 5 yr AO capability · Section 1.3: Clarified 5 yr AO capability · Section 1.4: Added proper King reference · Section 2.1.2.2: Allowed 20% reduction in science · Section 2.1.2.5: Replaced 281° with ambient temperature · Section 2.2.3: Replaced maximize with science opportunities, etc · Section 2.4.2.1: Describes natural guide star requirements but does not give a req # (this is handled in 2.4.2.10.2) · Section 2.4.2.4: Question about 190 nm with tilt removed · Section 2.4.2.10.2: Added 16.5 mag req for K band Strehl of 0.5		
17.5	• “Traceability” update completed: -Text of the SRD has been decomposed into requirements and discussions -Requirements have been added Extensive MS Word reformatting with standard TMT document templates and styles		December 1, 2008
17.5		J. Nelson, C. Steidel	September 8, 2008
17.2		J. Nelson	March, 2008
17.0		J. Nelson	October 8, 2007
16.4		J. Nelson	May 14, 2007
15.0		J. Nelson	2005

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1 EXECUTIVE SUMMARY

1.1 SUMMARY

This document describes the science-driven requirements for the Thirty-Meter Telescope (TMT) project. TMT will be one of 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, 8-10 m telescopes have produced critical scientific discoveries and often have 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 similarly complement future observatories both on the ground and in space. In 2010, the National Academy of Sciences (NAS) released its Astro2010 report, *New Worlds, New Horizons in Astronomy and Astrophysics*, (RD1), which also stresses that a Giant Segmented Mirror Telescope (GSMT) providing spectroscopic and high-resolution imaging capabilities is crucial for the future of ground-based astronomy, together with the Large Synoptic Survey Telescope (LSST), now the Rubin Observatory.

Responding to the Decadal Survey report, TMT is a 30-meter aperture facility with broad capabilities operating over the wavelength range 0.3 - 30 µm. TMT provides 9 times the collecting area of the current largest optical/IR telescopes and, using adaptive optics, will provide spatial resolution 12.5 times sharper than the Hubble Space Telescope and 3 times sharper than the largest current-generation O/IR telescopes. For many applications, diffraction-limited observations provide gains in sensitivity that scale like D^4 (where D is the primary-mirror diameter); thus, TMT will provide a sensitivity gain of a factor more than 100 as compared to current 8 m telescopes.

By design, TMT will provide new science opportunities in essentially every field of astrophysics. Furthermore, as has been the case historically when observational sensitivity improves by a large factor, the scientific impact of TMT will go far beyond what we envision today; 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 ~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 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 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. Studies of the matter power spectrum on small spatial scales, using direct observations of distant galaxies and the intergalactic medium, 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 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 play an important role 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 broad science goals have motivated a set of science-driven observatory capabilities and requirements that are described in this document, representing the consensus view of the Science Advisory Committee and the Project Scientist, after consultation with many expert engineers and scientists within the broad TMT community. The SAC has recommended an “early light” instrument suite that is intended to be commissioned with the telescope or very soon after. A larger set of instruments and capabilities are intended to be delivered within the first decade of TMT operation are also recommended; these “first decade” capabilities are subject to revision as astrophysics and technology advance. Essentially all science requirements in this document have undergone several iterations between astronomers and technical/engineering experts to ensure that they are both ambitious and technically feasible. Requirements are subject to change as more is learned about the cost impact and technical feasibility of meeting them. An ongoing dialog between the SAC and the TMT Project is maintained to ensure that science and engineering realities are appropriately balanced.

1.2 BACKGROUND AND MOTIVATION

The Thirty Meter Telescope (TMT) project is intended as 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 30 m 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 astrophysics in the coming decades.

1.3 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). To accommodate the science 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 the “Detailed Science Case” (RD3). In identifying the highest priority capabilities of TMT, the ability to carry out the programs described in the science case document has been carefully considered; however, 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 10 m 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. Thus, the TMT science requirements are also cognizant of the broad capabilities anticipated to open a large “discovery space”.

A final major consideration in the SAC deliberations has been complementarity to planned and anticipated 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 2.4 m Hubble Space Telescope and spectra from the largest ground-based telescopes. However, the current generation of 8 and 10 m telescope will be unable to provide spectra of faint sources discovered with a 6 m 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).

1.4 PRIORITIES

The capabilities and AO/instrument concepts described in the SRD have been prioritized into two groups, ordered by SAC consensus after considering scientific breadth, perceived "discovery space", technical risk, and finite budgets. The SAC recommends that all of the capabilities described here should be implemented in the first decade of TMT operation. The subset of first-light 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 initial 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 science and technical risk) that initially, up to 50% of the time the telescope may be used for seeing-limited observations. 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 this document, and briefly summarized below (see also Table 2-1).

1.4.1 FIRST LIGHT CAPABILITIES

- Near-IR Adaptive Optics System (NFIRAOS): A dual-conjugate (MCAO) system provides diffraction-limited images over the wavelength range 0.8 - 2.5 μm over a 30 arcsec field, and partially-corrected images over a > 2 arcmin field.
- InfraRed Imaging Spectrometer (IRIS): Diffraction-limited, R ~ 4000 spectral resolution, 0.8 μm to 2.5 μm spectroscopy (utilizing an integral field unit (IFU)) over a small field, and an imager covering a field of view of > 15 arcsec. IRIS is behind the NFIRAOS AO system.
- Wide-field Optical Spectrometer (WFOS): Seeing-limited multiplexed 1000 < R < 6000 spectral resolution, 0.31 - 1 μm spectroscopy over a wide (~ 40 arcmin^2) field.
- Multi-Objective Diffraction-limited High-Resolution Infrared Spectrograph (MODHIS): Diffraction-limited 0.95 μm to 2.4 μm spectroscopy, with R ~ 100,000, of up to 8 objects in a 5 arcsec radius field of view. MODHIS is behind the NFIRAOS AO system.

1.4.2 FIRST DECADE CAPABILITIES

- 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 μm region. For bright stars (I < 8) PFI detects planets 10^8 times fainter than the parent star, with a goal of 10^9, at angular distances greater than 50 mas from the star.
- Mid-IR High-resolution Echelle Spectrometer (MIRES): Diffraction-limited, 5000 < R < 100,000 spectral resolution, 8 - 28 μm spectroscopy. MIRES also has a mid-IR imaging/slit viewing capability.
- Near-IR High-resolution Echelle Spectrometer (NIRES-R): Diffraction-limited, high-spectral-resolution (R ~100,000) echelle spectroscopy in the 2.9 - 5 μm range. NIRES operates behind an adaptive optics system appropriate to the wavelength range.
- High-resolution Optical Spectrometer (HROS): spectroscopy with R < 50,000 for wavelengths ranging from the atmospheric cutoff at 0.31 μm to 1 μm (or longer if detectors exist that allow it) with wide spectral coverage in a single exposure. This capability is likely achieved via a large, echelle spectrometer.
- InfraRed Multi-Object Spectrometer (IRMOS): near-diffraction limited, R ~ 2000 - 10000 IFU-based spectrometer operating over a wavelength range 0.8 - 2.5 μm. IRMOS uses multiple IFUs to access a 5 arcmin diameter field. It is expected to benefit from developments in multi-object adaptive optics (MOAO).

1.5 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 μm), 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 μm, the atmosphere is relatively transparent, but a forest of extremely bright OH emission lines produced in the upper atmosphere dominates the terrestrial background. For broad-band observations (e.g., imaging), the night sky is approximately 600 times brighter per unit solid angle at 1 - 2.5 μm as compared to 0.4 μm.

However, using adaptive optics, the typical image quality for a point source can be improved from ~ 0.5 arc seconds in "seeing limited" mode, to ~ 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 ~ 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 - 10 m telescopes to a 30 m aperture will increase the sensitivity by a factor of 80 - 400 for some types of observations.

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

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

where background/arcsec^2 includes sky, telescope, optics, and detector dark current; throughput is the fractional throughput from the primary to the detected photons; and S is the Strehl ratio (the fraction of light in the diffraction-limited core of the image).

If we consider the science productivity of the telescope as a key parameter, a relatively simple approach to optimization can be used. Since many observations are limited by the background flux, not by the signal flux, the point source sensitivity (proportional to the science productivity) in this case can be shown (King 1983, RD2) to be

$$\mathrm{PSS} = \frac{1}{\mathrm{ENA}} = \int \mathrm{PSF}^2 d\Omega$$

where PSS = point source sensitivity
ENA = equivalent noise area
PSF = point spread function ($\int \mathrm{PSF} d\Omega = 1$)

This metric scales as 1/(image size)^2 or, with adaptive optics ~ S^2.

1.6 SUMMARY TABLE OF CAPABILITIES: FIRST-LIGHT + FIRST DECADE

Table 2-1 Instrument Capabilities

Function/Name	λ Range (µm)	Modes
IRIS/Diffraction-Limited NIR Imager and IFS	0.84–2.4 0.6 – 5 (goal)	NGSAO, LGS MCAO
WFOS/Wide Field Optical Spectrometer	0.31–1.0 0.3 – 1.5 (goal)	SL, GLAO
MODHIS/Multi-Objective Diffraction-Limited High-Resolution Infrared Spectrograph	0.95–2.4	NGSAO, LGS MCAO
PFI/Planetary Formation Instrument	1 – 2.5 1 – 5 (goal)	ExAO
MIRES/mid-IR AO fed Echelle Spectrometer	8 - 28	MIRAO
NIRES-R/Near IR AO-fed Echelle Spectrometer	2.9-5	MIRAO
HROS/High-Resolution Optical Spectrograph	0.31–1 0.31–1.3 (goal)	SL, GLAO
IRMOS/IR Multi-Object Spectrograph	0.8–2.5	MOAO

2 INTRODUCTION

2.1 SCOPE

This document contains science requirements in the following areas:

- General Constraints
- Telescope and Instrumentation Requirements
- Adaptive Optics Requirements
- First-light Instrumentation Requirements
- First-Decade Instrumentation Requirements

2.2 APPLICABLE DOCUMENTS

N/A

2.3 REFERENCE DOCUMENTS

RD1 New Worlds, New Horizons in Astronomy and Astrophysics (2010), The National Academies Press (2010)

https://www.nap.edu/catalog/12951/new-worlds-new-horizons-in-astronomy-and-astrophysics

RD2 Accuracy of measurement of star images on a pixel array by King, I. R.

PASP Vol. 95:163-168,

Number 564

http://iopscience.iop.org/article/10.1086/131139?fromSearchPage=true

RD3 Detailed Science Case (DSC)

TMT.PSC.TEC.07.007

https://docushare.tmt.org/docushare/dsweb/Get/Document-32176

RD4 Guide Star Requirements for NGST: Deep NIR Starcounts and Guide Star Catalogs by Spagna, A.

STScI-NGST-R-0013B

http://adsabs.harvard.edu

RD5 The universe at faint magnitudes. I - Models for the galaxy and the predicted star counts by Bahcall, J. N., & Soneira, R. M.

Astrophysical Journal Supplement Series, vol. 44, p. 73-110

http://adsabs.harvard.edu/abs/1980ApJS...44...73B

RD6 Keck Observatory Technical Note No. 400 - Atmospheric Refraction at Mauna Kea

TMT.SEN.TEC.17.006

KECK TN400

https://docushare.tmt.org/docushare/dsweb/Get/Document-61336

RD7 A synthetic view on structure and evolution of the Milky Way

TMT.SEN.JOU.17.002

A&A 409, 523-540

https://docushare.tmt.org/docushare/dsweb/Get/Version-61736

RD8 Keck Observatory Technical Note No. 331 - Point Spread Functions in Astronomy

TMT.SEN.TEC.17.019

https://docushare.tmt.org/docushare/dsweb/Get/Document-61802

2.4 ABBREVIATIONS

Acronym	Definition
ADC	Atmospheric Dispersion Corrector
ALMA	Atacama Large Millimeter Array
AO	Adaptive Optics
AOS	AO System
CCD	Charge Coupled Device
CELT	California Extremely Large Telescope
DM	Deformable Mirror
DSC	Detailed Science Case
EE	Enclosed Energy
FOV	Field of View
FWHM	Full Width at Half Maximum
GLAO	Ground-Layer AO
GSMT	Giant Segmented Mirror Telescope
HROS	High Resolution Optical Spectrograph
IFU	Integral Field Unit
IR	InfraRed
IRIS	Infrared Imaging Spectrometer
IRMOS	Infrared Multi-Object Spectrograph
JWST	James Webb Space Telescope
LGS	Laser Guide Star
LLNL	Lawrence Livermore National Laboratory
LRIS	Low Resolution Imaging Spectrograph
MCAO	Multi-Conjugate Adaptive Optics
MIRAO	Mid InfraRed Adaptive Optics
MIRES	Mid-Infrared Echelle Spectrograph
MK	Mauna Kea
MOAO	Multi-Object Adaptive Optics
MOSFIRE	Multi-Object Spectrometer for Infra-Red Exploration
NASA	National Aeronautics and Space Administration
NFIRAOS	Narrow Field Infrared Adaptive Optics System
NGS	Natural Guide Star
NGST	Next Generation Space Telescope
NIR	Near-Infrared
NIRES	Near Infrared Echellette Spectrograph
NSF	National Science Foundation
OH	Oxygen-Hydrogen Radical
PFI	Planet Formation Instrument
PSF	Point Spread Function
PSS	Point Source Sensitivity
RMS	Root Mean Square
SAC	Science Advisory Committee
SNR	Signal to Noise Ratio
SRD	Science Requirements Document
STScI	Space Telescope Science Institute
TBC	To Be Confirmed
TBD	To Be Defined or To Be Determined or To Be Done
TMT	Thirty Meter Telescope
UV	Ultraviolet

VLOT	Very Large Optical Telescope
WFOS	Wide Field Optical Spectrograph
WFS	Wavefront Sensor

3 SCIENCE REQUIREMENTS

3.1 SITE

3.1.1 KEY ASTRONOMICAL FEATURES

[REQ-0-SRD-0400] The site shall have a high fraction of clear nights.

[REQ-0-SRD-0405] The site shall have excellent image quality (large r_0, easier to achieve AO performance).

[REQ-0-SRD-0410] The site shall have a large isoplanatic angle (larger field of view for AO).

[REQ-0-SRD-0415] The site shall have long coherence time of atmosphere (easier for AO).

[REQ-0-SRD-0420] The site shall have smaller outer scale (L_0, improved image quality, easier AO).

[REQ-0-SRD-0425] The site shall have high fraction of spectroscopic nights.

[REQ-0-SRD-0430] The site shall have low precipitable water vapor distribution (lower IR absorption).

[REQ-0-SRD-0435] The site shall have low typical temperatures (lower thermal background).

[REQ-0-SRD-0440] The site shall have high altitude (transparency, low water vapor, low temperature, smaller atmosphere dispersion).

3.1.2 OTHER PERFORMANCE RELATED FEATURES

[REQ-0-SRD-0455] The site shall have low wind speed distribution to limit telescope buffeting.

[REQ-0-SRD-0460] The site shall have minimal change of temperature during the night (telescope and instrument athermalization).

[REQ-0-SRD-0465] The site shall have minimal seasonal temperature variations.

[REQ-0-SRD-0470] The site shall have minimal day-night temperature variations.

[REQ-0-SRD-0475] The site shall have a latitude (science opportunities) complementary with existing or future observatories.

3.1.3 COST RELATED FEATURES

[REQ-0-SRD-0480] The site shall have easy physical access for minimizing construction costs.

[REQ-0-SRD-0485] The site shall have good human access for minimizing operating costs.

[REQ-0-SRD-0490] Unrestricted access to the chosen site shall be available.

3.1.4 OTHER ENGINEERING/SAFETY FEATURES

[REQ-0-SRD-0495] The site shall have a high mechanical integrity of soil.

[REQ-0-SRD-0500] The site shall have a low seismicity.

3.1.5 ASSUMED MODEL ATMOSPHERE

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

3.2 ENCLOSURE

3.2.1 OPENING SIZE AND TRACKING

[REQ-0-SRD-0550] The enclosure opening shall not vignette light from the science field or from laser guide stars.

[REQ-0-SRD-0555] The enclosure motion shall follow motion of the telescope precisely enough that the science field and laser guide stars are not vignetted by the dome.

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

3.2.2 SLEWING

[REQ-0-SRD-0560] Enclosure motions shall not delay the beginning of scientific observations.

3.2.3 WIND PROTECTION

[REQ-0-SRD-0565] The enclosure shall 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.

[REQ-0-SRD-0570] The telescope shall meet its image quality specification when integrating over the wind speed probability distribution.

[REQ-0-SRD-0575] The enclosure shall minimize the amplitude and temporal frequency of wind forces.

3.2.4 THERMAL CONTROL AND LOCALLY INDUCED SEEING

[REQ-0-SRD-0580] Thermally induced seeing degradation caused by temperature differences shall be minimized by a suitable combination of natural ventilation, insulation, surface emissivity, 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.

3.2.5 WEATHER PROTECTION

[REQ-0-SRD-0585] The enclosure shall protect the telescope against adverse weather and daytime air leakage.

Discussion: Water and ice should not be allowed into the enclosure interior.

[REQ-0-SRD-0590] The observatory shall prevent condensation on the optics.

[REQ-0-SRD-0595] The enclosure shall prevent liquid drips on the primary mirror.

[REQ-0-SRD-0600] At night, the enclosure shall be operable at all times in good weather.

[REQ-0-SRD-0605] The enclosure shall minimize the buildup of snow and ice and provide for easy removal of snow and ice to allow for observing after storms.

[REQ-0-SRD-0610] The enclosure shall minimize daytime heat infiltration.

3.2.6 DUST PROTECTION

[REQ-0-SRD-0615] The observatory shall protect against accumulation of dust on the telescope and subsystems.

Discussion: This is to avoid problems of stray light and increased emissivity caused by accumulation of dust on the telescope optics. For example, this could be achieved 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.

3.2.7 OPENING AND CLOSING

[REQ-0-SRD-0620] The enclosure shall open or close in under 2 minutes to protect against sudden changes in weather.

3.2.8 SERVICING

[REQ-0-SRD-0625] The observatory shall provide suitable servicing facilities for the telescope, optics, AO, and instruments.

3.3 TELESCOPE

3.3.1 GENERAL DESCRIPTION

[REQ-0-SRD-0010] The observatory shall enable science over the wavelength range of 0.34 µm - 28 µm, with a goal of 0.31 µm.

Discussion: Wavelength limitations due to the atmosphere are given in Appendix A.

[REQ-0-SRD-0015] The observatory shall provide seeing-limited observations for 50% of the time, and diffraction-limited observations (using AO) for 50% of the time.

Discussion: This is based on current scientific interest and technology limitations. AO with laser beacons is 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 increase.

3.3.2 OPTICAL

3.3.2.1 OPTICAL CONFIGURATION

[REQ-0-SRD-0045] The telescope shall have a segmented primary mirror with entrance pupil equivalent to 30 m diameter.

[REQ-0-SRD-0050] The telescope optics shall be aplanatic with 20 arcmin field of view, 15 arcmin unvignetted.

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

Discussion: Prime focus is not required; 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.

Discussion: Cassegrain focus is not required; Nasmyth focus provides needed function with greater convenience (and acceptable light loss).

Discussion: Nasmyth focus provides needed function with greater convenience (and acceptable light loss)

[REQ-0-SRD-0065] The telescope shall provide multiple Nasmyth foci on two large Nasmyth platforms with size at least 350 m^2 each and ability to place multiple instruments per platform.

Discussion: It is desirable to have access to all Nasmyth instruments on any given night, thus platforms need to accommodate all planned instruments.

3.3.2.2 IMAGE AND WAVEFRONT QUALITY

[REQ-0-SRD-0070] The telescope image quality shall not degrade the science capability by more than 20% compared to a perfect telescope at the same site.

Discussion: The telescope image quality specification encompasses many effects, including those from optics, collimation, guiding, auto focus, wavefront sensing, wind, mirror and dome seeing.

Science capability (units of science/hr) for seeing-limited work is defined for background limited point sources, where science capability ~ $1/\theta^2$ and θ is the image size. This follows directly from

$$S/N \sim \frac{D^2 t}{\sqrt{D^2 t \theta^2}} \sim \frac{D t^{1/2}}{\theta}$$

where θ, the image size (PSF), determines how much background flux must be included in the S/N estimate. Here D is the telescope diameter, t is the integration time, and S/N is the achieved signal to noise ratio. Hence, we integrate over all site conditions (for our reference site) in interpreting this requirement on telescope-induced image blur. We assume that the 80% enclosed energy image diameter is a suitable measure of image size. If we assume the telescope behaves like an equivalent atmosphere, this leads to the telescope having an equivalent r_0 = 0.8 m. This in turn leads to a θ_{80} = 0.237 arcsec. The ADC and instrument rotators have a separate specification and are not included here. The PSF and enclosed energy curves from the median atmosphere are shown in Appendix I for reference.

[REQ-0-SRD-0075] The telescope wavefront errors shall be smooth and small compared to the site median atmosphere.

[REQ-0-SRD-0110] Image blur shall degrade with zenith angle at a rate up to $(\sec(z))^{3/5}$.

Discussion: This degradation with zenith angle follows the same rate as the atmosphere.

[REQ-0-SRD-0115] Wavefront errors shall degrade with zenith angle at a rate up to $(\sec(z))^{1/2}$.

Discussion: This degradation with zenith angle follows the same rate as the atmosphere.

3.3.2.3 ATMOSPHERIC DISPERSION COMPENSATION (ADC)

[REQ-0-SRD-0120] The observatory shall provide atmospheric dispersion compensation, applied either by the AO system or instrument, as agreed.

Discussion: Dispersion in the index of refraction of the atmosphere causes image blur for observations made away from the zenith. Atmospheric dispersion requiring compensation is described in Appendix H. Specific ADC requirements vary with instruments.

3.3.2.4 THROUGHPUT

[REQ-0-SRD-0125] Mirror reflectivity shall be as good as any broadband coatings available.

[REQ-0-SRD-0135] Blockage of the full aperture by structure only shall be ≤ 2.5%.

Discussion: Thin members 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. This requirement doesnt include the blockage generated by M2.

[REQ-0-SRD-0140] To the extent practical, blockages shall be simple in shape so they can be masked out by cold pupil stops.

3.3.2.5 BACKGROUNDS AND STRAY LIGHT

[REQ-0-SRD-0145] Baffling shall be provided by the instruments and AO systems as required by the science cases, and in addition small baffles shall be provided around the clear aperture of the M2 and M3.

Discussion: Stray light is a potential problem for science observations. This may be mitigated by small M2 and M3 baffles and by instrument baffles.

[REQ-0-SRD-0150] Thermal background radiation from the telescope and their primary, secondary, and tertiary mirrors shall be ≤ 7% of a blackbody at the average ambient night-time temperature for fresh coatings.

Discussion: At wavelengths longer than about 2 µm, the thermal emission of the telescope optics can dominate the natural sky background.

[REQ-0-SRD-0155] The observatory shall provide means for re-coating of the telescope optics to maintain throughput and minimize thermal emission.

[REQ-0-SRD-0160] The secondary support structure optical cross section shall be minimized to reduce thermal background.

Discussion: Beyond these measures, it may be necessary to cool 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 D.

3.3.3 MOTION

3.3.3.1 SLEWING AND ACQUIRING

[REQ-0-SRD-0200] The observatory shall move from any point in the sky to any other and be ready to begin observing in less than 3 minutes.

Discussion: This time includes time needed to rotate the instrument, rotate the dome, acquire a guide star, and set up the ADC and AO system. For the telescope this includes moves that may be as much as 360° in azimuth. This implies maximum velocities > 2°/s. For the enclosure, these moves may be as large as 180°.

[REQ-0-SRD-0210] The observatory shall quickly perform accurate acquisition offsets without guider feedback to support the efficient acquisition of science objects.

[REQ-0-SRD-0215] The observatory shall perform accurate acquisition offsets of up to 1 degree on the sky to support the efficient acquisition of science objects.

3.3.3.2 POINTING AND OFFSETTING

Definition: Pointing and offsetting are moves done without reference to stars.

[REQ-0-SRD-0220] The telescope shall point to within 1 arcsec rms with a goal of 0.5 arcsec rms over the whole accessible sky.

Discussion: Accurate pointing greatly reduces overheads in acquiring fields so that science observations can begin.

[REQ-0-SRD-0225] The telescope shall perform accurate guider offsets of up to 5 arcminutes on the sky.

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

3.3.3.3 GUIDING/TRACKING

[REQ-0-SRD-0235] The observatory shall guide/track at any rate up to 1.1 times the sidereal rate and with an error contained within the overall image blur specification in [REQ-0-SRD-0070].

[REQ-0-SRD-0237] Observatory instruments and adaptive optics systems shall implement hardware, including cameras or wavefront sensors, to provide acquiistion or guiding error feedback and perform guider offsetting.

3.3.3.4 ZENITH AND AZIMUTH ANGLE RANGE

[REQ-0-SRD-0240] The observatory shall observe anywhere on the sky from 1° to 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.

Discussion: Performance degrades below 1 degree zenith angle.

[REQ-0-SRD-0245] The 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.

Discussion: The range and center of travel of the azimuth axis must continuously track any object transiting north or south of zenith, within the elevation axis horizon limits, without running into an end of travel. If the operational maximum zenith angle were considered the required azimuth range would be very slightly smaller that this requirement, but not significantly so. A considerable margin in azimuth range in addition to this minimum requirement is expected from the design.

3.3.3.5 NODDING, DITHERING, AND CHOPPING

Definition: Telescope nodding and dithering (small steps in either 1 or 2 dimensions) is needed to reduce systematic drifts in backgrounds or to improve detector calibration. This is a motion of the telescope as a whole.

[REQ-0-SRD-0250] The observatory shall provide telescope nod capability, spending at least 80% of the cycle at the end points on average.

[REQ-0-SRD-0255] Telescope position errors at nod end points of less than 10 arsec shall be no more than 0.05 arcsec rms for seeing-limited observations.

[REQ-0-SRD-0260] Telescope position errors at nod end points shall be no more than λ/10D for diffraction-limited observations.

Discussion: The accuracy needed for diffraction-limited imaging can be achieved with AO fast tip-tilt optics.

[REQ-0-SRD-0265] The telescope shall provide nod capability with amplitude of at least ±1 arcsec, a half period of at least 10 seconds, and integration time at least 80%.

[REQ-0-SRD-0270] The telescope shall provide nod capability with amplitude of at least ±10 arcsec, a half period of at least 20 seconds, and integration time at least 80%.

Discussion: Chopping by the secondary mirror is not needed.

[REQ-0-SRD-0280] The observatory shall provide telescope dither capability, supporting a pattern of non-redundant dithers, extending over a period of 4 hours with a time interval between two consecutive dithers as short as 20 seconds.

Discussion: Many science programs with deep, pointed observations (e.g., Galactic Center) will be using exposure-to-exposure dither motions to remove geometric distortions, improve flatfielding and boost spatial resolution. A dither move might follow every single exposure, and series of exposures extending over many hours may be needed. Furthermore, the dither pattern may not be a regular grid to mitigate spatial aliasing. This requirement captures the sustained aspect of this observing mode. It has obvious control implications and may also have mechanical implications.

3.3.4 INSTRUMENT SUPPORT

3.3.4.1 SPACE

[REQ-0-SRD-0300] The observatory shall provide space at the Nasmyth foci for instruments/AO Facilities, with individual masses up to 55 metric tons.

3.3.4.2 SUPPORT FACILITIES

[REQ-0-SRD-0305] The observatory shall provide power, cooling, compressed air, and signal lines at instrument locations.

[REQ-0-SRD-0310] The observatory shall provide access to instruments by personnel for servicing and repairs.

3.3.4.3 FIELD ROTATION

[REQ-0-SRD-0320] Observatory instruments or adaptive optics systems shall de-rotate the field within the error contained in the overall image blur specification in [REQ-0-SRD-0070].

3.4 FIRST LIGHT

3.4.1 FIRST LIGHT ADAPTIVE OPTICS

Narrow Field, Diffraction-Limited, Near-IR, or Narrow Field IR Adaptive Optics System (NFIRAOS): NIR spectroscopy with an on-axis IFU or slit sampled at or near the diffraction limit should deliver a field of 10 arcsec, with nearly 100% sky coverage. Near-IR images of high Strehl should deliver a contiguous 30 arcsec field. The primary scientific drivers of this system are precision photometry of point sources in crowded fields, and precision astrometry. Ideally this system should work over the whole range 0.6 µm - 2.5 µm with high Strehl ratio. In addition, NFIRAOS should provide significant image size reduction over a field of view of 2.3 arcmin diameter to allow multi-object spectroscopy. All spectroscopic applications require that the system emissivity is kept low for high sensitivity at wavelengths > 1.6 µm.

3.4.1.1 SMALL FIELD, DIFFRACTION-LIMITED, NEAR-IR (NFIRAOS)

3.4.1.1.1 GENERAL DESCRIPTION

This AO system is intended to deliver diffraction-limited images over a small field, sufficient for either an IFU or a slit, and provide a contiguous 30 arcsec field that delivers near-IR images of high Strehl ratio to an imager. The primary scientific drivers of this system are diffraction-limited IFU or echelle spectroscopy, precision photometry of point sources in crowded fields, and precision astrometry. In addition, NFIRAOS must provide very significant reduction of image size over a field up to 2.3 arcmin. A natural guide star mode is also needed, with the largest practical sky coverage at a level of performance that delivers a Strehl ratio of at least 0.5 in the K band, using a 16.5th magnitude guide star.

3.4.1.1.2 WAVELENGTH RANGE

[REQ-0-SRD-0800] NFIRAOS throughput to science instruments shall exceed 60% over 0.8 - 1.0 microns, and 80% over the 1.0 - 2.4 micron wavelength range [Goal: 90% from 0.6 to 2.5 microns].

Discussion: The throughput requirement applies to the AO system alone. Poor throughput becomes emissivity at the temperature of the AO system.

3.4.1.1.3 FIELD OF VIEW

[REQ-0-SRD-0810] The NFIRAOS unvignetted field of view shall be at least 2 arcmin diameter.

[REQ-0-SRD-0815] Useful NFIRAOS correction shall be achieved over a 2.3 arcmin diameter field of view, with no more than 30% vignetting.

Discussion: The 30 arcsec field is intended to support IFU spectroscopy and imaging at the diffraction limit with a science instrument such as IRIS. The 2.3 arcmin field requirement is intended to service a multi object (multi slit) spectrometer that can use this field.

3.4.1.1.4 IMAGE/WAVEFRONT QUALITY

[REQ-0-SRD-0805] NFIRAOS LGS MCAO shall deliver a K-band Strehl ratio > 0.7 over at least a 30 arcsec diameter, with a goal of K-band Strehl ratio > 0.86 for the NFIRAOS upgrade.

[REQ-0-SRD-0840] Under median conditions, the J band energy in a 160 mas slit shall be at least 30% averaged over the 2.3 arcmin diameter field of view.

Discussion: Seeing-limited value is 9%.

[REQ-0-SRD-0845] Under median conditions, the K band energy in a 160 mas slit shall be at least 40% averaged over the 2.3 arcmin diameter field of view.

Discussion: Seeing-limited value is 13%.

3.4.1.1.5 SKY COVERAGE

[REQ-0-SRD-0850] NFIRAOS sky coverage shall be > 50% at the galactic poles, with < 2.3 mas rms tip-tilt jitter.

Discussion: Sky coverage is limited by the density of natural guide stars for tip/tilt correction. Tip/tilt sensing is done in the infrared in order to take advantage of image sharpening by the AO system. Such infrared tip-tilt guide stars are particularly useful for imaging of obscured regions where visible tip-tilt stars may be absent. See appendix 6 for a discussion.

3.4.1.1.6 BACKGROUND

[REQ-0-SRD-0855] NFIRAOS shall not increase the (inter-OH) background by more than 15% over natural sky (see Appendix D) + telescope background (assume 7% emissivity at 273 K).

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

3.4.1.1.7 DIFFERENTIAL AO PHOTOMETRIC PRECISION

[REQ-0-SRD-0860] Systematic errors in differential AO photometry due to PSF residual spatial variability shall be less than 2% for 10-minute integrations, at 1 µm, over the 30 arcsec FOV.

Discussion: A single standard star is assumed for each image.

3.4.1.1.8 ABSOLUTE AO PHOTOMETRIC ACCURACY

[REQ-0-SRD-0865] Absolute AO photometric accuracy shall be better than 10%, with a goal of 5%, with suitable observations of photometric standards.

3.4.1.1.9 DIFFERENTIAL AO ASTROMETRY

[REQ-0-SRD-0870] Residual time-dependent one-dimensional distortions over a 30 arcsec AO FOV (after a fit to physically allowed distortion measured with field stars) shall be no larger than 50 µas rms in the H band, for a 100 s integration time, with errors falling as $t^{-1/2}$.

Discussion: Modest static field distortions are removed by initial calibration and the use of field stars within the image that can remove residual “static” errors that the AO system might introduce, dependent on the exact tip-tilt guide star configuration. It is important that errors fall below the 50 µas requirement, with greater integration time, as this enables important scientific programs.

[REQ-0-SRD-0872] Systematic one-dimensional position uncertainties over a 30 arcsec AO FOV shall be no larger than 10 µas rms in the H band.

3.4.1.1.10 OPERATIONAL MODES

3.4.1.1.10.1 MULTIPLE LASERS

[REQ-0-SRD-0875] The observatory shall provide multiple synthetic beacons (Na guide stars) in order to tomographically measure the atmosphere, allow the desired AO correction, and achieve significant sky coverage.

3.4.1.1.10.2 SINGLE NATURAL GUIDE STAR, NO LASERS.

[REQ-0-SRD-0880] NFIRAOS NGSAO shall deliver a K-band Strehl ratio > 0.82 over the natural angular limits imposed by the isoplanatic angle, using a single R < 8 magnitude guide star.

[REQ-0-SRD-0881] NFIRAOS NGSAO shall deliver a K-band Strehl ratio > 0.74 over the natural angular limits imposed by the isoplanatic angle, using a single R < 12 magnitude guide star.

3.4.1.1.11 OPERATIONAL EFFICIENCY-DITHERING

[REQ-0-SRD-0885] Dither pattern losses shall be under 1 second for up to 5 arcsec and 5 seconds for up to 30 arcsec.

[REQ-0-SRD-0890] The observatory shall execute dither patterns with moves from 1 arcsec to 30 arcsec.

Discussion: We want the MCAO setup to be fully automated, and have as a goal that 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.

3.4.2 FIRST LIGHT 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 (≥0.1 arcsec).

Background light can influence the sensitivity of all instruments. For observations shortward of about 1.8 μm, 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.

Our solution to this issue is to require the instruments provide suitable baffles, rather than the telescope.

Atmospheric dispersion can adversely affect many observations. Atmospheric dispersion compensators need to be built into 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 H.

3.4.2.1 INFRARED IMAGING SPECTROMETER (IRIS)

3.4.2.1.1 GENERAL DESCRIPTION

This instrument provides diffraction-limited moderate spectral resolution (R ~ 4000) spectra and images over a small field of view, using an integral field unit (IFU). It also obtains diffraction-limited images over a > 15-arcsec field. This instrument relies on AO and uses the unique diffraction-limited resolution of TMT.

This instrument uses the small field diffraction-limited, near-IR AO system, NFIRAOS (2.4.2).

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

3.4.2.1.2 WAVELENGTH RANGE

[REQ-0-SRD-1000] The IRIS wavelength range shall be at least 0.84 μm - 2.4 μm, with a goal of 0.6 μm - 5 μm.

3.4.2.1.3 FIELD OF VIEW

[REQ-0-SRD-1005] The IRIS IFU shall have a field of view > 3 arcsec along spatial direction.

[REQ-0-SRD-1010] The IRIS imager shall have a field of view greater than 30 x 30 arcsec.

Discussion: The imager in IRIS is responsible for most near-IR diffraction-limited imaging with TMT at first light; larger fields of view and/or multiple imaging fields each of which satisfies the above requirement is a goal.

3.4.2.1.4 IMAGE QUALITY

[REQ-0-SRD-1015] IRIS shall preserve the wavefront quality delivered by the AO system for all modes in which the diffraction limit is critically sampled.

[REQ-0-SRD-1020] IRIS, in the case of coarser IFU plate scales, shall not decrease the ensquared energy per spatial pixel by more than 10% over that provided by the AO system.

3.4.2.1.5 SPATIAL SAMPLING

[REQ-0-SRD-1030] The IRIS imager shall provide spatial sampling of 0.004 arcsec per pixel (Nyquist sampled at ~ 1 micron).

[REQ-0-SRD-1035] The IRIS IFU shall provide selectable plate scales of 0.004, 0.009, 0.025, 0.050 arcsec/spaxel.

Discussion: With a geometry of ~ 64 x 64 spatial samples or a comparable total number of spatial samples ~ 4,000.

3.4.2.1.6 SPECTRAL RESOLUTION AND COVERAGE

[REQ-0-SRD-1040] The IRIS IFU shall provide spectral resolution R > 3500 over entire z, Y, J, H, K bands, one band at a time.

Discussion: A larger IFU field of view with smaller wavelength coverage is desirable for some applications.

[REQ-0-SRD-1045] The IRIS imager shall provide a spectral resolution R = 5 - 100.

Discussion: A facility allowing a tunable narrow band for specialized imaging applications is a goal, if feasible.

3.4.2.1.7 BACKGROUND

[REQ-0-SRD-1050] IRIS shall not increase the (inter-OH) background by more than 15% over natural sky (see Appendix D) + telescope background (assume 7% emissivity at 273 K).

[REQ-0-SRD-1055] The IRIS imager shall not increase the K-band background by more than 15% over natural sky.

3.4.2.1.8 ASTROMETRY

[REQ-0-SRD-1060] IRIS 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 13.3 μ-arcseconds in the H band for a 100s integration time.

[REQ-0-SRD-1065] IRIS systematic errors contribution shall be no more than 10 μas.

Discussion: We assume that there are modest static field distortions, but these are removed by initial calibration and the use of field stars within the image that can remove residual “static” errors that the AO system might introduce, dependent on the exact tip-tilt guide star configuration. Every effort should be made to achieve a 10 μas floor, or less.

3.4.2.1.9 SENSITIVITY

[REQ-0-SRD-1070] IRIS detector dark current and read noise shall not increase the effective background by more than 5% for an integration time of 900 s.

Discussion: In the 1 - 2.5 μm region, dark current ≤ 0.002 e-/s and read noise ≤ 2 e- after multiple reads should be sufficient. Existing detectors can achieve dark currents of 0.002 e-/s and read noises of ~ 3 - 6 e-.

[REQ-0-SRD-1075] IRIS sky subtraction accuracy for IFU modes shall be dominated by the photon statistics of the background for integrations > 900 s for the two coarsely sampled IFU modes.

3.4.2.1.10 THROUGHPUT

[REQ-0-SRD-1080] The IRIS IFU throughput shall be > 30% (excluding the AO system and telescope).

3.4.2.2 WIDE FIELD OPTICAL IMAGING SPECTROMETER (WFOS)

3.4.2.2.1 GENERAL DESCRIPTION

WFOS 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 is required. If partial AO image correction proves feasible, a detailed review of its capabilities and these requirements will be required.

3.4.2.2.2 WAVELENGTH RANGE

[REQ-0-SRD-1200] The WFOS wavelength range shall be at least 0.31 μm - 1.0 μm, with a goal of 0.31 μm - 1.3 μm.

Discussion: The initial performance of the telescope mirrors in the UV may limit the wavelength range to > 0.34 μm; however, the spectrograph optics should work as closely as possible to the *atmospheric limit (0.32 μm for 3000 m sites, 0.31 μm for 4000 m sites). When used at spectral resolution R ~ 1000, it should be possible to record the whole wavelength range in a single exposure. At the highest spectral resolution, the widest possible wavelength coverage should be obtained in a single exposure. It may be advantageous to optimize the performance vs. wavelength using multiple arms and a dichroic beamsplitter.*

3.4.2.2.3 FIELD OF VIEW

[REQ-0-SRD-1205] The WFOS spectroscopy field of view shall be ≥ 25 arcmin^2.

Discussion: The field need not be contiguous. While larger fields are very beneficial, the total slit length is more important than total field area.

[REQ-0-SRD-1207] WFOS shall be able to take an image of its spectrometric mode field of view.

3.4.2.2.4 TOTAL SLIT LENGTH

[REQ-0-SRD-1210] The WFOS total slit length shall be ≥ 500 arcsec.

Discussion: The total slit length is the most important factor for a greater multiplex advantage. A single, contiguous field may provide practical advantages for field acquisition and mechanical simplicity, all other things being equal.

3.4.2.2.5 IMAGE QUALITY

[REQ-0-SRD-1215] WFOS imaging mode shall yield an image quality including polychromatic correction residuals no worse than 0.45 arcsec FWHM.

[REQ-0-SRD-1220] WFOS spectroscopy mode shall yield encircled energy > 80% within an angular diameter of 0.25 arcsec on-sky.

Discussion: These apply to the spectrograph optics alone, and do not include the atmosphere or the telescope contributions to final image quality.

[REQ-0-SRD-1225] WFOS image positions shall be achromatic to better than 0.05 arcsec over the full range of telescope zenith angles.

Discussion: This requirement implies that an ADC must provide adequate correction over the spectrograph wavelength range. The ADC may be permanently in place (i.e., not removable from the beam) as long as its optical throughput is 95% or greater.

3.4.2.2.6 SPECTRAL RESOLUTION

[REQ-0-SRD-1235] WFOS shall have a spectral resolution of R = 1500 - 3500, with a 0.75 arcsec slit.

Discussion: Complete spectral coverage in low-resolution mode is required; complete coverage is desirable in the high-resolution mode.

3.4.2.2.7 THROUGHPUT

[REQ-0-SRD-1240] WFOS, in spectroscopy mode, shall have an on-axis throughput of ≥ 25% from 0.31 μm - 1.00 μm, and ≥ 30% from 0.35 μm - 0.90 μm, not including the telescope.

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.

3.4.2.2.8 SENSITIVITY

[REQ-0-SRD-1245] WFOS spectra shall be photon noise limited (negligible systematic errors from background subtraction, negligible detector read noise and dark current) for any exposure longer than 300 seconds.

Discussion: In order to achieve photon-statistics-limited sky subtraction nod and shuffle, or fast beam-switching may be required.

3.4.2.2.9 FIELD ACQUISITION

3.4.2.2.10 DESIRABLE FEATURES

[REQ-0-SRD-1265] A goal is for WFOS to provide imaging through 0.5% - 1% bandwidth filters.

[REQ-0-SRD-1270] A goal is for WFOS to provide an IFU option.

[REQ-0-SRD-1275] A goal is for WFOS to exploit AO-based image quality improvements (i.e., GLAO).

3.4.2.3 MULTI-OBJECTIVE DIFFRACTION-LIMITED HIGH-RESOLUTION INFRARED SPECTROGRAPH (MODHIS)

3.4.2.3.1 GENERAL DESCRIPTION

MODHIS is a diffraction-limited, high spectral resolution échelle spectrograph in the 0.95 µm - 2.4 µm range. MODHIS operates behind NFIRAOS. MODHIS is primarily envisioned to service the exoplanet science field.

3.4.2.3.2 WAVELENGTH RANGE

[REQ-0-SRD-1160] The MODHIS science channel shall provide wavelength coverage over the 0.95 µm - 2.4 µm range.

[REQ-0-SRD-1162] The MODHIS science channel shall provide simultaneous coverage for a given science target across the full yJ and HK astronomical bands.

3.4.2.3.3 SPECTRAL RESOLUTION

[REQ-0-SRD-1164] MODHIS shall provide an average spectral resolution R ≥ 100,000 over its entire science passband.

Discussion: The intended pixel sampling is 3 pixels per resolution element.

3.4.2.3.4 WAVELENGTH STABILITY

[REQ-0-SRD-1166] MODHIS shall provide an instrumental radial velocity precision of ≤ 30 cm/s (goal of 10 cm/s).

3.4.2.3.5 MULTIPLEXING

[REQ-0-SRD-1170] The MODHIS science channel shall be capable of performing science on a single target with a goal of offering a multiplex of up to 4 separate simultaneous science targets.

Discussion: Multi-object capability is provided to broaden the reach of the instrument beyond exoplanets. It is acknowledged that exoplanet science requires only one target.

Discussion: The MODHIS design has assumed a fiber-based architecture. Each science object includes fibers for an object, the sky, and calibration.

3.4.2.3.6 FIELD OF REGARD

[REQ-0-SRD-1172] MODHIS shall provide an unvignetted field-of-regard ≥ 4 x 4 arcsecs square.

Discussion: To maximize image quality the MODHIS field-of-regard is assumed to be centered on-axis relative to the 2 arcminute field-of-regard relayed by NFIRAOS.

Discussion: The MODHIS field-of-regard is deliverable to both its science channel as well as any required field acquisition/monitoring channel.

Discussion: If the instrument goal of offering a multi-object capability is adopted the field-of-regard for the instrument must be re-assessed and possibly expanded.

Discussion: WFS architecture is permitted to patrol outside this field but is required to provide WFS capabilities within the 2 arcmin diameter field as delivered by NFIRAOS.

3.4.2.3.7 SPATIAL SAMPLING

[REQ-0-SRD-1175] The MODHIS science channel shall be capable of Nyquist sampling a point source from within the field-of-regard in each of y, J, H, and K bands.

Discussion: MODHIS does not require spatial information from its science targets.

3.4.2.3.8 THROUGHPUT

[REQ-0-SRD-1180] The MODHIS science channel end-to-end throughput shall be ≥ 10%.

Discussion: The requirement excludes the performance of both the telescope and NFIRAOS.

3.4.2.3.9 IMAGE QUALITY

[REQ-0-SRD-1185] MODHIS's front end instrument shall not degrade the wavefront quality of that delivered by NFIRAOS by more than 40 nm rms.

[REQ-0-SRD-1187] The MODHIS spectrograph shall provide an ensquared energy ≥ 80% within a single pixel across 95% of the detector area.

3.4.2.3.10 BACKGROUND

[REQ-0-SRD-1190] MODHIS shall enable subtraction of the background to better than 1%.

3.4.2.3.11 CONTRAST

[REQ-0-SRD-1192] MODHIS shall provide raw contrast ratio of ≥ 100 from 0.5 λ/D to 2 λ/D and ≥ 1,000 from 2 λ/D to the edge of the field of regard.

3.4.2.3.12 POLARIMETRY

[REQ-0-SRD-1195] MODHIS shall provide spectropolarimetry with 0.1% (goal) polarimetric precision in y and J bands.

3.5 FIRST DECADE

The first decade adaptive optics and science instrument requirements presented in this section will be refined by the SAC later on based on changing science priorities, advances in technology, and overall funding.

3.5.1 FIRST DECADE ADAPTIVE OPTICS

- 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 IFUs for multiplexed spectroscopy of ~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 μm range, and should be optimized for throughput and low emissivity.
- Small Field, Diffraction-Limited Mid-IR (MIRAO): the highest priority mid-IR science (5 - 28 μm) 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.

3.5.1.1 WIDE FIELD, NEAR-DIFFRACTION-LIMITED (0.6-2.5μM) (MOAO)

3.5.1.1.1 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. Conceptually, IFU's could then be distributed over this field and could be fed diffraction-limited images for analysis.

3.5.1.1.2 WAVELENGTH RANGE

[REQ-0-SRD-0900] MOAO throughput shall exceed 85% from 0.6 µm to 2.5 µm.

Discussion: Due to high backgrounds, the number of objects detectable in the 3 - 5 µm window is greatly reduced relative to the object density at shorter wavelengths. Thus, the long wavelength cutoff is set to 2.5 µm. Single object work is discussed in 3.4.1.

3.5.1.1.3 FIELD OF VIEW

[REQ-0-SRD-0905] The MOAO system shall provide at least 10 corrected regions, each > 5 arcsec diameter, with adjustable positions over a > 20 arcmin^2 field of view.

[REQ-0-SRD-0910] The minimum separation of the MOAO-corrected regions shall be < 20 arcsec.

Discussion: A 5-arcmin field matches the size of the JWST imaging field. The typical sizes of objects of interest are 0.1 - 2 arcsec; the surface density of potential targets ranges from a few over the 5-arcmin field to tens per square arc minute. A reasonable IFU sampling and field size is 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 at 2 µm. When a larger contiguous field is desired (~ 5 arcsec) somewhat coarser sampling may be used.

3.5.1.1.4 IMAGE/WAVEFRONT QUALITY

[REQ-0-SRD-0915] The MOAO system shall deliver at least 50% of the flux from a point source at 1 µm wavelength into a 0.05 arcsec square.

Discussion: Much of the anticipated use of MOAO is 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.

3.5.1.1.5 SKY COVERAGE

[REQ-0-SRD-0920] MOAO sky coverage shall be at least 90% at the galactic poles.

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 may be sufficient. See Appendix 6 for a discussion.

3.5.1.1.6 BACKGROUND

[REQ-0-SRD-0925] The MOAO system shall not increase the (inter-OH) background by more than 15% over natural sky (see Appendix D) + telescope background (assume 7% emissivity at 273 K).

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

3.5.1.1.7 LASER ASTERISM AND FLEXIBILITY

[REQ-0-SRD-0930] Lasers shall 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.

3.5.1.2 SMALL FIELD, DIFFRACTION-LIMITED MID-IR (MIRAO)

3.5.1.2.1 GENERAL DESCRIPTION

The highest priority mid-IR science (4.5 - 28 µm) 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.

3.5.1.2.2 WAVELENGTH RANGE

[REQ-0-SRD-0950] MIRAO throughput shall exceed 85% from 4.5 μm to 28 μm.

3.5.1.2.3 FIELD OF VIEW

[REQ-0-SRD-0955] The MIRAO field of view shall be > 10 arcsec diameter with a goal of 1 arcmin diameter.

Discussion: Goal field of view allows future imaging modes.

3.5.1.2.4 IMAGE/WAVEFRONT QUALITY

[REQ-0-SRD-0960] The MIRAO system shall have a wavefront error < 750 nm rms, goal < 350 nm rms.

Discussion: We understand that this implies poor performance at L band (3.8 μm); we envision that L band imaging could be accomplished with MOAO and L-band spectroscopy with MIRAO/NIRES-R

3.5.1.2.5 SKY COVERAGE

[REQ-0-SRD-0965] MIRAO sky coverage shall be all sky, limited only by availability of tip-tilt natural guide stars.

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

3.5.1.2.6 BACKGROUND

[REQ-0-SRD-0970] The MIRAO system shall not increase the N band background by more than 15% over natural sky (see Appendix D) + telescope background (assume 7% emissivity at 273 K).

Discussion: In order to reduce black body flux at 10 μm by a factor of 10, the body must be cooled to 85 K.

3.5.1.2.7 MIRAO PHOTOMETRY

[REQ-0-SRD-0975] Systematic, uncalibrated errors in MIRAO photometry due to PSF residual spatial variability shall be < 5% in the N band (10 μm) over a 1 arcmin field.

3.5.1.2.8 MIRAO ASTROMETRY

[REQ-0-SRD-0980] The MIRAO system shall provide sufficient calibration information so as not to degrade differential astrometric precision beyond the limits set by the atmosphere.

3.5.2 FIRST DECADE INSTRUMENTS

3.5.2.1 NEAR-INFRARED, MULTI-OBJECT SPECTROMETER (IRMOS)

3.5.2.1.1 GENERAL DESCRIPTION

IRMOS 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 regard. Each deployable AO corrector connects to its deployable IFU that samples the field of view (≤ 3 arcsec) and feeds the spatially divided information into a spectrometer. Each spectrometer may process information from multiple IFUs depending on the actual instrument design.

This instrument is intended to study multiple extended objects. Because they are extended, spatial resolution ~ 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.

3.5.2.1.2 WAVELENGTH RANGE

[REQ-0-SRD-1300] The IRMOS wavelength range shall be at least 0.8 µm - 2.5 µm.

Discussion: The low density of observable sources beyond 2.5 µm makes coverage beyond 2.5 µm unnecessary.

3.5.2.1.3 FIELD OF REGARD

[REQ-0-SRD-1305] IRMOS shall provide IFU heads deployable over > 2 arcmin diameter field of regard (goal 5 arcmin).

3.5.2.1.4 IMAGE QUALITY

[REQ-0-SRD-1310] IRMOS shall preserve the wavefront quality delivered by the AO system (50% ensquared energy in 0.050 arcsec).

3.5.2.1.5 SPATIAL SAMPLING

[REQ-0-SRD-1315] IRMOS shall provide spatial sampling of 0.05 x 0.05 arcsec (other scales TBD). Goal: additional sampling when needed of 0.01 arcsec.

[REQ-0-SRD-1320] Each IRMOS IFU shall have a field of view at least 3 arcsec diameter.

[REQ-0-SRD-1325] IRMOS shall provide at least 10 integral field units.

[REQ-0-SRD-1330] IRMOS IFU heads shall be positionable to within <20 arcsec of each other.

3.5.2.1.6 SPECTRAL RESOLUTION

[REQ-0-SRD-1335] The IRMOS IFU shall provide spectral resolution R = 2000 - 10000.

[REQ-0-SRD-1340] The IRMOS IFU shall capture the individual z, Y, J, H, K bands in a single exposure at R = 4,000'.

3.5.2.1.7 THROUGHPUT

[REQ-0-SRD-1345] IRMOS throughput shall be > 30%, excluding the AO system and telescope.

3.5.2.1.8 BACKGROUND

[REQ-0-SRD-1350] IRMOS shall not increase the (inter-OH) background by more than 15% over natural sky (see Appendix D) + telescope background (assume 7% emissivity at 273 K).

3.5.2.1.9 DETECTOR

[REQ-0-SRD-1355] IRMOS detector dark current and read noise shall not increase the effective background by more than 5% for an integration time of 900 s.

Discussion: In the 1 - 2.5 µm region, dark current ≤ 0.002 e-/s and read noise ≤ 5 e- after multiple reads should be sufficient.

3.5.2.2 MID-IR ECHELLE SPECTROMETER (MIRES)

3.5.2.2.1 GENERAL DESCRIPTION

MIRES is fed by the MIRAO system. Large sky coverage is desired, so the AO system is 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 MIRAO.

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.

3.5.2.2.2 WAVELENGTH RANGE

[REQ-0-SRD-1400] The MIRES wavelength range shall be at least 8 µm - 18 µm, with a goal of 4.5 µm - 28 µm.

3.5.2.2.3 FIELD OF VIEW OF SCIENCE CAMERA

[REQ-0-SRD-1410] As a desirable goal, the MIRES science camera shall be provided with the same field of view and sampling as the acquisition camera (10 arcsec diameter and Nyquist Sampling at 5 µm).

Discussion: This camera should work in N (10 µm) band at least, and be able to image through narrow band filters.

3.5.2.2.4 SLIT LENGTH

[REQ-0-SRD-1415] MIRES shall have a slit length > 3 arcsec, sampled at < 0.04 arcsec/pixel.

Discussion: This slit length should accommodate nodding along the slit.

3.5.2.2.5 SPECTRAL RESOLUTION

[REQ-0-SRD-1420] MIRES shall provide spectral resolution R = 5000 - 100,000 with a diffraction-limited slit.

[REQ-0-SRD-1425] MIRES single exposures at R = 100,000 mode shall provide continuous coverage over the imaged orders, 8 - 14 µm.

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

3.5.2.2.6 BACKGROUND

[REQ-0-SRD-1430] MIRES shall not increase the N band background by more than 15% over natural sky (see Appendix D) + telescope background (assume 7% emissivity at 273 K).

Discussion: Integration time to reach a given SNR is proportional to the total background.

3.5.2.2.7 THROUGHPUT

[REQ-0-SRD-1435] MIRES throughput shall be > 20%.

3.5.2.2.8 SENSITIVITY

[REQ-0-SRD-1440] MIRES sensitivity shall be limited by photon statistics in the background, and not limited by any systematic errors, up to an 8 hr integration.

3.5.2.2.9 NODDING

[REQ-0-SRD-1445] The telescope with feedback from MIRES shall support small motions along a slit that keep the science target within a slit width of 0".10 to maintain the slit light loss below 30%.

[REQ-0-SRD-1450] The telescope nod amplitude shall cover the length of the MIRES slit with an accuracy of λ/10D at 8 µm.

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 λ/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.

3.5.2.2.10 CHOPPING

Discussion: Chopping is 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.

3.5.2.3 PLANET FORMATION INSTRUMENT (PFI)

3.5.2.3.1 GENERAL DESCRIPTION

PFI instrument seeks to directly image and obtain spectra of extra-solar planets, including reflected light detection of mature giant planets in the solar neighborhood and imaging of thermal emission from forming protoplanets in star-forming regions such as Taurus and Ophiuchus. PFI requires a sophisticated AO system with high accuracy and stability, as well as a coronagraph or similar instrument to block the starlight. This instrument should be capable of detecting planets that are 10^8 to 10^9 fainter than the parent star, at distances from the star as small as 30 mas.

3.5.2.3.2 WAVELENGTH RANGE

[REQ-0-SRD-1500] The PFI wavelength range shall be at least 1 µm - 2.5 µm, with a goal of 1 µm - 5 µm.

Discussion: The blue end is limited by extreme AO and if feasible a bluer cut-off is desirable.

3.5.2.3.3 FIELD OF VIEW

[REQ-0-SRD-1505] PFI shall have a field of view of 1 arcsec radius with respect to the exoplanet star.

Discussion: Performance is required between the diffraction limit and the 1 arsec radius.

3.5.2.3.4 IMAGE QUALITY

[REQ-0-SRD-1510] PFI shall deliver an H-band resolution of 14 milliarcsecs with a Strehl ratio greater than 0.9.

3.5.2.3.5 SPATIAL SAMPLING

[REQ-0-SRD-1515] PFI shall be Nyquist sampled at 1 µm ($\lambda/2D = 0.0035$ arcsec).

3.5.2.3.6 SPECTRAL RESOLUTION

[REQ-0-SRD-1520] The PFI IFU shall have spectral resolution R up to 100.

Discussion: An IFU is likely to be more useful than a slit

3.5.2.3.7 CONTRAST

[REQ-0-SRD-1525] PFI shall exceed a planet detection contrast ratio of 10^8 (goal 10^9) before systematic errors dominate in H band on stars with I < 8 mag and at inner working angles of 50 mas.

[REQ-0-SRD-1530] PFI shall exceed a planet detection contrast ratio of 10^6 (goal 5×10^6) with H < 10 at inner working angles > 30 mas.

Discussion: For typical younger, distant, dusty stars (such as Taurus) contrast is defined as the 5-σ ratio of primary star brightness to the residual speckle and photon noise, i.e., the spatial standard deviation of the final intensity of the PSF halo in a small region.

Discussion: Speckles are expected to be the major background limiting reliable planet detection. Speckle amplitude is defined (for TMT) as the 5-σ amplitude of speckle brightness.

It is expected that suitable data gathering methods and data reduction methods allow reliable planet detection to take place at 1/10 of the speckle amplitude. Thus, the actual telescope quality should be such that contrasts 10x smaller than the above numbers should be produced by the telescope and PFI system, prior to data reduction.

3.5.2.3.8 POLARIZATION

[REQ-0-SRD-1535] PFI shall detect polarized light at a level of 1% of the residual stellar halo, and measure absolute polarization to an accuracy of 10%.

Discussion: e.g., from scattering off circumstellar dust.

3.5.2.4 NEAR-IR ECHELLE SPECTROMETER RED (NIRES-R)

3.5.2.4.1 GENERAL DESCRIPTION

The NIRES-R spectrometer is generally used with a diffraction-limited slit for point sources. It is placed behind MIRAO that delivers a high quality image over a small field of view. We assume an 8k x 8k detector mosaic will be available.

3.5.2.4.2 WAVELENGTH RANGE

[REQ-0-SRD-1605] The NIRES-R wavelength range shall be at least 2.4 μm - 5.0 μm.

3.5.2.4.3 SLIT LENGTH

[REQ-0-SRD-1615] NIRES-R slit length shall be > 2 arcsec, to provide the ability to nod along the slit to improve background subtraction.

3.5.2.4.4 IMAGE QUALITY

[REQ-0-SRD-1620] NIRES-R shall deliver diffraction-limited images to the detector, as delivered by the MIRAO system.

3.5.2.4.5 SPATIAL SAMPLING

[REQ-0-SRD-1625] NIRES-R shall provide spatial sampling of $\lambda/2D = 0.01$ arcsec per pixel (Nyquist sampled at 2.9 μm).

3.5.2.4.6 SPECTRAL RESOLUTION

[REQ-0-SRD-1632] The NIRES-R spectral resolution shall be R > 100,000.

3.5.2.4.7 BACKGROUND

[REQ-0-SRD-1635] NIRES-R shall not increase the background by more than 15% over natural sky (see Appendix D) + telescope background (assume 7% emissivity at 273 K).

3.5.2.4.8 DETECTOR

[REQ-0-SRD-1640] NIRES-R detector dark current and read noise shall not increase the effective background by more than 5% for an integration time of 900 s.

3.5.2.4.9 THROUGHPUT

[REQ-0-SRD-1645] NIRES-R throughput shall be > 20%.

3.5.2.5 HIGH-RESOLUTION OPTICAL SPECTROMETER (HROS)

3.5.2.5.1 GENERAL DESCRIPTION

HROS provides high spectral resolution data in the optical range, suitable for detailed study of stars, quasars, and planet radial velocity programs.

3.5.2.5.2 WAVELENGTH RANGE

[REQ-0-SRD-1700] The HROS wavelength range shall be at least 0.31 μm - 1.0 μm, with a goal of 0.31 μm - 1.3 μm.

Discussion: Working into the infrared is scientifically valuable, but CCDs cut off at 1.0 μm. New detectors would be needed to reach the long wavelength limit.

3.5.2.5.3 SLIT LENGTH

[REQ-0-SRD-1710] HROS slit length shall be > 5 arcsec, with > 5 arcsec separation between orders.

3.5.2.5.4 IMAGE QUALITY

[REQ-0-SRD-1715] HROS image quality (including only HROS optics) shall be no worse than 0.2 arcsec FWHM at the detector.

3.5.2.5.5 SPATIAL SAMPLING

[REQ-0-SRD-1720] HROS spatial sampling shall be no coarser than 0.2 arcsec, to adequately sample the best optical images provided by the telescope.

3.5.2.5.6 SPECTRAL RESOLUTION

[REQ-0-SRD-1725] HROS shall provide spectral resolution R = 50,000 with a 1 arcsec slit, and R ≥ 90,000 with an image slicer.

Discussion: Options include single slit, fiber feed for multiplexing

3.5.2.5.7 SENSITIVITY

[REQ-0-SRD-1730] HROS throughput shall be > 25% from telescope focal plane to detected photons.

Discussion: To maintain 30 m aperture advantage over existing similar instruments on 8 - 10 m telescopes.

3.6 BEYOND FIRST DECADE CAPABILITIES

3.6.1 GLAO NEAR-IR MULTI-OBJECT IMAGING SPECTROMETER

Depending on the site characteristics, it may be advantageous to develop a ground layer AO system. Such a system would probe the atmosphere over a wide angle, and the average of these wavefronts would largely represent the ground layer of the atmosphere. This average could then be corrected by an AO system and would result in improved image quality over a large field of view. A near IR multi-object spectrometer (R ~ 4000) could then work over this large field of view (> 5 arcmin) with significantly improved image quality and hence sensitivity. The AO correction may be internal to the instrument or could be provided by an adaptive secondary.

3.6.2 MID-IR DIFFRACTION-LIMITED IMAGING SPECTROMETER

Although MIRES has superb very high spectral resolution properties, there may be significant science interest in lower spectral resolution (R ~ 5 - 100) and diffraction-limited imaging in the mid-IR over a larger field than that provided by MIRES.

4 APPENDICES

The appendices below are only to be used as initial references. TMT will analyze and update this preliminary information in their traceability and flowdown.

4.1 APPENDIX A: ATMOSPHERIC TRANSMISSION FOR THE SUMMIT OF MAUNA KEA

A ground-based telescope is limited in the wavelengths it can observe. This is set fundamentally by the transparency of the atmosphere, shown here. These typical transmission curves differ somewhat from site to site and under varying conditions. 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 generally have better atmospheric transmission, particularly longward of 10 µm. We require that the telescope be functional with high throughput from 0.31 µm to 30 µm. Details of the spectrum are given by Lord.

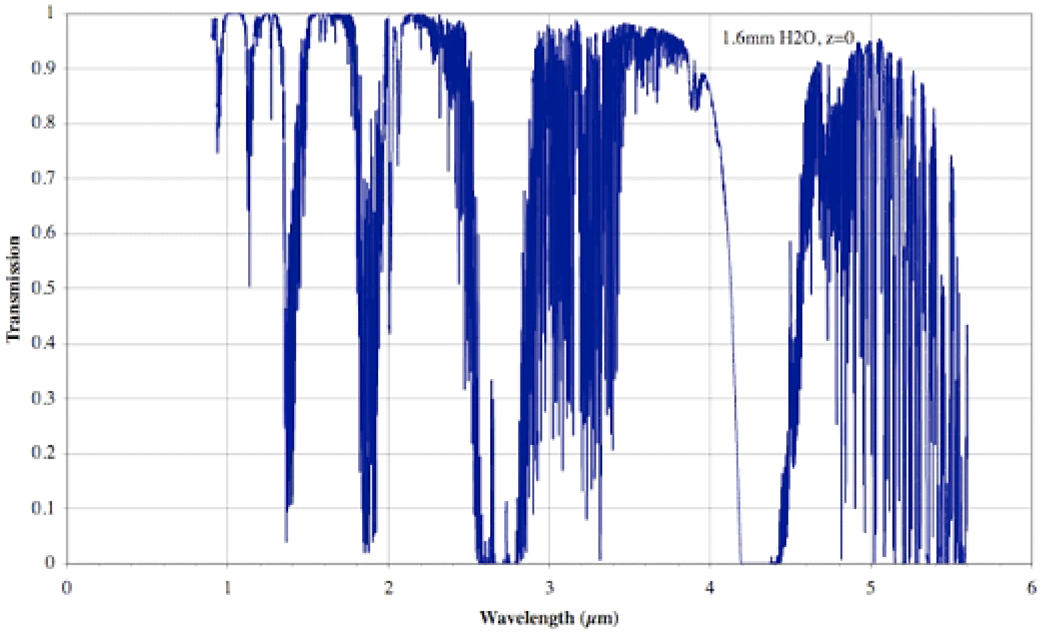

Figure 4-1 Atmospheric transmission in near-infrared (< 6 µm) - Mauna Kea

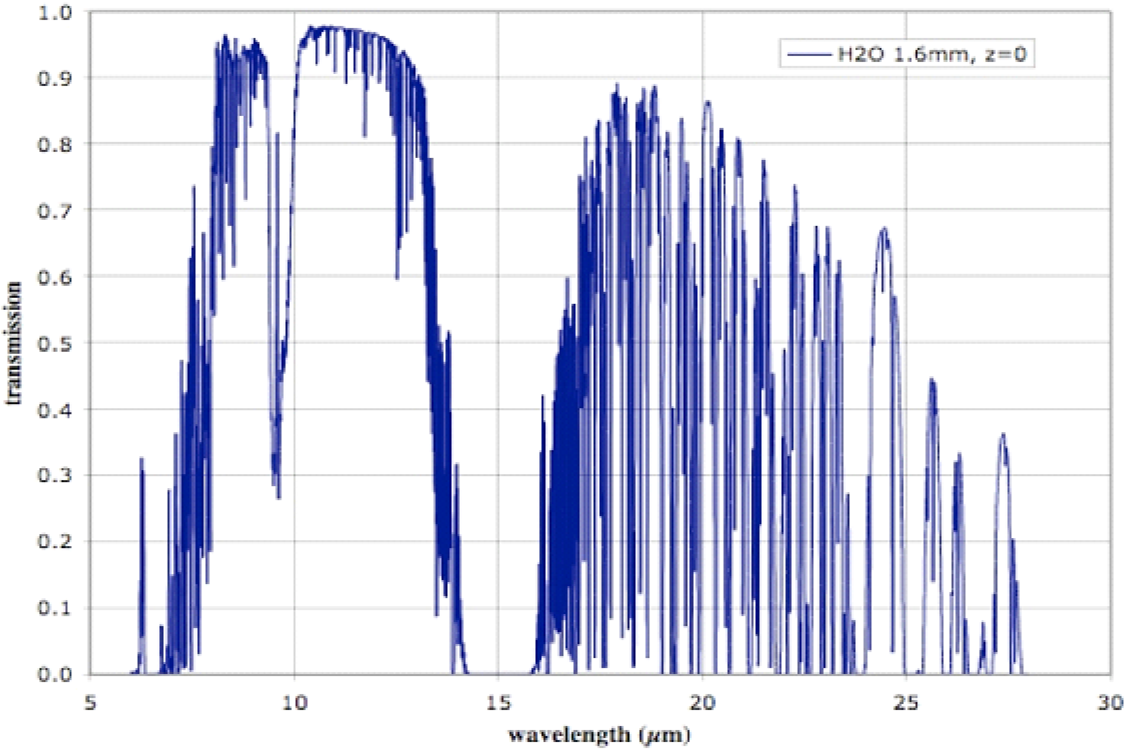

Figure 4-2 Atmospheric transmission in mid-infrared (5 - 30 μm) - Mauna Kea

4.2 APPENDIX B: 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 σ 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.

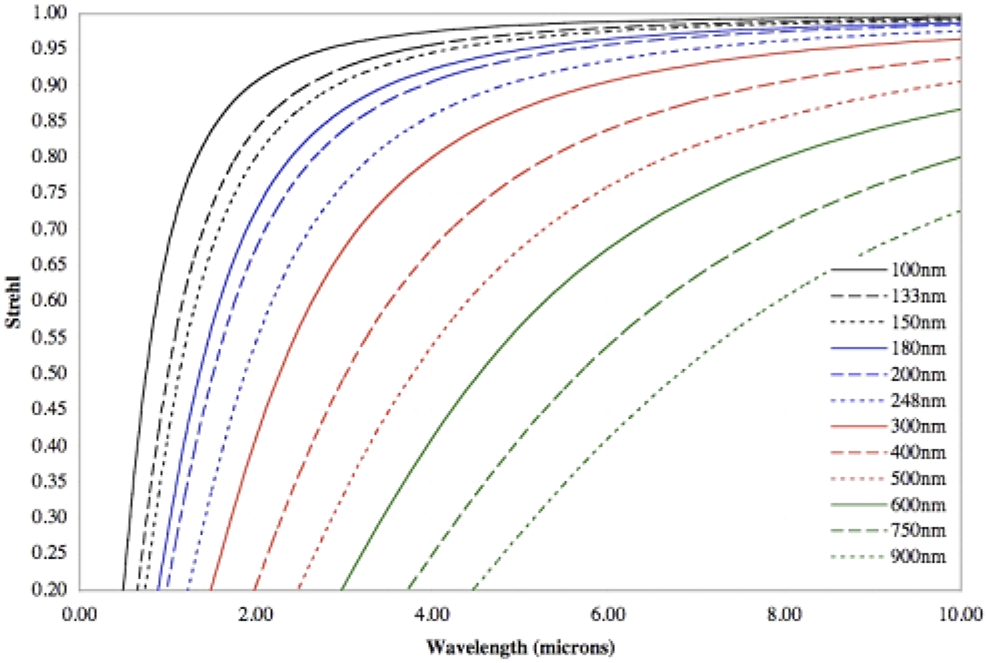

Figure 4-3 Strehl ratio versus wavelength (< 10 µm)

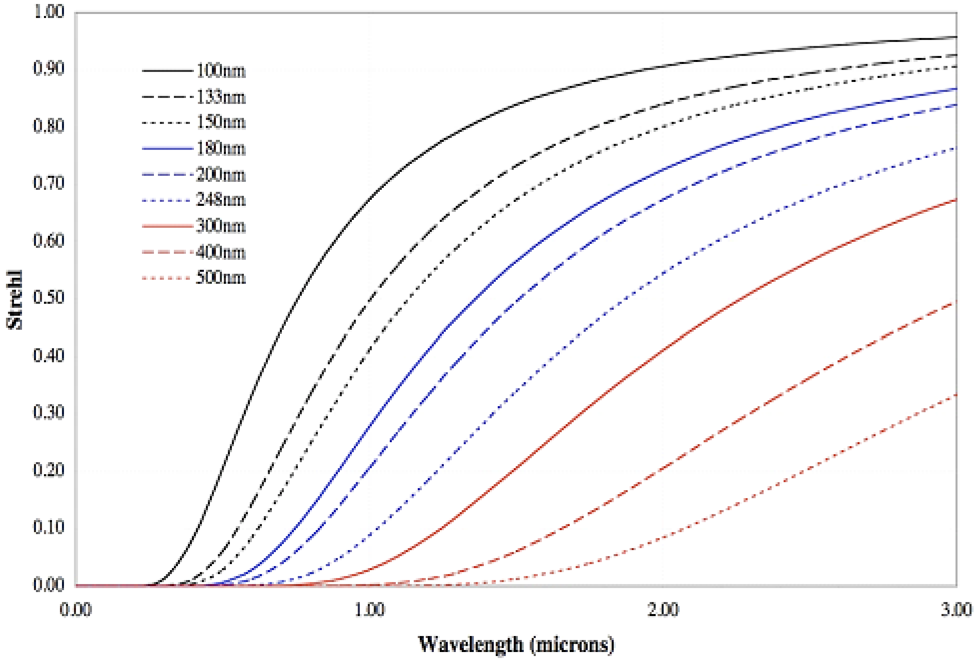

Figure 4-4 Strehl ratio versus wavelength (< 3 µm)

4.3 APPENDIX C: REFLECTIVITIES OF POTENTIAL MIRROR COATINGS

Mirror reflectivity is the most critical parameter limiting throughput. Figure 4-5 and Figure 4-6 show 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 340 nm to 10 µm. The Keck LRIS collimator coating developed by LLNL is shown in the figure. Coatings of this type will improve throughput by ~ 15% and are essential for TMT. Since TMT is a three mirror telescope, the throughput at any wavelength varies as the cube of the single mirror reflectivity curve. Actual optics also become dirty and age, so average reflectivities will be lower than those of the fresh coatings.

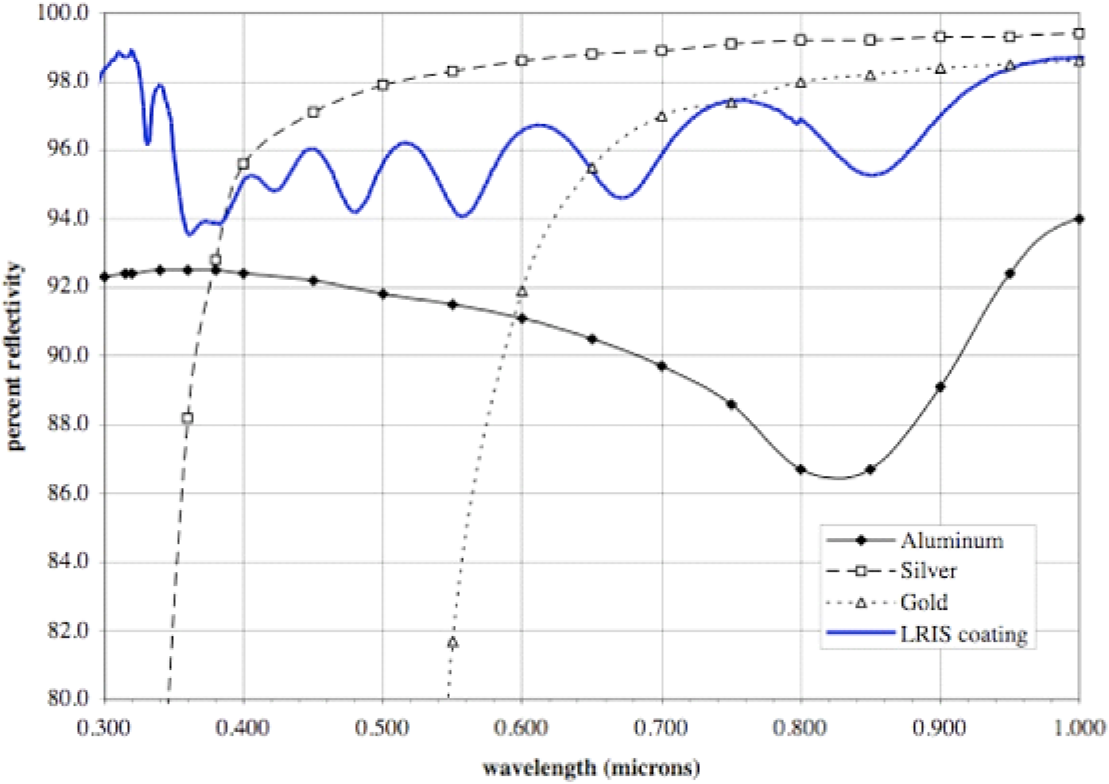

Figure 4-5 Reflectivities of Metals and LRIS coating (0.3 - 1 µm)

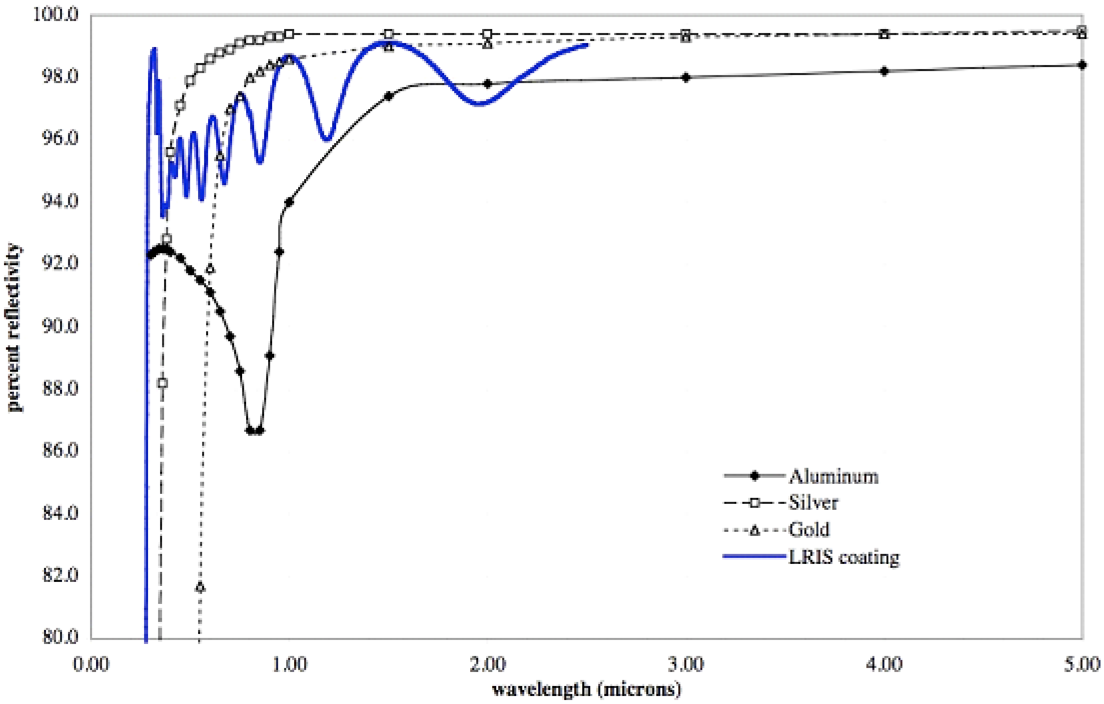

Figure 4-6 Reflectivities of Metals and LRIS coating (< 5 µm)

4.4 APPENDIX D: SKY AND THERMAL BACKGROUNDS

Shown below is the emission from the night sky in the near infrared. Also shown are typical fluxes in standard photometric bands. For reference, we also show the expected flux from a blackbody at the indicated temperatures. The finite reflectivity of the optics cause some fraction (emissivity) of the blackbody radiation to be emitted by the optics. Such local background sources are added to the natural night sky flux.

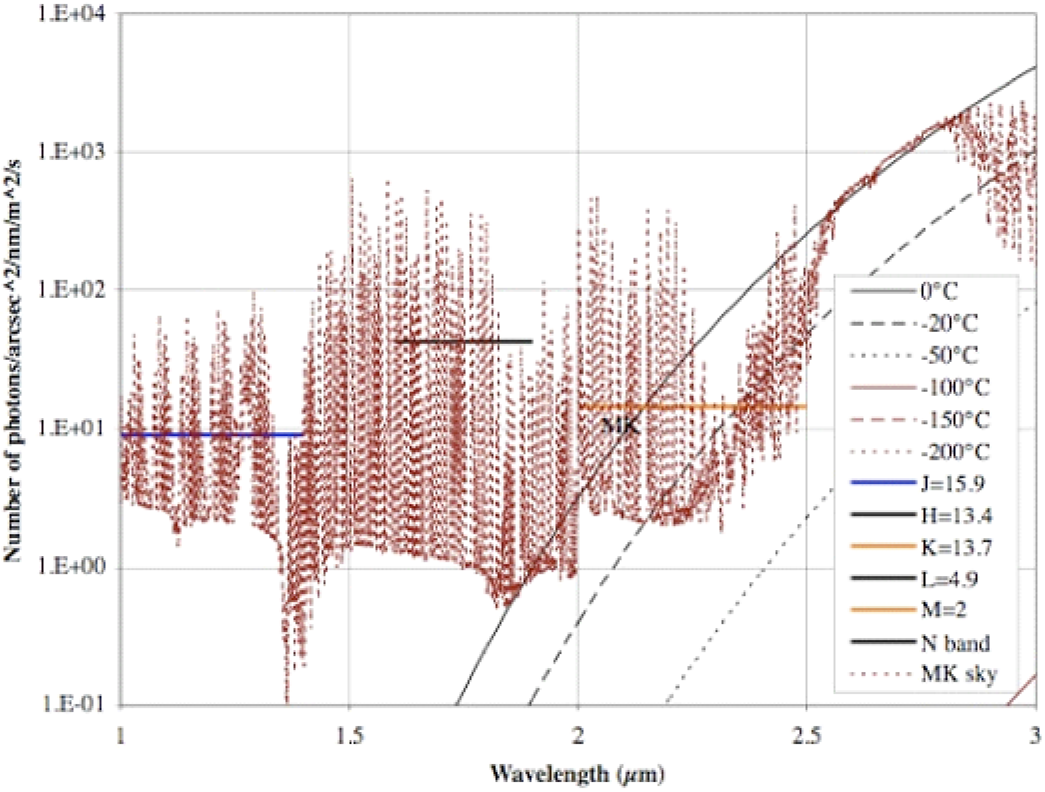

Figure 4-7 Sky (MK) and Blackbody flux versus wavelength

4.5 APPENDIX E: 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 an Armazones 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 μm)

T = 281° (90% between 2.5° and 11.3°)

Precipitable H_2O = 2.9 mm

r_0 = 0.16 m

L_0 = 30 m (highly uncertain, will make image size ~ 15% smaller than Kolmogorov atmosphere-see Tokovinin (2002)). This produces an effective r_0 that can be used to predict image size.

Effective r_0 = 0.10, 0.20, 0.30 m (10, 50, 90 percentile)

θ_0 = 2.00 arcsec

τ_0 = 3 ms

integrated C_n^2 = 3.20e-13 $m^{1/3}$

observations at the zenith

Table 4-1 C_n^2 profile of standard atmosphere

h(km)	% total C_n^2
0	0.54
0.5	0.05
1.0	0.01
2.0	0.05
4.0	0.09
8.0	0.14
16.0	0.12

θ_{iso} = 41 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.

τ_{iso} = 10 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.

4.6 APPENDIX F: STAR DENSITIES AND SKY COVERAGE FOR TIP-TILT STARS

The use of laser beacons for measurements of atmospheric wavefront errors implies that any tip-tilt components cannot be measured by the laser beacons and must be separately measured with natural guide stars (tip-tilt stars). Ideally, sky coverage analysis would use real stellar catalogs obtained from wide-field, deep surveys. However, such catalogs, especially in the near-infrared, do not yet exist (although they will exist within the near future). Therefore, we use models of the Milky Way to generate the star counts that are then incorporated into the TMT sky coverage analysis.

To date, we have used three different Milky Way models for sky average analyses: 1) Bahcall & Soneira (1980, ApJ Suppl. 44, 73) (RD5), 2) Spagna (2001, STScI-NGST-R-0013B) (RD4), and 3) Besançon (Robin, Reyle, Derriere, Picaud 2003, A&A, 409, 523 (RD7)). The Besançon model has four advantages over the other two models: 1) the output of the Besançon model is a star catalog as opposed to number counts, which gives the user access to colors as well as counts, 2) the Besançon model is the most modern Milky Way model, incorporating the latest knowledge of initial mass functions and the different kinematic components (especially compared to Bahcall & Soneira), 3) the Besançon model is refereed, well-cited, and can produce custom catalogs through an easy-to-use web interface (especially compared to the Spagna model), 4) the Besançon model can be used to generate optical and near-infrared star counts (the Spagna model gives near-infrared counts and the Bahcall & Soneira model gives optical counts). Despite the differences between the models, the predicted number counts are similar (see figure below). This is particularly true for the density of faint stars in J band at the galactic pole, i.e., the case which has been considered for all LGS MCAO sky coverage analysis to date. Because of the advantages, of working with the Besançon model, it will be adopted for use in future sky coverage analysis.

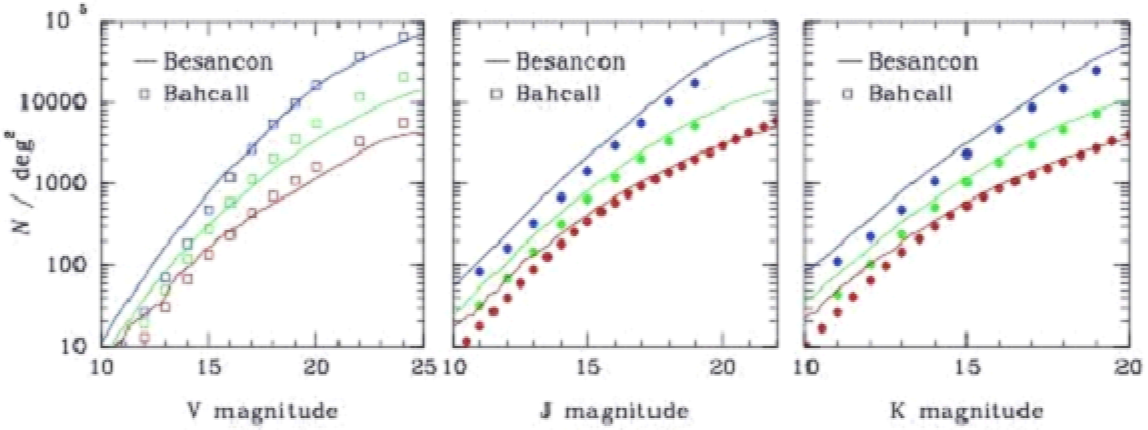

Figure 4-8 Comparison of the cumulative stars per square degree at a given magnitude predicted by different star count models.

Comparison of the cumulative number of stars per square degree at a given magnitude predicted by the Besançon model (solid lines) versus the Bahcall & Soneira model in V-band (open squares) and the Spagna model in J and K-bands (closed circles). This comparison is made at galactic latitudes of 90° (red), 50° (green) and 30° (blue) and a galactic longitude of 0°. The predicted number counts of the different models are all in close agreement. [Need to fix the legend in the J and K magnitude plots]

4.7 APPENDIX G: ASTROMETRIC CONSIDERATIONS

Astrometry with adaptive optics is not yet a mature field of endeavor and all issues associated with it are not understood. In general, the more stars in a field of view, the better slowly varying distortions can be removed and real differential motions measured.

An astrometric MCAO system must constrain quadratic field distortions using either a single natural guide star (NGS) that 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 changes 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%).

4.8 APPENDIX H: ATMOSPHERIC DISPERSION

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

$$n(\lambda) = 1.0001702 + 9.32x10^{-7}\lambda^{-2.102}$$

$$\frac{dn}{d\lambda} = -1.959x10^{-6}\lambda^{-3.102}$$

where λ is the wavelength in units of μm. (Nelson, 1994, Atmospheric Refraction at Mauna Kea, Keck Technical Note 400 (RD6))

At different sites the index of refraction (n-1) is 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

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

Table 4-2 gives the dispersive blur within various atmospheric windows of interest, evaluated for a zenith angle of 45° for Mauna Kea. We also list the diffraction limited image size (λ/D) and compare them. When the dispersed image is larger than the diffraction limit, atmospheric dispersion compensation (ADC) is useful. When this ratio is less than 1, it can probably be omitted, depending on the actual error budget of the system under consideration.

Table 4-2 Dispersive blur within various atmospheric windows of interest

Band	Wavelength (μm)	Full Width (μm)	Dispersive Blur (μm)	Diffraction λ/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

4.9 APPENDIX I: 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 λ is the observing wavelength.

The point spread function is given by

$$PSF(\theta) = K\int_{0}^{\infty} J_0(2\pi f\theta)MTF(f)fdf$$

and the enclosed energy is given by

$$EE(\theta) = 2\pi\int_{0}^{\theta} PSF(u)udu$$

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

$$\frac{\theta}{\theta_0} = \left(\frac{\lambda}{\lambda_0}\right)^{-1/5}$$

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 Keck Technical Note 331, Point Spread Functions in Astronomy (Mast, 1992) (RD8).

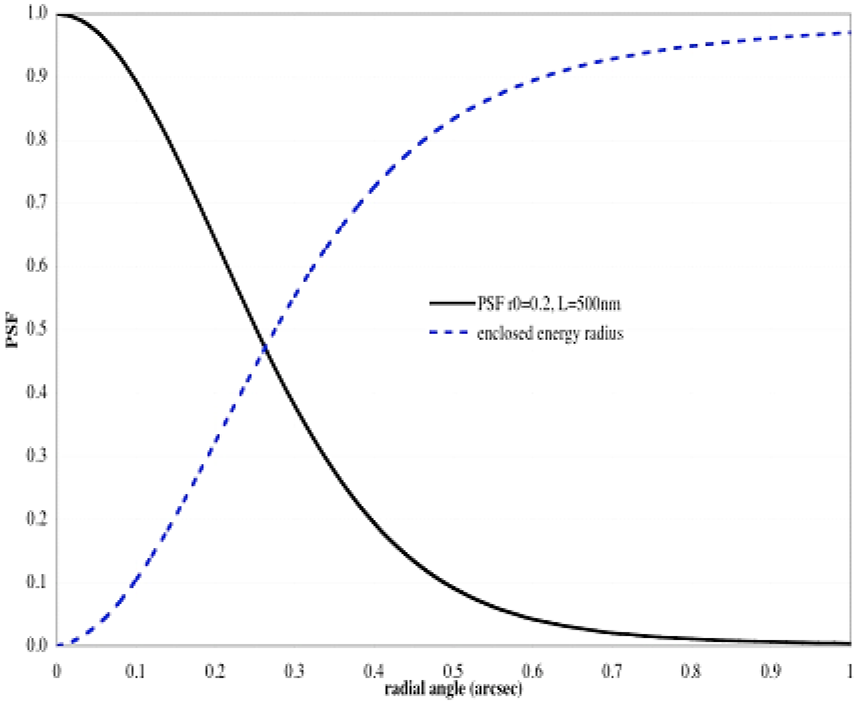

Figure 4-9 Image PSF and EE for Kolmogorov atmosphere