SCIENCE-BASED REQUIREMENTS DOCUMENT

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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 and named [REQ-0-SRD-0280] • 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 16.5mag req for K band Strehl of 0.5	See approval Page in CCR18	January 16, 2009
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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

This document describes the science-driven requirements for the Thirty-Meter Telescope (TMT) project. TMT will be the first of the next-generation giant optical/infrared ground-based telescopes and will be a flagship facility for addressing the most compelling areas in astrophysics: the nature of Dark Matter and Dark Energy, the assembly of galaxies, the growth of structure in the Universe, the physical processes involved in star and planet formation and the characterization of extra-solar planets. In the current era, 8-10m 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. A 30m-class optical/IR observatory was identified as the highest-priority ground-based facility in the 2001 National Academy of Sciences report "Astronomy and Astrophysics in the New Millennium" (RD11) (also known as the 2001 "Decadal Survey").

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 D4 (where D is the primary-mirror diameter); thus, TMT will provide a sensitivity gain of a factor more than 100 as compared to current 8m 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 recently-discovered tight correlation between central black hole mass and stellar bulge velocity dispersion strongly implies that black hole formation and growth is closely tied to the processes that form galaxies. This result also suggests that super massive black holes are at the centers of most or all large galaxies. The TMT combination of high spatial resolution and moderate-to-high spectral resolution will provide unprecedented capability for extending the detection and investigation of central black holes to cosmological redshifts. In addition to investigations designed to understand the black hole-galaxy growth issue, nearby supermassive black holes can be analyzed with very high physical resolution. This will allow us to measure

general relativistic effects at the center of the Galaxy and to spatially resolve the accretion disks for active black holes in the centers of galaxies to the distance of the Virgo cluster.

- Exploration of planet-formation processes and the characterization of extra-solar planets. Two of the most exciting challenges to astrophysics in the next decades are to understand the physical processes that lead to star and planet formation and to characterize the properties of extra-solar planets. TMT will 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-based 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.

Because of the long lifetime of TMT and the often-rapid advancement of astrophysics into new areas, this document emphasizes capabilities whose broad applications to current astrophysical problems are clear at this time, and where the gains in sensitivity and angular resolution provide for a large “discovery space” for phenomena that are currently unknown.

The level of scientific detail presented here is deliberately limited so that the technical requirements are provided in a compact and easily readable form. More detailed discussion of specific science cases that have been used to drive the science-based requirements can be found in the TMT Detailed Science Case (RD6).

The proposed TMT capabilities are divided into “Early Light” and ”First Decade”. The Early Light suite of capabilities includes a facility adaptive optics (AO) system that will provide diffraction-limited images over the wavelength range 0.8-2.5 μm from the very start of TMT operations. The initial AO system (NFIRAOS) will deliver wavefront errors under 190 nm rms, over a 30-arcsec field of view; within 5 years we expect that delivered wavefront errors will drop to no more than 133 nm rms over 30 arcsec and 120 nm rms on axis. Additional adaptive optics systems optimized for the mid-IR (MIRAO) and for near-IR correction of numerous small patches of sky over a large (5 armin) field of view (MOAO) are also expected within the first decade of operations.

Early Light Capabilities:

- Near-IR Adaptive Optics System (NFIRAOS): a dual-conjugate (MCAO) system provides diffraction-limited images over the wavelength range 0.8-2.5μm over a 30 arcsec field, and partially-corrected images over a >2 arcmin field.
- InfraRed Imaging Spectrometer (IRIS); Diffraction-limited, R~4000 spectral resolution, 0.8μm to 2.5μm 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, 0.31-1μm spectroscopy over a wide (~40 arcmin2) field.
- Infrared Multislit Spectrometer (IRMS): Near-IR (0.95-2.45μm) imaging spectrometer (R~3000-5000) that will use a multi-slit mechanism over a contiguous field of view of ~2’ with >40 slits. IRMS is used behind the NFIRAOS AO system, taking advantage of the substantial

AO correction over the full field; it is expected to provide some of the IRMOS capabilities for early light.

First Decade Capabilities:

- InfraRed Multi-Object Spectrometer (IRMOS): near-diffraction limited, R~2000 – 10000 IFU-based spectrometer operating over a wavelength range 0.8-2.5µm. Will use multiple IFUs and access a 5 arcmin diameter field. It is expected to benefit from developments in multi-object adaptive optics (MOAO).
- Mid-IR High-resolution Echelle Spectrometer (MIRES): Diffraction-limited, 5000 < R < 100,000 spectral resolution, 8-28µm spectroscopy. MIRES will also have a mid-IR imaging/slit viewing capability.
- 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 – 2.5µm region. For bright stars (I<8) will be able to detect planets108 times fainter than the parent star, with a goal of 109, at angular distances greater than 50mas from the star.
- Near-IR High-resolution Echelle Spectrometer (NIRES): Diffraction-limited, high-spectral-resolution (20000 < R < 100,000) echelle spectroscopy in the 1-2.5µm and 3-5µm range. NIRES will operate 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 0.31µm to 1µm (or longer if detectors exist that will allow it) with wide spectral coverage in a single exposure. This capability will likely be achieved via a large, echelle spectrometer.
- Wide-field Infrared Camera (WIRC): Diffraction-limited imaging in the 0.8-5µm wavelength range over a > 30 arcsec contiguous field.

2. INTRODUCTION

2.1 BACKGROUND AND MOTIVATION

A 30m-class "Giant Segmented Mirror Telescope" was the top priority recommendation of the 2001 Astronomy and Astrophysics Decadal Survey of the U.S. National Research Council. The Survey also recommended that this telescope be a public-private partnership. Such a telescope, operating from the UV to the mid-IR, is seen as an essential tool for science ranging from understanding star and planet formation to unraveling the history of galaxies and the development of structure in the universe. Because of the extremely high angular resolution achievable at the diffraction limit of a 30m aperture, and because of the ten-fold increase in collecting area over existing optical/IR telescopes, such a facility will mark gains in sensitivity over existing facilities ranging from a factor of 10 to a factor of 100, depending on the application. The "GSMT" is also envisioned to play an essential complementary role to the James Webb Space Telescope (JWST), an infrared optimized 6.5m aperture space telescope to be launched early in the next decade, and the Atacama Large Millimeter Array (ALMA), an array of 64 antennae that will revolutionize astrophysics at sub-mm and mm wavelengths. Many of the key scientific questions to be addressed by the next generation giant ground-based telescope are in common with those of JWST and ALMA; the complementary power of state-of-the art telescopes on the ground is largely based on the ability to obtain spectra of extremely faint sources in the optical and near-IR, and to achieve unprecedented angular resolution when operating at the diffraction limit at wavelengths between 0.6 and 30 µm.
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 30m segmented-mirror telescope, the adaptive optics (AO) systems required to achieve diffraction-limited performance, and the instruments required to use this facility to address the most compelling questions in astrophysics in the coming decades.

2.2 BASIS FOR SCIENCE REQUIREMENTS

This document describes the science-driven capabilities required of the TMT as agreed to by the TMT Science Advisory Committee (SAC) representing the three partners in the project. To accommodate the science-based goals, the SRD describes the requirements on the TMT site characteristics, the telescope performance, the adaptive optics (AO) performance and the instrument suite and performance. Specific science drivers and the flow down from science case to requirements and goals are described in depth in TMT Report 53, the "Detailed Science Case", which is available together with other reports at http://www.tmt.org/documents. 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 10m telescopes (e.g. extra-solar planets, the accelerating Universe, the nature of gamma-ray bursts sources) were not part of the original science case on which the observatory design was based. Thus, the TMT science-based requirements have also been 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 2.4m Hubble Space Telescope and spectra from the largest ground-based telescopes. However, the current generation of 8 and 10m telescope will be unable to provide spectra of faint sources discovered with a 6m O/IR space telescope. We will require the capabilities of TMT to take full advantage of the discoveries made by JWST (and other future missions).

2.3 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 early-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, 50% or more of the time the telescope may be used for seeing-limited (i.e., UV/optical) 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).

In order to enable these diffraction-limited capabilities, an adaptive optics system is needed for TMT. We will require an initial AO system that delivers wavefront errors below 190 nm rms over a 30 arcsec field of view, in median seeing, with at least 50% sky coverage at the galactic pole. Within a few years an AO system that delivers rms wavefront errors below 120 nm on axis and 133 nm over 30 arcsec field of view, and provides excellent correction over 2 arcmin field of view should be possible.

2.3.1 Early-Light Capabilities

- Near-IR Adaptive Optics System (NFIRAOS): a dual-conjugate (MCAO) system provides diffraction-limited images over the wavelength range 0.8-2.5µm over a 30 arcsec field, and partially-corrected images over a >2 arcmin field.
- InfraRed Imaging Spectrometer (IRIS); Diffraction-limited, R~4000 spectral resolution, 0.8µm to 2.5µm 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 < 5000 spectral resolution, 0.31-1µm spectroscopy over a wide (~40 arcmin^2) field.
- Infrared Multislit Spectrometer (IRMS): Near-IR (0.95-2.45µm) imaging spectrometer (R~3000-5000) that will use a multi-slit mechanism over a contiguous field of view of ~2’ with >40 slits. IRMS is used behind the NFIRAOS AO system, taking advantage of the substantial AO correction over the full field; it is expected to provide some of the IRMOS capabilities for early light.

2.3.2 First Decade Capabilities

- InfraRed Multi-Object Spectrometer (IRMOS): near-diffraction limited, R~2000 – 10000 IFU-based spectrometer operating over a wavelength range 0.8-2.5µm. Will use multiple IFUs and access a 5 arcmin diameter field. It is expected to benefit from developments in multi-object adaptive optics (MOAO).
- Mid-IR High-resolution Echelle Spectrometer (MIRES): Diffraction-limited, 5000 < R < 100,000 spectral resolution, 8-28µm spectroscopy. MIRES will also have a mid-IR imaging/slit viewing capability.
- 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 – 2.5µm region. For bright stars (I<8) will be able to detect planets108 times fainter than the parent star, with a goal of 109, at angular distances greater than 50mas from the star.
- Near-IR High-resolution Echelle Spectrometer (NIRES): Diffraction-limited, high-spectral-resolution (20000 < R < 100,000) echelle spectroscopy in the 1-2.5µm and 3-5µm range. NIRES will operate 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 0.31µm to 1µm (or longer if detectors exist that will allow it) with wide spectral coverage in a single exposure. This capability will likely be achieved via a large, echelle spectrometer.
- Wide-field Infrared Camera (WIRC): Diffraction-limited imaging in the 0.8-5µm wavelength range over a >30 arcsec contiguous field.

2.4 GENERAL COMMENTS REGARDING LARGE-TELESCOPE CAPABILITIES

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

A 30-m class ground-based telescope operating from the UV to the mid-IR will contribute in unique ways to astrophysical discovery, and the nature of these contributions is largely a function of wavelength. In the UV and optical part of the electromagnetic spectrum (0.31-1µm), 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 1-2.5µm, 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 1-2.5µm as compared to 0.4µm.

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 6.5-10m telescopes to a 30m 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 will be 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, RD4) 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.

2.5 SUMMARY TABLE OF CAPABILITIES: EARLY-LIGHT + FIRST DECADE

Table 2-1 Instrument Capabilities

FUNCTION/NAME	MODE	FIELD OF VIEW	SPECTRAL RESOLUTION	WAVELENGTH RANGE (μM)	COMMENTS
InfraRed Imager and Spectrometer (IRIS)	DL	<3" IFU >15"imaging	> 3500 5-100(imaging)	0.8 – 2.5 0.6 – 5(goal)	NFIRAOS
Wide-field Optical spectrometer and imager (WFOS)	SL	>40 arcmin^2 >100 arcmin^2 (goal) Slit length>500"	1000-5000@0.75" slit >7500 @0.75" (goal)	0.31-1.0 0.3-1.5(goal)	
InfraRed Multislit Spectrometer (IRMS)	n-DL	2 arcmin field, up to 120" arcsec total slit length with 46 deployable slits	R=4660 @ 0.16 arcsec slit	0.95-2.45	NFIRAOS
Multi-IFU imaging spectrometer (IRMOS)	n-DL	3" IFUs over >5' diameter field	2000-10000	0.8-2.5	MOAO
Mid-IR AO-fed echelle spectrometer (MIRES)	DL	3" slit length 10" imaging	5000-100000	8-18 4.5-28 (goal)	MIRAO
Planet Formation Instrument (PFI)	DL	1" outer working angle, 0.05" inner working angle	R=100	1-2.5 1-5 (goal)	10^8 contrast 10^9 goal
Near-IR AO-fed echelle spectrometer (NIRES)	DL	2"slit length	20000-100000	1-5	NFIRAOS
High-Resolution Optical Spectrometer (HROS)	SL	5" slit length	50000	0.31-1.1 0.31-1.3(goal)	
"Wide"-field AO imager (WIRC)	DL	30" imaging field	5-100	0.8-5.0 0.6-5.0(goal)	MCAO

2.6 SCOPE

This document contains science-based requirements in the following areas:

- General Constraints
- Telescope and Instrumentation Requirements
- Site and enclosure requirements
- Adaptive Optics Requirements
- Early-light Instrumentation Requirements
- First-Decade Instrumentation Requirements

- Data Handling Requirements
- Nighttime operations Requirements

2.7 APPLICABLE DOCUMENTS

AD1 DELETED

2.8 REFERENCE DOCUMENTS

RD1
California Extremely Large Telescope: Conceptual Design for a Thirty-Meter Telescope
CELT Report Number 34
http://authors.library.caltech.edu/46821/

RD2
Enabling a Giant Segmented Mirror Telescope for the Astronomical Community
http://www.gsmt.noao.edu/book/

RD3
VLOT Project Book Section A. Table of Contents
TMT.SEN.TEC.03.001
https://docushare.tmt.org/docushare/dsweb/Get/Document-181

RD4
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

RD5
Frontier Science Enabled by a Giant Segmented Mirror Telescope, Prepared for the Astronomy Division of the NSF by the GSMT Science Working Group

http://www.gsmt.noao.edu/gsmt_swg/SWG_Report/SWG_Report_7.2.03.pdf

RD6 Detailed Science Case (DSC)
TMT.PSC.TEC.07.007
https://docushare.tmt.org/docushare/dsweb/Get/Document-32176

RD7
A New Software Tool for Computing Earth's Atmospheric Transmission of Near- and Far-Infrared Radiation by Steven D. Lord
NASA-TM-103957
http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19930010877.pdf

RD8
From Differntial Image Motion to Seeing by Tokovinin, A.
PASP Vol. 114:1156-1166,
Number 800
http://iopscience.iop.org/article/10.1086/342683?fromSearchPage=true

RD9
Guide Star Requirements for NGST: Deep NIR Starcounts and Guide Star Catalogs by Spagna, A.
STScI-NGST-R-0013B
http://adsabs.harvard.edu

RD10
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

RD11
Astronomy and Astrophysics in the New Millennium, Astronomy and Astrophysics Survey Committee, Commission on Physical Sciences, Mathematics and Applications, National Research Council
http://www.nap.edu/openbook.php?isbn=0309070317

RD12 DELETED

RD13 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

RD14 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

RD15 Astrometry with TMT – Cameron Lu
TMT.AOS.PRE.07.036
https://docushare.tmt.org/docushare/dsweb/Get/Document-9167

RD16 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

2.9 ABBREVIATIONS

See Table below

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
IRMS	Infrared Multi-Slit Spectrometer
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
WIRC	Wide Field Infrared Camera

3. SCIENCE-BASED REQUIREMENTS

3.1 TELESCOPE

3.1.1 General Description

[REQ-0-SRD-0010] Expected science covers a wide range of wavelengths, generally needing the highest sensitivities or angular resolution.

Discussion: Wavelength limitations due to the atmosphere are given in Appendix 1. The TMT will be the largest ground-based telescope in the world. It will carry out a variety of forefront science over a wide range of wavelengths. The telescope requirements are designed to support these expected and potential future uses.

[REQ-0-SRD-0015] Initially, the telescope is expected to be used roughly 50% of time for seeing-limited observations and 50% of the time for diffraction-limited observations (using AO).

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.

3.1.2 Optical

3.1.2.1 Optical Configuration

[REQ-0-SRD-0045] Segmented mirror primary, entrance pupil equivalent to 30m diameter.

[REQ-0-SRD-0050] Aplanatic configuration 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.

[REQ-0-SRD-0055] Prime focus is not required

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

[REQ-0-SRD-0060] Cassegrain focus is not required.

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

[REQ-0-SRD-0065] Two Nasmyth foci with two large Nasmyth platforms needed with expected sizes each of ~350m^2 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.

3.1.2.2 Image and Wavefront Quality

[REQ-0-SRD-0070] Telescope image quality should 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=0.8m. 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 9 for reference.

[REQ-0-SRD-0075] We require the telescope to introduce additional wave front errors that are smooth and small compared to the site median atmosphere.

Discussion: Since we plan extensive use of adaptive optics, where diffraction limited performance is desired, we also constrain the image and wave front quality in a language suitable for AO. AO systems are capable of correcting relatively low order aberrations in the wave front.

[REQ-0-SRD-0080] Exoplanets must be detectable at a contrast ratio of 1e-8 of the parent star in H-band

Discussion: Requirements will vary from application to application, but the most stringent application is for Extreme Adaptive Optics, used to detect planets around stars. This could be achieved with an AO system with a 128x128 DM

[REQ-0-SRD-0085] Actual speckle amplitude should be no more than 1e-7.

Discussion: See the PFI instrument requirements for details

[REQ-0-SRD-0090] Prior to AO, individual segment wavefront errors should be no more than about 20 nm rms.

Discussion: Individual segment surface smoothness and accuracy is critical to achieve [REQ-0-SRD-0085].

[REQ-0-SRD-0100] Telescope optical errors must be sufficiently small and smooth that a 60x60 deformable mirror can reduce the optical errors to 45 nm rms wavefront.

Discussion: This is needed to allow high Strehl observations

[REQ-0-SRD-0105] Telescope optical errors must be sufficiently small and smooth that a 128x128 deformable mirror can reduce the optical errors to 25 nm rms wavefront.

[REQ-0-SRD-0110] Image blur is allowed to degrade as $(\sec z)^{3/5}$

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

[REQ-0-SRD-0115] Wavefront errors are allowed to degrade as $(\sec z)^{1/2}$.

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

3.1.2.3 Atmospheric Dispersion Compensation (ADC)

[REQ-0-SRD-0120] ADC compensation will be needed and applied either by the telescope, 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 8. Specific ADC requirements will vary with instruments.

3.1.2.4 Throughput

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

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

[REQ-0-SRD-0130] Telescope night-time lost to servicing mirrors should be minimized.

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

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

Discussion: Thin members will block light and also diffract an equal amount of light into large angles where it is useless, hence the blockage is effectively twice the cross-sectional area.

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

3.1.2.5 Backgrounds and Stray Light

[REQ-0-SRD-0145] Telescope shall be unbaffled.

Discussion: Stray light is a potential problem for science observations. This may be mitigated by telescope baffles or by instrument baffles. Determining the optimal solution will require detailed trade studies. Consideration of both emissivity and wind buffeting suggest it is better to resolve this within the instrument.

[REQ-0-SRD-0150] Thermal background radiation from the telescope and its optics should be minimized. Including primary, secondary and tertiary (M1+ M2+ M3), total thermal background should be ≤ 5% of a blackbody at the average ambient night-time temperature for fresh coatings.

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

[REQ-0-SRD-0155] The reflectivity of the telescope optics should be as high as possible to minimize thermal emission.

[REQ-0-SRD-0160] The secondary support structure also adds thermal background and its optical cross section should be minimized.

Discussion: Beyond these measures, it may be necessary to cool all optics beyond M1, M2, and M3 (which must be in an ambient environment). The brightness of the night sky and black body radiation curves are shown in Appendix 4.

[REQ-0-SRD-0165] Mirrors shall be cleaned frequently to preserve their low emissivity and high reflectivity.

Discussion: Actual cleaning frequency will depend on site characteristics but is likely to exceed 1/month.

3.1.3 Motion

3.1.3.1 Slewing and Acquiring

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

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] To support the efficient acquisition of science objects, the telescope system shall be able to quickly perform accurate acquisition offsets without guider feedback.

[REQ-0-SRD-0215] To support the efficient acquisition of science objects, the telescope system shall be able to perform accurate acquisition offsets of up to 1 degree on the sky.

3.1.3.2 Pointing and Offsetting

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

[REQ-0-SRD-0220] Point to 1 arcsec rms in each direction 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 system shall be able to perform accurate guider offsets of up to 5 arcminutes on the sky.

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

3.1.3.3 Guiding

[REQ-0-SRD-0235] Guiding/tracking is possible for rates that are up to 10% different from sidereal rates and with an error contained within the overall image blur specification in 2.1.2.2.

3.1.3.4 Zenith and Azimuth Angle Range

[REQ-0-SRD-0240] The telescope is required to operate within specifications from within 1° of zenith 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.

[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 be designed to be able to 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.

3.1.3.5 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 TMT must be able to nod (motion of the telescope), spending at least 80% of the cycle at the end points.

[REQ-0-SRD-0255] Position errors at the end points shall be no more than 0.01 arcsec rms for seeing-limited observations

[REQ-0-SRD-0260] Position errors at the 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] Nod amplitude of ±1 arcsec with a half period of 10 seconds with 80% integration should be possible.

[REQ-0-SRD-0270] Nod amplitude of ±10 arcsec with a half period of 20 seconds with 80% integration should be possible.

[REQ-0-SRD-0275] Chopping by the secondary mirror is not needed for the TMT

[REQ-0-SRD-0280] Telescope motions shall be able to support a pattern of non-redundant dithers extending over a period of 4 hours with a time interval between two consecutive dithers 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.

3.1.4 Instrument Support

3.1.4.1 Space

[REQ-0-SRD-0300] Require sufficient space at the telescope foci for large (~400m^3) instruments, with individual masses <~50 metric tons

3.1.4.2 Support facilities

[REQ-0-SRD-0305] Require power, cooling, signal lines, servicing equipment at instrument locations.

[REQ-0-SRD-0310] Also require convenient access to instruments by personnel for servicing and repairs.

3.1.4.3 Rapid access

[REQ-0-SRD-0315] Require ability to begin observing with any instrument, at night, in <10 minutes.

> Discussion: With queue scheduled instruments, ready availability is essential for the virtues of the scheduling to be gained. Even in classically scheduled observations, the ability to switch instruments will allow for rapid reaction to changing conditions or targets of opportunity.

3.1.4.4 Field rotation

[REQ-0-SRD-0320] Observatory must make suitable plans to correct for field rotation for all instruments. Field rotation rates are larger near the zenith, and must satisfy 2.1.3.4.

3.2 SITE

3.2.1 General Description

The site is not known at this time. The principal parameters to be measured for use in the final site analysis are identified and are incorporated into a signal-to-noise based merit function. This science metric function to aid in site selection has been developed in collaboration with the Site Testing Group. This allows technical/science comparison of site potential.

3.2.2 Key Astronomical Features

[REQ-0-SRD-0400] High fraction of clear nights.

[REQ-0-SRD-0405] Excellent image quality (large r_0, easier to achieve AO performance).

[REQ-0-SRD-0410] Large isoplanatic angle (larger field of view for AO).

[REQ-0-SRD-0415] Long coherence time of atmosphere (easier for AO).

[REQ-0-SRD-0420] Smaller outer scale (L_0, improved image quality, easier AO).

[REQ-0-SRD-0425] High fraction of spectroscopic nights.

[REQ-0-SRD-0430] Low precipitable water vapor distribution (lower IR absorption).

[REQ-0-SRD-0435] Low typical temperatures (lower thermal background).

[REQ-0-SRD-0440] High altitude (transparency, low water vapor, low temperature, smaller atmosphere dispersion).

3.2.3 Other Performance Related Features

[REQ-0-SRD-0455] Low wind speed distribution to limit telescope buffeting.

[REQ-0-SRD-0460] Minimal change of temperature during the night (telescope and instrument athermalization).

[REQ-0-SRD-0465] Minimal seasonal temperature variations.

[REQ-0-SRD-0470] Minimal day-night temperature variations.

[REQ-0-SRD-0475] Latitude (science opportunities, complementary with existing or future observatories).

3.2.4 Cost Related Features

[REQ-0-SRD-0480] Easy physical access for minimizing construction costs.

[REQ-0-SRD-0485] Good human access for minimizing operating costs.

[REQ-0-SRD-0490] Availability of site.

3.2.5 Other Engineering/Safety Features

[REQ-0-SRD-0495] High mechanical integrity of soil.

[REQ-0-SRD-0500] Low seismicity.

3.2.6 Assumed Model Atmosphere

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

3.3 ENCLOSURE

3.3.1 Opening Size and Tracking

[REQ-0-SRD-0550] Opening should be sufficiently large to avoid vignetting of light from the science field or from laser guide stars.

[REQ-0-SRD-0555] Enclosure motion should follow motion of the telescope precisely enough that vignetting of the science field and or laser guide stars by the dome is avoided.

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

3.3.2 Slewing

[REQ-0-SRD-0560] Enclosure motions should never be a cause of delays in beginning scientific observations.

3.3.3 Wind Protection

[REQ-0-SRD-0565] 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 specification (2.1.2.2) must be met when integrating over the wind speed probability distribution.

[REQ-0-SRD-0575] The enclosure design should minimize the amplitude and temporal frequency of these forces.

3.3.4 Thermal Control and Locally Induced Seeing

[REQ-0-SRD-0580] Thermally induced seeing degradation caused by temperature differences should 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.

3.3.5 Weather Protection

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

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

[REQ-0-SRD-0590] Condensation on the optics should be prevented at all times.

[REQ-0-SRD-0595] Liquid drips on the primary should be avoided.

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

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

[REQ-0-SRD-0610] Daytime infiltration is a potential source of excess heat and needs to be minimized.

3.3.6 Dust Protection

[REQ-0-SRD-0615] Design of the enclosure should minimize the accumulation of dust on the telescope.

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.

3.3.7 Opening and Closing

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

3.3.8 Servicing

[REQ-0-SRD-0625] Observatory must provide suitable servicing facilities for telescope, optics, AO, and instruments

3.4 ADAPTIVE OPTICS

There are a number of different science observational modes requiring adaptive optics to achieve diffraction-limited performance in the 0.6μm-28μm wavelength range. Here we summarize these modes; more detailed requirements are presented below

- **Narrow Field, Diffraction-Limited, Near-IR, or Narrow Field IR Adaptive Optics System (NFIRAOS):** We expect this mode will be used for NIR spectroscopy with an on-axis IFU or slit sampled at or near the diffraction limit. The delivered field need only be 10 arcsec for this application (but with nearly 100% sky coverage), but in addition, a contiguous 30″ field is required that delivers near-IR images of high Strehl to an imager or other instrument. 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 0.6-2.5μm 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 > 1.6μm.
- **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 0.6-2.5μm range, and should be optimized for throughput and low emissivity.
- **Small Field, Diffraction-Limited Mid-IR (MIRAO):** the highest priority mid-IR science (5-28μm) 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.

3.4.1 Overall efficiency of Adaptive Optics modes

[REQ-0-SRD-0700] The AO systems should be available on 10-minute notice.

[REQ-0-SRD-0705] Down time due to technical problems should be under 1%.

[REQ-0-SRD-0710] Night-time calibration should need no more than 1% of the observing time.

3.4.2 Small Field, Diffraction-Limited, Near-IR (NFIRAOS)

3.4.2.1 General description

This AO system is intended to deliver diffraction-limited images over a small field, sufficient for either an IFU or a slit, 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. Instruments to be fed by NFIRAOS include a multislit spectrometer with a 2.3 arcmin field of view. 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 16.5^{th} magnitude guide star.

3.4.2.2 Wavelength range

[REQ-0-SRD-0800] Over 0.8-2.5µm the throughput should exceed 85%, goal is 0.6µm to 2.5µm

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

3.4.2.3 Field of view

[REQ-0-SRD-0805] The diameter of the field of view should be 30 arcsec with high Strehl ratio.

[REQ-0-SRD-0810] There should be no vignetting over a 2.0 arcmin field of view.

[REQ-0-SRD-0815] No more than 30% vignetting over a 2.3 arcmin field of view, and useful AO correction should be achieved over this field.

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

3.4.2.4 Image/wavefront quality

[REQ-0-SRD-0820] Tilt-removed RMS wavefront error should be less than 173 nm on axis, in median seeing conditions, for NFIRAOS with a goal of less than 120nm for NFIRAOS upgrade

Discussion: RMS tip-tilt errors should be as small as natural guide star density will allow. All wavefront errors except tip-tilt are included, down to the instrument detector. The intent is to achieve Strehl ratios of better than 0.5 at 1μm for feeding a diffraction-limited slit or IFU. Achieving the stated photometric and astrometric accuracy is critical. An ADC will be needed and should be in the AO system or instrument

[REQ-0-SRD-0825] Tilt-removed RMS WFE should be less than 190nm over a 30 arcsec field of view, in median seeing conditions, for NFIRAOS with a goal of less than 133nm for NFIRAOS upgrade.

Discussion: RMS tip-tilt errors should be as small as natural guide star density will allow. All wavefront errors except tip-tilt are included, down to the instrument detector. The intent is to achieve Strehl ratios of better than 0.5 at 1μm for feeding a diffraction-limited slit or IFU. Achieving the stated photometric and astrometric accuracy is critical. An ADC will be needed and should be in the AO system or instrument

[REQ-0-SRD-0835] Over a larger 2.3 arcmin field of view, we would like the image size to be small, so slits with 160-250mas slit width will collect most of the energy.

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

Discussion: Seeing-limited value is 9%.

[REQ-0-SRD-0845] Under median conditions, the K band energy in a 160mas slit should be at least 50% averaged over the field of view.

Discussion: Seeing-limited value is 13%.

3.4.2.5 Sky coverage

[REQ-0-SRD-0850] Sky coverage should be > 50% at the galactic poles, with < 2 mas rms tip-tilt jitter.

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

3.4.2.6 Background

[REQ-0-SRD-0855] The AO system should not increase the (inter-OH) background by more than 15% over natural sky (see Appendix 4) + telescope background (assume 5% emissivity at 273K).

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

3.4.2.7 Differential Photometric Precision

[REQ-0-SRD-0860] Systematic errors in differential photometry due to PSF residual spatial variability should be under 2% for 10-minute integrations, at 1μm, over the 30 arc-sec FOV.

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

3.4.2.8 Absolute Photometric Accuracy

[REQ-0-SRD-0865] With suitable observations of photometric standards, photometry on an absolute scale should be possible to <10% with a goal of 5%.

3.4.2.9 Differential Astrometry

[REQ-0-SRD-0870] Residual time-dependent rms distortions (after a fit to physically allowed distortion measured with field stars) should be no larger than 50 μas in the H band, for a 100s integration time. Errors should fall as $t^{-1/2}$. These are one-dimensional position uncertainties. This should be achieved over a 30 arcsec FOV. Systematic errors should be no more than 10 μas.

Discussion: We assume that there will be modest static field distortions, but these will be removed by initial calibration and the use of field stars within the image that can remove residual "static" errors that the AO system might 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 will enable important scientific programs. Every effort should be made to achieve a 10 μas floor, or less.

3.4.2.10 Operational Modes:

3.4.2.10.1 Multiple lasers

[REQ-0-SRD-0875] In order to achieve significant sky cover as described above, multiple synthetic beacons (Na guide stars) are expected to be needed in order to tomographically measure the atmosphere and allow the desired AO correction.

3.4.2.10.2 Single Natural Guide Star, no Lasers.

[REQ-0-SRD-0880] The system should be operable with a single bright natural star, producing rms wavefront errors of <157 nm on axis, in median seeing, using an R < 8 magnitude star. The natural angular limits imposed by the isoplanatic angle are acceptable.

[REQ-0-SRD-0881] The system should be operable with a single bright natural star, producing rms wavefront errors of <185 nm on axis, in median seeing, using an R < 12 magnitude star. The natural angular limits imposed by the isoplanatic angle are acceptable.

3.4.2.11 Operational Efficiency-Dithering

[REQ-0-SRD-0885] Dither pattern losses should be under 1 second for up to 5 arc-sec and 5 sec for up to 30 arc-sec.

[REQ-0-SRD-0890] Dither patterns may have moves from 1-30 arc-sec.

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

3.4.3 Wide Field, Near-Diffraction-Limited (0.6-2.5µm) (MOAO)

3.4.3.1 General description

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

3.4.3.2 Wavelength range

[REQ-0-SRD-0900] From 0.6µm to 2.5µm the throughput should exceed 85%.

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

3.4.3.3 Field of View

[REQ-0-SRD-0905] Each AO-corrected "patch" needs to be 1-5 arcsec, with as many as 10-20 such patches at adjustable positions over a 20 $arcmin^2$ region.

[REQ-0-SRD-0910] Minimum separation between AO patches: goal should be as small as 20 arcsec.

Discussion: A 5-arcmin field matches the size of the JWST imaging field. The typical sizes of objects of interest will be 0.1-2 arcsec; the surface density of potential targets will range from a few over the 5-arcmin field to tens per square arc minute. A reasonable IFU sampling and field size would be 0.05 arcsec samples over a 2 arcsec field, or roughly 40 x 40 spatial sampling per IFU head. Note that this is roughly 3 times the diffraction limit at 2µm. When a larger contiguous field is desired (~ 5 arcsec) somewhat coarser sampling may be used.

3.4.3.4 Image/wavefront quality

[REQ-0-SRD-0915] At least 50% of the flux from a point source at 1µm wavelength should go into a 0.05 arcsec square.

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

3.4.3.5 Sky coverage

[REQ-0-SRD-0920] Sky coverage should 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.

3.4.3.6 Background

[REQ-0-SRD-0925] The AO system should not increase the (inter-OH) background by more than 15% over natural sky (see Appendix 4) + telescope background (assume 5% emissivity at 273K).

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

3.4.3.7 Laser Asterism and Flexibility

[REQ-0-SRD-0930] Lasers must be deployable in a flexible way over the 5-arcmin-diameter field to maximize the effectiveness of the AO correction depending on the geometry of the field being observed and the distribution of targets within it.

3.4.4 Small Field, Diffraction-Limited Mid-IR (MIRAO)

3.4.4.1 General description

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

3.4.4.2 Wavelength range

[REQ-0-SRD-0950] From 4.5μm to 28μm the throughput should exceed 85%

3.4.4.3 Field of view

[REQ-0-SRD-0955] Field of view shall be 10 arcsec with a goal of 1 arcmin

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

3.4.4.4 Image/wavefront quality

[REQ-0-SRD-0960] Wavefront error <750 nm rms, goal< 350 nm rms

Discussion: We understand that this implies poor performance at L band (3.8μm); we envision that L band imaging could be accomplished with MOAO and L-band spectroscopy with NFIRAOS/NIRES (if the AO system allows).

3.4.4.5 Sky coverage

[REQ-0-SRD-0965] Sky coverage should be all sky, limited only by availability of natural tip-tilt stars

Discussion: System should be operable with natural guide stars. Natural guide stars will probably not provide all sky coverage for the AO correction and need to be supplemented with laser beacons. Here the coverage will be limited by the availability of natural tip-tilt stars. See Appendix 6 for details.

3.4.4.6 Background

[REQ-0-SRD-0970] The AO system should not increase the N band background by more than 15% over natural sky (see Appendix 4) + telescope background (assume 5% emissivity at 273K).

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

3.4.4.7 Photometry

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

3.4.4.8 Astrometry

[REQ-0-SRD-0980] Differential astrometry is important, and the AO system should provide sufficient calibration information so as not to degrade the astrometric capabilities beyond the limits set by the atmosphere.

3.5 EARLY 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 1.8µm, 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 designed and built into the telescope, the AO system or the science instruments. Design options and locations are complex and still under discussion. The basic dispersion facts are given in Appendix 8.

3.5.1 InfraRed Imaging Spectrometer (IRIS)

3.5.1.1 General description

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

This instrument will use the small field diffraction-limited, near-IR AO system, NFIRAOS (2.4.2) or possibly the wide field, near-diffraction-limited AO system, MOAO (2.4.3).

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

3.5.1.2 Wavelength range

[REQ-0-SRD-1000] 0.8-2.5µm, goal 0.6-5µm

3.5.1.3 Field of view

[REQ-0-SRD-1005] Up to 3 arcsec for IFU

[REQ-0-SRD-1010] Imaging mode >15x15 arcsec.

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

3.5.1.4 Image quality

[REQ-0-SRD-1015] Wavefront quality delivered by the AO system should be preserved for all modes in which the diffraction limit is critically sampled.

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

[REQ-0-SRD-1025] At least one imager field should be close enough to the optical axis of the AO science field that it is within the range for re-positioning the optimal AO correction. This field will be used for imaging programs demanding the best possible image quality.

3.5.1.5 Spatial sampling

[REQ-0-SRD-1030] Imager: 0.004 arcsec per pixel (Nyquist sampled at 1 micron) over 4096x4096 pixels would provide a 16.4 arcsec square field.

[REQ-0-SRD-1035] IFU: Plate scales selectable 0.004, 0.010, 0.025, 0.050 arcsec/pixel with 64x64 spatial samples, corresponding to IFU fields of view of 0.26, 0.64, 1.60, and 3.29 arcsec, respectively.

3.5.1.6 Spectral resolution and coverage

[REQ-0-SRD-1040] R>3500 over entire Y, J, H, K bands, one band at a time; a larger IFU field of view with smaller wavelength coverage would be desirable for some applications.

[REQ-0-SRD-1045] R=5-100 for imaging mode.

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

3.5.1.7 Background

[REQ-0-SRD-1050] The instrument should not increase the (inter-OH) background by more than 15% over natural sky (see Appendix 4) + telescope background (assume 5% emissivity at 273K).

[REQ-0-SRD-1055] In imaging mode the instrument should not increase the K-band background by more than 15% over natural sky.

3.5.1.8 Astrometry

[REQ-0-SRD-1060] Residual time-dependent rms distortions (after a fit to physically allowed distortion measured with field stars) should be no larger than 50 µas in the H band, for a 100s integration time. Errors should fall as $t^{-1/2}$. These are one-dimensional position uncertainties. This should be achieved over a 30 arcsec FOV.

[REQ-0-SRD-1065] Systematic errors should be no more than 10 µas.

> Discussion: We assume that there will be modest static field distortions, but these will be removed by initial calibration and the use of field stars within the image that can remove residual “static” errors that the AO system might 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 will enable important scientific programs. Every effort should be made to achieve a 10 µas floor, or less.

3.5.1.9 Sensitivity

[REQ-0-SRD-1070] Detector dark current and read noise shall not increase the effective background by more than 5% for an integration time of 1000 s.

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

[REQ-0-SRD-1075] Sky subtraction accuracy for IFU modes should be limited by the photon statistics of the background for integrations >600s for the two coarsely sampled IFU modes.

3.5.1.10 Throughput

[REQ-0-SRD-1080] High throughput is important for this instrument, particularly for the coarsely sampled IFU modes. Instrumental throughput of >30% should be achievable (excluding the AO system and telescope).

3.5.2 Infrared Multi-Object Spectrometer (IRMS)

3.5.2.1 General Description

IRMS is a near diffraction-limited instrument that can gather multi-object near IR spectra over a 2 arcmin field of view. It is intended to allow some of the science objectives of MOAO/IRMOS but be simpler, less risky, less expensive, and available for first light. It is expected to be a clone of the MOSFIRE instrument being built for Keck Observatory, thus greatly reducing its risk and cost. It will have cryogenic adjustable slit masks. It is expected to operate behind NFIRAOS with the image quality that NFIRAOS can deliver.

3.5.2.2 Wavelength Range

[REQ-0-SRD-1100] 0.95-2.45μm range

3.5.2.3 Field of view

[REQ-0-SRD-1105] 2.05x 2.05 arcmin square unvignetted field of view with AO correction by NFIRAOS. The MOSFIRE field of view is 2.26 arcmin diameter

Discussion: A 2048x2048 detector with 18 micron pixels will cover a 2.03 arcmin square field, though the full field allowed by the instrument optics would be 2.26 arcmin in diameter.

3.5.2.4 Total slit length

[REQ-0-SRD-1110] 46 adjustable cryogenic slits with total slit length of up to 120 arcsec. Slits have discrete lengths of 2.43 arcsec and can be combined as desired in discrete steps. Gaps between slits are 0.17” when slits are not aligned into longer contiguous units. Slit widths are continuously variable. Slit mask remotely configurable in 3-5 minutes.

3.5.2.5 Image quality

[REQ-0-SRD-1115] >80% ensquared energy in 0.12” by 0.16” (2 pixel) box in spectroscopic mode; rms image diameters <0.07” in direct imaging mode over full bandwidth without re-focus.

Discussion: This is based on MOSFIRE optics.

3.5.2.6 Spatial sampling

[REQ-0-SRD-1120] Sampling will be 0.060 arcsec/pixel in the spatial direction and 0.08 arcsec/pixel in the dispersion direction, for a 2Kx2K detector with 18μm pixels that cover 2.05 arcmin x 2.05 arcmin.

Discussion: This is much coarser than the diffraction limit, but well suited to the slightly extended distant galactic targets that are its primary science objectives. It may be advantageous to use a 4096^2, 10μm pitch detector and achieve sampling of 0.033 arcsec and cover a full 2.26 arcmin field.

3.5.2.7 Spectral resolution and coverage

[REQ-0-SRD-1125] R=3270 with 3 pixel slit (0.24 arcsec)

[REQ-0-SRD-1130] R=4660 with 2 pixel slit (0.16 arcsec)

[REQ-0-SRD-1135] All of Y, J, H or K for slits placed at the center of the field. Dispersion achieved with a reflection grating used in order 6, 5, 4, and 3 with two grating angles, optimized for Y/J or H/K.)

Discussion: It is feasible to obtain spectra covering Y+J or H+K at the same resolution by inserting a cross-dispersing grism in the filter wheel. In this mode, the multiplex advantage would be halved, but the wavelength coverage would be doubled.

3.5.2.8 Imaging

[REQ-0-SRD-1140] Entire NFIRAOS 2 arcmin field of view with 0.06 arcsec sampling for 2k x 2k 18micron pitch detector; goal 0.033" sampling for 4k x 4k 10 micron device.

3.5.2.9 Throughput

[REQ-0-SRD-1145] >40% for imaging; >30% on order blaze in each band.

3.5.2.10 Sensitivity

[REQ-0-SRD-1150] Instrument background should not increase the inter-OH background by more than 10% over the natural sky+telescope +AO system background. Spectroscopic observations shall be background-limited for any exposure > 60 seconds.

3.5.3 Wide Field Optical Imaging Spectrometer (WFOS)

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

3.5.3.2 Wavelength range

[REQ-0-SRD-1200] 0.31 - 1.0μm (required); 0.3 - 1.5μm (goal)

Discussion: The initial performance of the telescope mirrors in the UV may limit the wavelength range to > 0.34μm; however, the spectrograph optics should work as closely as possible to the atmospheric limit (0.32 μm for 3000m sites, 0.31 μm for 4000m 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.

3.5.3.3 Field of view

[REQ-0-SRD-1205] >40 $arcmin^2$, goal >100 $arcmin^2$

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

3.5.3.4 Total slit length

[REQ-0-SRD-1210] 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.

3.5.3.5 Image quality

[REQ-0-SRD-1215] For imaging, image quality ≤ 0.2 arcsec FWHM over any 0.1μm wavelength interval.

[REQ-0-SRD-1220] For spectroscopy, image quality less than 0.2 arcsec FWHM at every wavelength without re-focus.

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] Image positions must be achromatic at the 0.05 arcsec level over the full range of telescope zenith distances.

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.

3.5.3.6 Spatial sampling

[REQ-0-SRD-1230] < 0.15 arcsec per pixel, goal < 0.1 arcsec

3.5.3.7 Spectral resolution

[REQ-0-SRD-1235] R = 1000-1500 for low-resolution mode; R>5000 for high-resolution mode, each for a slit of width 0.75 arcsec slit. Goal: R>7500 for high resolution mode.

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

3.5.3.8 Throughput

[REQ-0-SRD-1240] ≥ 30% from 0.31 - 1.0μm.

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.

3.5.3.9 Sensitivity

[REQ-0-SRD-1245] Spectra should 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.

3.5.3.10 Field Acquisition

[REQ-0-SRD-1250] Field acquisition for multi-slit masks must be short (< 3 minutes once telescope is in position).

[REQ-0-SRD-1255] Fast (< 1 min) acquisition of single targets onto a long slit must be supported.

Discussion: This capability is crucial for follow-up of transient objects. It may imply the need for a slit-viewing acquisition camera.

3.5.3.11 Desirable features

[REQ-0-SRD-1260] Cross-dispersed mode for smaller sampling density and higher R.

[REQ-0-SRD-1265] Imaging through narrowband filters (0.5-1% bandwidth filters).

[REQ-0-SRD-1270] IFU option

[REQ-0-SRD-1275] AO based image quality improvements (i.e., GLAO).

3.6 FIRST DECADE INSTRUMENTS

3.6.1 Near-InfraRed, Multi-Object Spectrometer (IRMOS)

3.6.1.1 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 view. Each deployable AO corrector will then connect to its deployable IFU that will sample the field of view (≤3 arcsec) and feed the spatially divided information into a spectrometer. Each spectrometer may process information from multiple IFU's depending on the actual instrument design.

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

3.6.1.2 Wavelength Range

[REQ-0-SRD-1300] 0.8 - 2.5μm.

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

3.6.1.3 Field of Regard

[REQ-0-SRD-1305] IFU heads deployable over >2 arcmin diameter field, with each IFU head covering 3x3 arcsec (TBC). A goal is a field of regard of 5 arcmin in diameter.

3.6.1.4 Image quality

[REQ-0-SRD-1310] The instrument should not degrade the image quality delivered by the AO system (50% ensquared energy in 0.050 arcsec)

3.6.1.5 Spatial sampling

[REQ-0-SRD-1315] Sampling: 0.05x0.05 arcsec (other scales TBD). Goal: additional sampling when needed of 0.01 arcsec.

[REQ-0-SRD-1320] IFU head size: 3.0″ IFU heads.

[REQ-0-SRD-1325] Number of IFU units: ≥10.

[REQ-0-SRD-1330] Smallest head separation on the plane of the sky: as small as practical, no greater than 20 arcsec.

3.6.1.6 Spectral Resolution

[REQ-0-SRD-1335] R= 2000-10000.

[REQ-0-SRD-1340] Complete atmospheric band covered in a single exposure at R=4000.

3.6.1.7 Throughput

[REQ-0-SRD-1345] High throughput is important for this instrument (>30%).

3.6.1.8 Background

[REQ-0-SRD-1350] The instrument should not increase the (inter-OH) background by more than 15% over natural sky (see Appendix 4) + telescope background (assume 5% emissivity at 273K).

3.6.1.9 Detector

[REQ-0-SRD-1355] Detector dark current and read noise shall not increase the effective background by more than 5% for an integration time of 600 s.

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

3.6.2 Mid-IR Echelle Spectrometer (MIRES)

3.6.2.1 General description

MIRES will be fed by the MIRAO system. Large sky coverage is desired, so the AO system will probably be fed either by natural guide stars (NGS) or lasers. The AO correction location (deformable mirror) is unknown at this time. It could be with an adaptive secondary, or with a deformable mirror downstream. In order to keep thermal backgrounds to a minimum, a downstream deformable mirror should be cold.

The guider for this instrument might be associated with the AO system. This instrument might be a slit instrument or could be an IFU fed spectrometer. It is desirable (goal) that this instrument can also serve as a mid IR imager.

3.6.2.2 Wavelength range

[REQ-0-SRD-1400] 8μm- 18μm, goal 4.5-28μm

3.6.2.3 Field of view of field acquisition camera

[REQ-0-SRD-1405] 10 arcsec, Nyquist sampled at 5μm (0.017 arcsec pixels)

Discussion: A field acquisition camera is needed for accurate positioning of the science object onto the diffraction-limited slit. The images should be of scientific quality (low distortion, good uniformity, etc.). This camera can work in K band.

3.6.2.4 Field of view of science camera

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

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

3.6.2.5 Slit Length

[REQ-0-SRD-1415] > 3 arcsec, sampled at 0.04 arcsec/pixel

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

3.6.2.6 Spectral Resolution

[REQ-0-SRD-1420] 5000≤R≤100,000 (diffraction-limited slit)

[REQ-0-SRD-1425] Single exposures at R=100,000 should give continuous coverage over the orders imaged, 8 - 14μm

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

3.6.2.7 Background

[REQ-0-SRD-1430] The instrument should not increase the N band background by more than 15% over natural sky (see Appendix 4) + telescope background (assume 5% emissivity at 273K).

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

3.6.2.8 Throughput

[REQ-0-SRD-1435] High throughput is a priority for this instrument; > 20% should be achievable.

3.6.2.9 Sensitivity

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

3.6.2.10 Nodding

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

[REQ-0-SRD-1450] Range should cover length of slit at an accuracy of λ/10D at 8μm

[REQ-0-SRD-1455] Frequency-amplitude constraints are TBD

Discussion: Nodding is viewed as the process by which we move the telescope optical axis (moving the telescope). We expect to nod along the slit, distances of many 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.

3.6.2.11 Chopping

[REQ-0-SRD-1460] No chopping is required.

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

3.6.2.12 Duty cycle

[REQ-0-SRD-1465] At least 80%

Discussion: This is the integration time per clock time, limited by nodding and chopping.

3.6.3 Planet Formation Instrument (PFI)

3.6.3.1 General description

PFI instrument seeks to directly image and obtain low-resolution 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 30mas.

3.6.3.2 Wavelength range

[REQ-0-SRD-1500] 1-2.5μm, goal 1-5μm

3.6.3.3 Field of view

[REQ-0-SRD-1505] 0.03-1 arcsec radius with respect to star

3.6.3.4 Image quality

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

3.6.3.5 Spatial sampling

[REQ-0-SRD-1515] Critically sampled at 1μm (λ/2D =0.0035 arcsec)

3.6.3.6 Spectral resolution

[REQ-0-SRD-1520] R ≤ 100

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

3.6.3.7 Achievable contrast with coronagraph

[REQ-0-SRD-1525] The system should reach planet detection sensitivity of 10^8 before systematic errors dominate. This should be achieved in H band on stars with I< 8 mag and at working distances of 50 mas. The goal is 10^9.

[REQ-0-SRD-1530] For younger, distant, dusty stars (such as Taurus) may require IR WFS but have brighter planets, so the goal is planet detection sensitivity of 10^6 with H<10 at inner working angles of 30mas, with a goal of $5x10^6$.

> Discussion: 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 will 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.

3.6.3.8 Polarization

[REQ-0-SRD-1535] Detect polarized light (e.g., from scattering off circumstellar dust) at a level of 1% of the residual stellar halo, and measure absolute polarization to an accuracy of 10%.

3.6.4 Near-IR Echelle Spectrometer (NIRES)

3.6.4.1 General Description

The NIRES spectrometer (likely two instruments) will generally be used with a diffraction-limited slit for point sources. It will be placed behind the early light AO system (NFIRAOS) that delivers a high quality image over a small field of view. We assume an 8kx8k detector mosaic will be available.

3.6.4.2 Wavelength Range

[REQ-0-SRD-1600] 1μm- 5μm

[REQ-0-SRD-1605] Simultaneous coverage from 1.0μm-2.4μm or from 3.5μm-5.0μm at a resolution of R > 20,000

> Discussion: Because of the wide wavelength coverage, we expect that NIRES will actually be two instruments, one for the NIR (1-2.5μm, NIRES-B) and the second for 3.5-5μm (NIRES-R).

3.6.4.3 Field of view of field acquisition camera

[REQ-0-SRD-1610] An acquisition camera with field of view of 10 arcsec is needed, Nyquist sampled at 1μm (0.0035 arcsec per pixel)

3.6.4.4 Length of slit

[REQ-0-SRD-1615] A slit length of ~2 arcsec is needed, to provide the ability to nod along slit to improve background subtraction.

3.6.4.5 Image quality

[REQ-0-SRD-1620] The spectrometer should deliver diffraction-limited images to the detector, as delivered by the AO system.

3.6.4.6 Spatial sampling

[REQ-0-SRD-1625] Nyquist sampled (λ/2D) (0.004 arcsec)

3.6.4.7 Spectral resolution

[REQ-0-SRD-1630] R~20,000 (1-2.5 μm); R~100,000 (3-5 μm)

3.6.4.8 Background

[REQ-0-SRD-1635] The instrument should not increase the (inter-OH) background by more than 15% over natural sky (see Appendix 4) + telescope background (assume 5% emissivity at 273K).

3.6.4.9 Detector

[REQ-0-SRD-1640] Detector dark current and read noise shall not increase the effective background by more than 5% for an integration time of 2000 s.

Discussion: In the 1-2.5μm region, dark current ≤0.002 e-/s and read noise ≤ 3e- after multiple reads should be sufficient.

3.6.4.10 Throughput

[REQ-0-SRD-1645] High throughput is a priority for this instrument; > 20% should be achievable.

3.6.5 High-Resolution Optical Spectrometer (HROS)

3.6.5.1 General description

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

3.6.5.2 Wavelength range

[REQ-0-SRD-1700] 0.31μm- 1.1μm, goal 0.31-1.3μm

Discussion: Working into the infrared is scientifically valuable, but CCDs cut off at 1.1μm. New detectors would be needed to reach the long wavelength limit.

3.6.5.3 Field of view

[REQ-0-SRD-1705] >10 arcsec for the acquisition camera/slit viewing camera

3.6.5.4 Slit length

[REQ-0-SRD-1710] A slit length of >5 arcsec is needed, with > 5" separation between orders

3.6.5.5 Image quality

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

3.6.5.6 Spatial sampling

[REQ-0-SRD-1720] Sampling should be no coarser than 0.2 arcsec, to adequately sample the best optical images provided by the telescope

3.6.5.7 Spectral resolution

[REQ-0-SRD-1725] R=50,000 (1 arcsec slit, image slicer for R≥90,000)

Discussion: Options include single slit, fiber feed for multiplexing

3.6.5.8 Sensitivity

[REQ-0-SRD-1730] Must maintain 30m aperture advantage over existing similar instruments. This would imply throughput >20% from telescope focal plane to detected photons.

3.6.6 Wide-field InfraRed Camera (WIRC)

3.6.6.1 General description

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

Discussion: Given the expected MCAO nature of NFIRAOS and its field of view, it quite possible that WIRC will be fed by NFIRAOS. It may also be the case that an adequate approximation to WIRC may be provided by the imaging camera of IRIS. Hence, whether WIRC becomes a distinct instrument is currently uncertain.

3.6.6.2 Wavelength range

[REQ-0-SRD-1800] 0.8μm- 5μm, goal 0.6μm-5μm

Discussion: Note that no planned AO system currently works well in the 2.5-5μm range.

3.6.6.3 Field of view

[REQ-0-SRD-1805] > 30 x 30 arcsec (contiguous field).

3.6.6.4 Image quality

[REQ-0-SRD-1810] Uncorrectable wavefront errors should be such that they make a negligible (<5%) contribution to the AO+instrument error budget.

Discussion: This needs to be coupled to the AO error budget.

3.6.6.5 Spatial sampling

[REQ-0-SRD-1815] Nyquist sampled or better at the observing wavelength, from 1-5 μm.

Discussion: This need is clearly wavelength and field angle dependent.

3.6.6.6 Background

[REQ-0-SRD-1820] The instrument should not increase the (inter-OH) background by more than 15% over natural sky (see Appendix 4) + telescope background (assume 5% emissivity at 273K).

3.6.6.7 Spectral Resolution

[REQ-0-SRD-1825] R = 5-100 with a range of broad, medium, and narrow-band filters that are changed infrequently.

3.6.6.8 Throughput

[REQ-0-SRD-1830] Throughput is a key consideration for this instrument. The requirement is for the throughput to be as good as other existing instruments, to preserve the aperture advantage of the telescope.

3.6.6.9 Repeatability, stability, flexure

[REQ-0-SRD-1835] Allow mosaicing of multiple fields together with no more than 1% image quality degradation.

Discussion: This implies a stable and well-characterized plate scale and a small amount of optical distortion.

3.6.6.10 Astrometry

See requirements for NFIRAOS and IRIS.

3.7 POSSIBLE ADDITIONAL INSTRUMENTS

3.7.1 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. The early light IRMS instrument may allow some fraction of the science to be done, albeit over a 2 arcmin field of view.

3.7.2 Mid-IR Diffraction-limited Imaging Spectrometer

Although MIRES will have 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.

3.8 DATA HANDLING

[REQ-0-SRD-1900] The observatory should provide the basic ability to archive all science data collected by the science instruments.

[REQ-0-SRD-1905] All associated engineering data should be stored and should be available for data reduction.

[REQ-0-SRD-1910] At a minimum all the data collected should be stored and made available to the scientist responsible for the data.

[REQ-0-SRD-1915] Only a relatively simple data archive is required.

> Discussion: Although desirable, we do not require that the Observatory make all science data available to anyone who wants it. As a goal, we want a broadly accessible and useful data archive.

[REQ-0-SRD-1920] The science instruments are expected to deliver basic data reduction pipelines that are suitable to the data that each instrument generates. As a goal, we want the Observatory to provide complete data reduction packages that can provide publishable data sets.

[REQ-0-SRD-1925] The instrument teams will deliver basic data reduction software to the Observatory

[REQ-0-SRD-1930] Observatory has responsibility for maintaining and upgrading such software.

3.9 NIGHTTIME OPERATIONS MODELS

[REQ-0-SRD-1950] The Observatory should provide to the astronomer a working telescope and suitable instruments to support the astronomers proposed work.

[REQ-0-SRD-1955] Appropriate personnel should be provided to properly and efficiently use the telescope and instruments and ensure they are working properly.

> Discussion: We do not expect the astronomer will understand all the technical details of the observatory or instruments, thus some technical support will be essential.

[REQ-0-SRD-1960] Queue scheduling is not required

> Discussion: Although significant efficiencies may result from the use of queue scheduling, where the actual observing program is chosen to best fit the local observing conditions, we do not require that the Observatory provide this level of support. As experience develops we may increasingly migrate to this mode of observing, so the observatory design should not preclude or hinder the possible future use of such a model of observing.

[REQ-0-SRD-1965] To encourage maximum use of the telescope in changing conditions, all the science instruments should be available on every night, whenever possible.

[REQ-0-SRD-1970] An astronomer should be able to switch from one instrument to another in no more than 10 minutes.

4. APPENDICES

4.1 APPENDIX 1: 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 will 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 will generally have better atmospheric transmission, particularly longward of 10μm. We require that the telescope be functional with high throughput from 0.31μm to 30μm. Details of the spectrum are given by Lord.

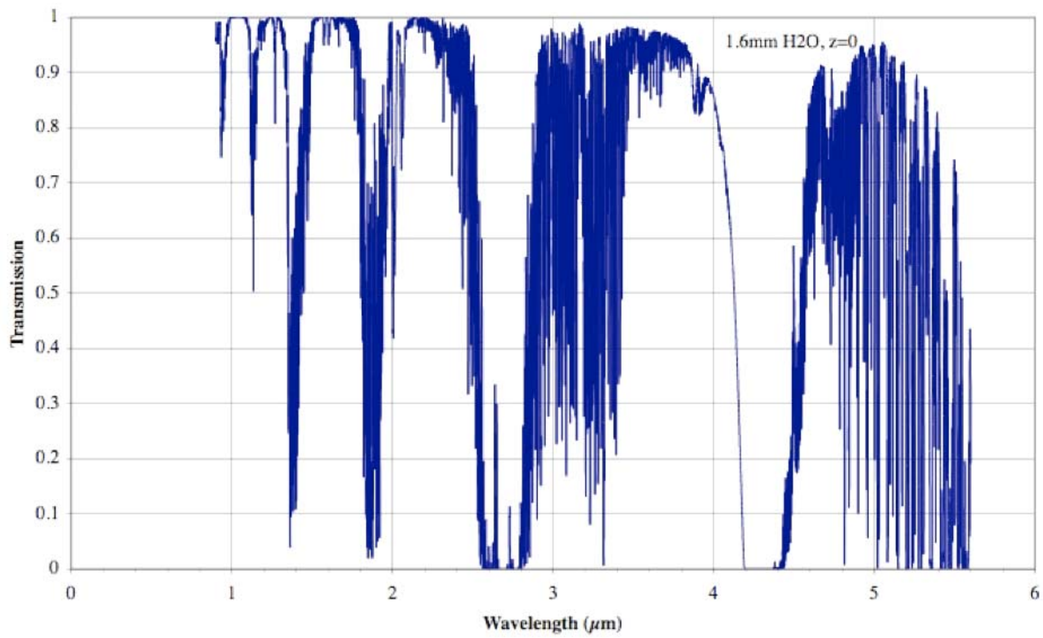

Figure 4-1 Atmospheric transmission in near-infrared (< 6 μm) - Mauna Kea

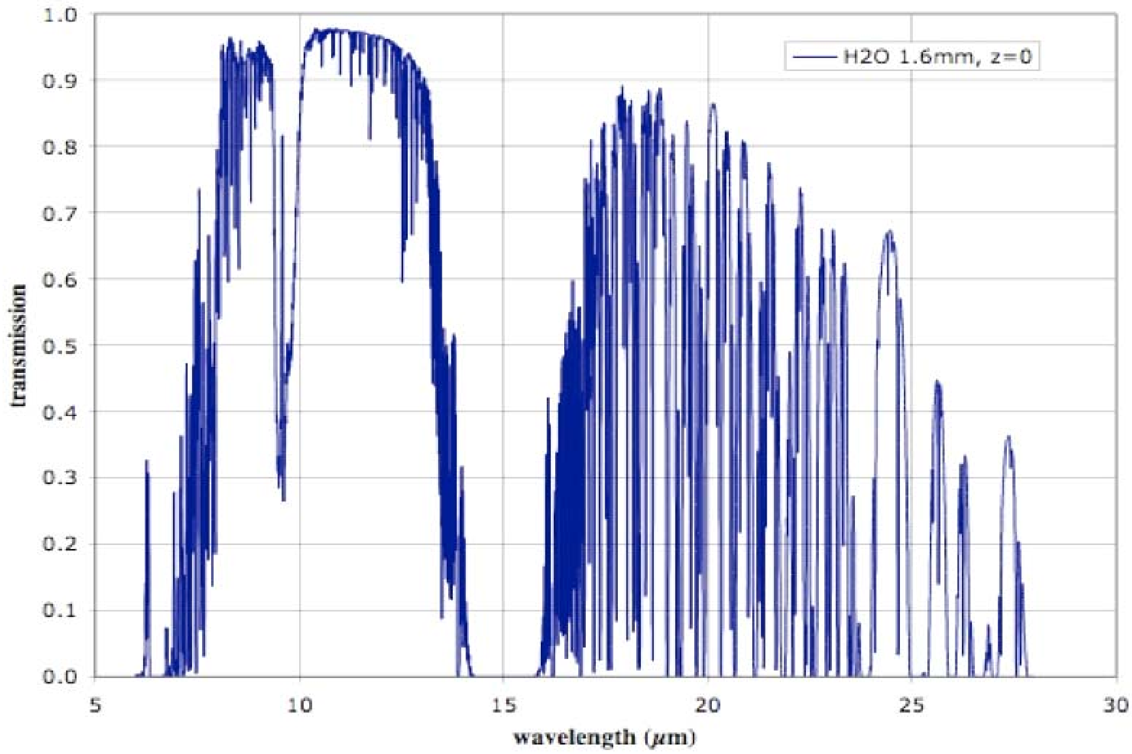

Figure 4-2 Atmospheric transmission in mid-infrared (5 - 30 µm) - Mauna Kea

4.2 APPENDIX 2: STREHL RATIO FOR VARIOUS WAVELENGTHS AND WAVEFRONT ERRORS

It is frequently useful to describe AO –achieved image quality by its Strehl ratio (S). The Strehl ratio is the image peak intensity divided by the maximum (diffraction-limited) peak intensity. For S>0.2 one can approximate S as $\exp(-(2\pi\sigma/\lambda)^2)$ where 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.

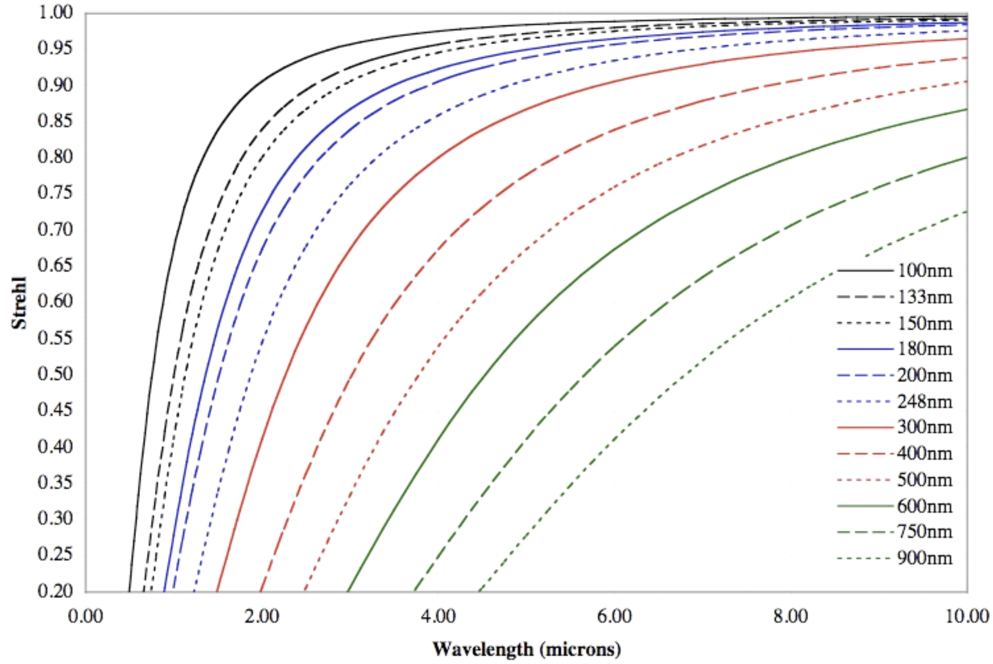

Figure 4-3 Strehl ratio versus wavelength (< 10 μm)

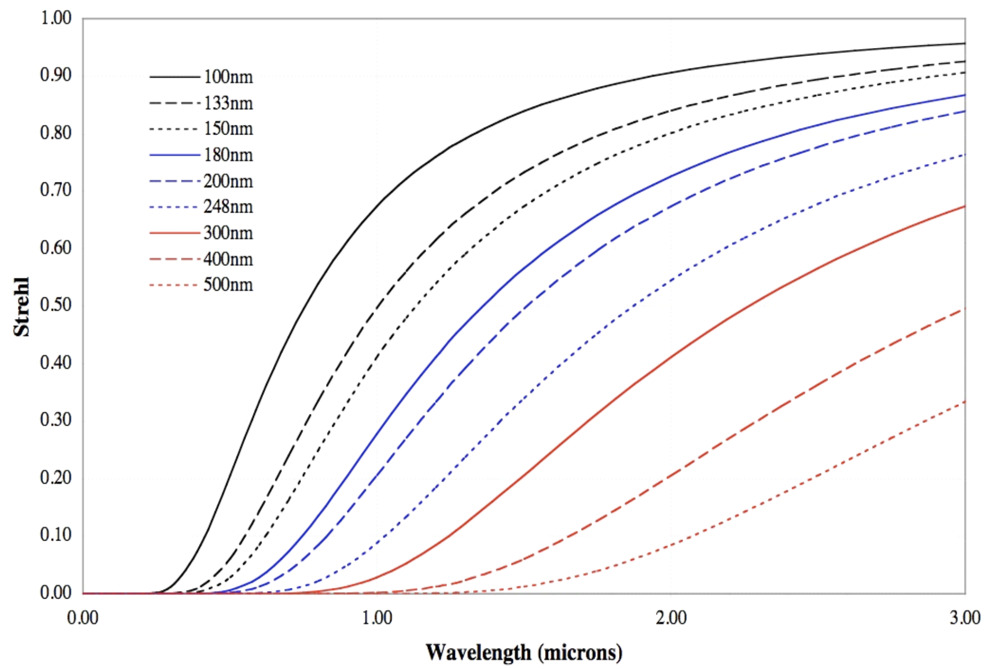

Figure 4-4 Strehl ratio versus wavelength (< 3 μm)

4.3 APPENDIX 3: 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 340nm 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 will vary 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.

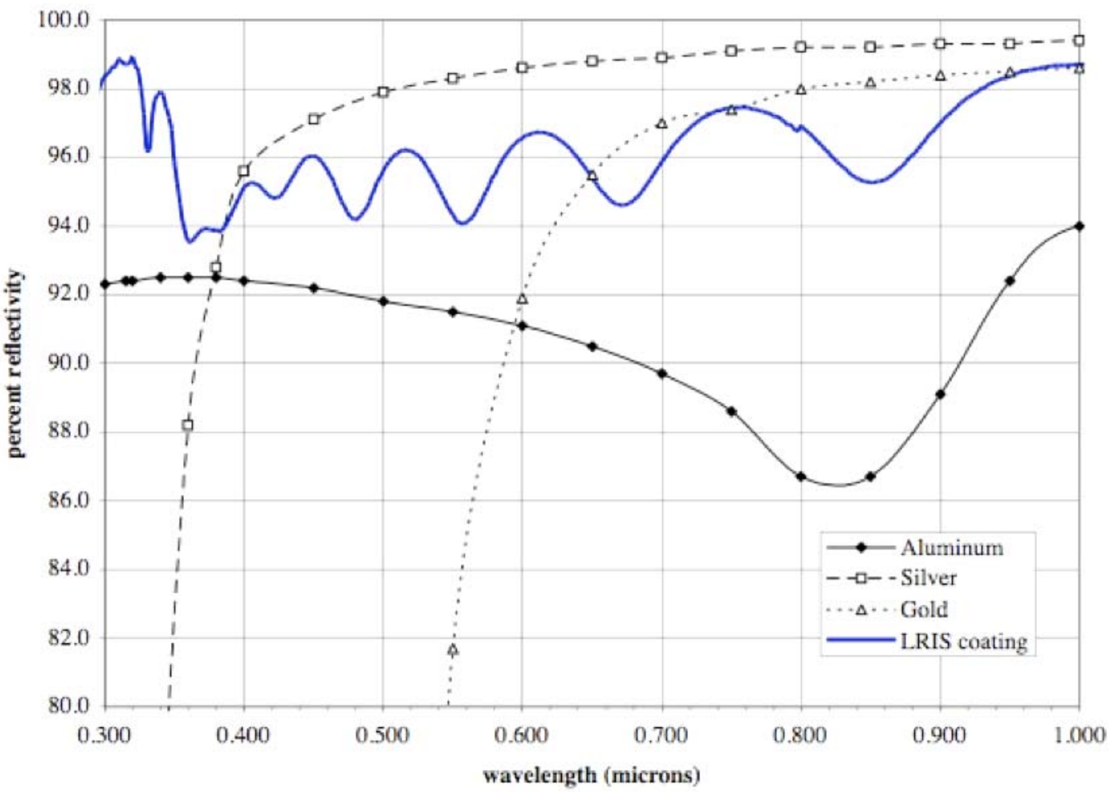

Figure 4-5 Reflectivities of Metals and LRIS coating (0.3 - 1 μm)

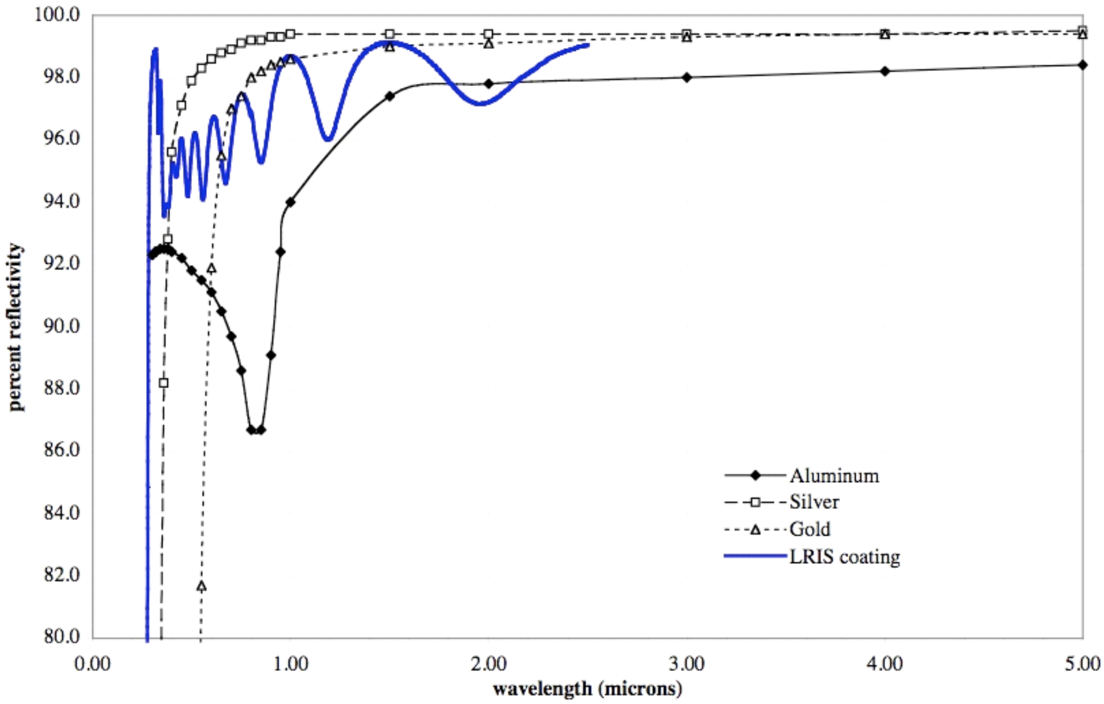

Figure 4-6 Reflectivities of Metals and LRIS coating (< 5 µm)

4.4 APPENDIX 4: 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 will cause some fraction (emissivity) of the blackbody radiation to be emitted by the optics. Such local background sources will be added to the natural night sky flux.

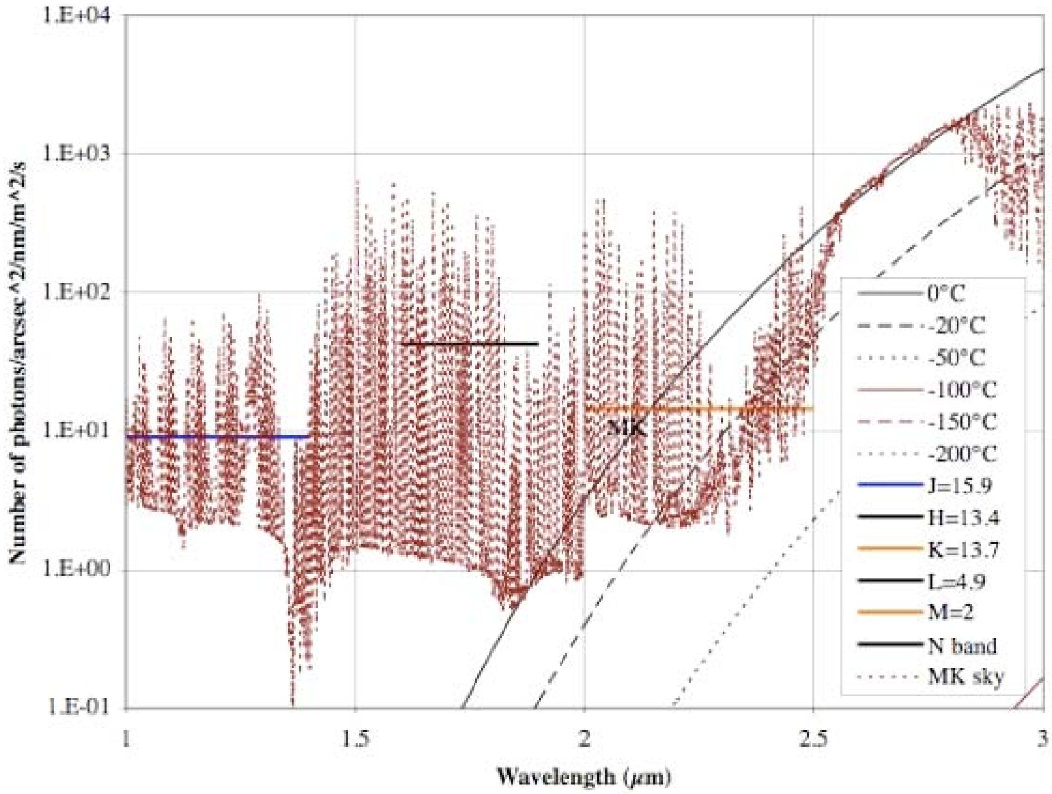

Figure 4-7 Sky (MK) and Blackbody flux versus wavelength

4.5 APPENDIX 5: STANDARD ATMOSPHERE ASSUMPTIONS

In order to define the AO performance requirements, we define "Standard Conditions" under which the requirements should be met. When conditions differ from these, performance may be better or worse. The conditions are based on 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 0.5µm)

T = 281° (90% between 2.5° and 11.3°)

Precipitable H_2O = 2.9mm

r_0 = 0.16m

L_0 = 30m (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, 0.30m (10, 50, 90 percentile)

θ_0 = 2.00 arcsec

τ_0 = 3 ms

integrated C_n^2 = 3.20e-13 m1/3

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} = 10ms 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 6: 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) (RD10), 2) Spagna (2001, STScI-NGST-R-0013B) (RD9), and 3).Besançon (Robin, Reyle, Derriere, Picaud 2003, A&A, 409, 523; (RD14)) .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.

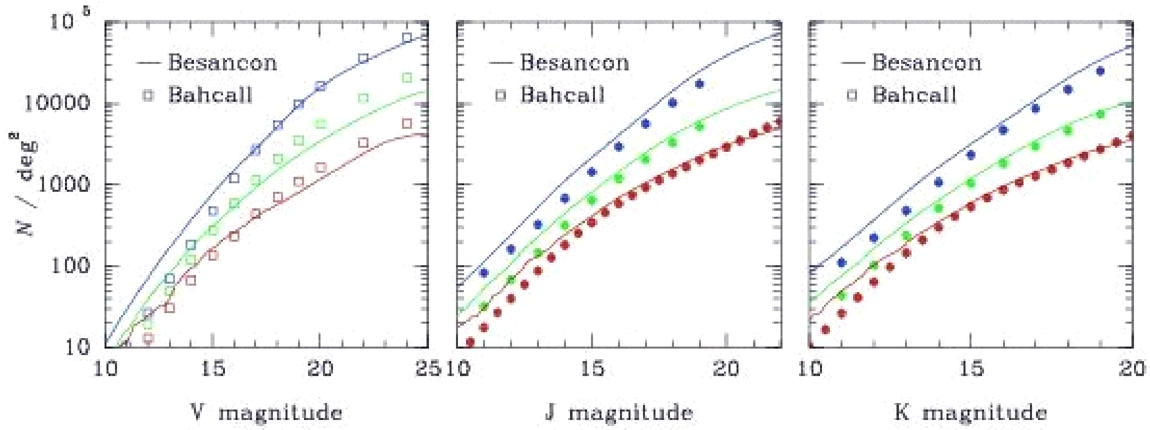

Figure 4-8 Comparison of the cumulative stars per square degree at a given magnitude predicted by different star count models.

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 7: 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. As shown in Astrometry with TMT (RD15) experience at Keck Observatory suggests that the achievable precision varies as 1/√ t and that a precision of 100μas can be achieved in 2 minutes.

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 will change if the upper DM has a static defocus. Calibration procedures must be applied to ensure that these errors do not compromise the astrometric performance of an MCAO system (e.g., flattening of the upper DM before closing the loop).
To ease the astrometric challenge, the static distortions in the field of view should be under 10% (goal 1%).

4.8 APPENDIX 8: 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, (RD13))

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

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

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

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) will be useful. When this ratio is less than 1, it can probably be omitted, depending on the actual error budget of the system under consideration.

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 9: 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 = 0.8m.
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.
and 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 will scale inversely with r_0. Doubling r_0 will halve the image size. For a given r_0 at a given wavelength, changing wavelength will change r_0, and thus the image size. The image size produced by a Kolmogorov atmosphere varies as

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

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 = 0.2m, 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)(RD16).

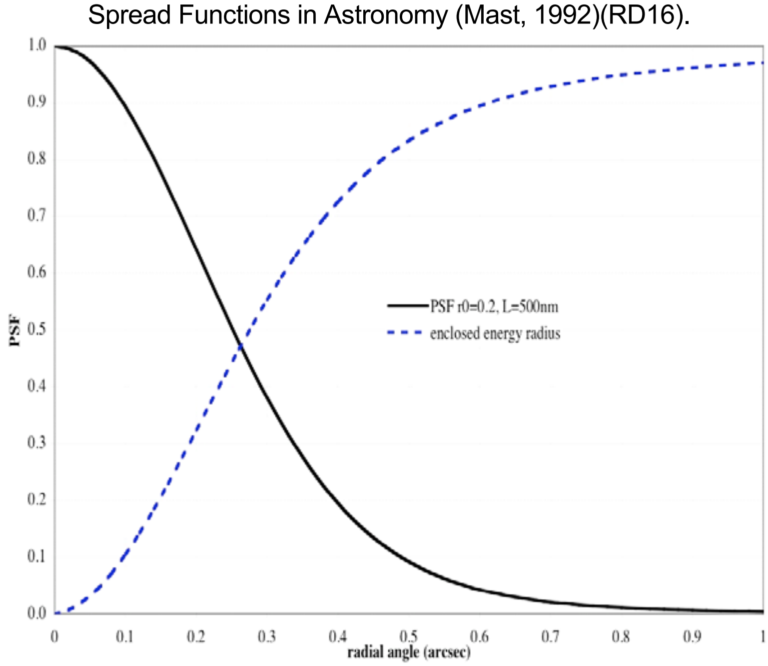

Figure 4-9 Image PSF and EE for Kolmogorov atmosphere