4 SCIENCE REQUIREMENTS

4.1 Summary

The GMT science requirements flow down from the science goals presented in the GMT Science Case along with other science goals that were not fully developed there. The requirements specify the conditions that the telescope, associated facilities and instruments must meet to enable completion of the science program on a reasonable time scale. The desired properties of the facility are specified as requirements, or goals, or some combination of both. Long-term development programs and goals are identified as such and are not cast as requirements.

Our discussion of the GMT science requirements are broken out into the following areas: 1) high level science goals, 2) definition of the telescope and related systems, 3) site requirements, 4) candidate first generation instrument requirements, 5) adaptive optics goals, 6) supporting facilities, 7) operational requirements, and 8) image size and wave-front requirements. These areas are developed more fully in subsequent chapters of this volume.

A detailed listing of the science requirements by area is given in Appendix 4-1. The discussion presented here highlights the principal science goals and the requirements that flow from them.

4.2 High Level Science Goals

The primary science goals for the GMT are laid out in the GMT Science Case. Here we define the quantitative requirements that these goals place on the telescope, site, adaptive optics and instruments. For the sake of brevity we restrict the scientific discussion to a bare minimum.

4.2.1 Planets and Their Formation

The key elements of our program to understand the properties and formation of extrasolar planetary systems include imaging extrasolar planets, detecting new low-mass systems via reflex motion studies of low mass stars, and exploring the link between disk and planet formation. Our own solar system provides our best laboratory for studies of low mass bodies and presents special requirements. Star and planet formation are intimately linked and our priorities in this area include understanding the origin of the IMF and probing the collapse of molecular clouds to stars and disks.

4.2.1.1 Imaging of Extrasolar Planets

Imaging of exoplanets, whether via reflected light or thermal emission, requires high-contrast on angular scales from < 10mas to roughly 5 arcsec. GMT imaging studies of exoplanets will address both systems discovered from reflex motion and transit surveys as well as searches for objects with $M > 20M_J$ and $5 < a < 40$ AU, a range of parameter space not probed by radial velocity and transit surveys. Massive young planets will be most readily detected via thermal radiation in the 3-10μm windows. At a benchmark distance of 500pc (e.g. Orion), the required angular scales are 10-100mas and contrast ratios of 10^4 – 10^6 are required. Nulling interferometry and coronagraphy may be the techniques of choice for these studies. Known giant exoplanets have separations ranging from 0.04 to ~ 4AU, corresponding to angular scales from 2-200 mas (see Science Case Figure 3.4). The GMT should be able to access systems with angular sizes greater than ~ 3-5λ/D (40-65mas at 1.5μm). Direct imaging via reflected light and low-resolution spectroscopy of known exoplanets will reveal much about their evolutionary histories and the compositions of their atmospheres. The required contrast ratios at ~ 1.5μm range from ~10^5 to >10^8 as shown in Figure 3.4.

4.2.1.2 Radial velocity searches for exoplanets around low mass stars

Reflex motion studies of low-mass, late-type, parent stars require high-resolution spectroscopy in either the visible or near-IR. The high-resolution spectrograph should be able to reach stars with V = 13.5 in observations spanning no more than three hours with a velocity precision of a few m/s. A spectral resolution of R=50,000 over the 4000-9000A range of the spectrum is required.

4.2.1.3 Structure and Dynamics of Proto-planetary Debris Disks

Spatially resolved spectroscopy to determine the constituents of disks, including finding the locations of water ice reservoirs, requires high spatial resolution and contrast. While we would like to resolve disk structure on the smallest scales possible. A critical area to probe is the snow-line; the demarcation between solid and liquid water. In A-F type stars this lies at several AU. With angular resolutions of 15-30mas in the near-infrared, the GMT will study planet-forming disks at a resolution of 3 AU in the nearest star-formation regions. Effective imaging will require a high-dynamic-range adaptive optics system coupled to a near-infrared imager and low-resolution spectrograph and a mid-IR imager/spectrometer.

4.2.1.4 Star Formation and the Initial Mass Function

To study nearby regions of star-formation at unprecedented sensitivity and spatial resolution, we require a near-IR imager and multi-object spectrograph operating at the diffraction limit from 1-2.5μm over 30-40" FOV, most likely requiring an LTAO or MCAO optimized imager/spectrograph. This same capability will be needed to probe the ratio of high to low mass stars in extreme regions of star formation in the Milky Way and local group. Studies of the dynamics and chemistry of young stars requires high-resolution spectroscopy, particularly in the 1-5μm region. Understanding the formation processes of individual protostars will also require high spatial resolution mid-IR imaging and modest resolution spectroscopy.

4.2.2 Stellar Populations and Chemical Evolution

The study of stellar populations and the evolution of the chemical elements require both high spatial and high spectral resolution capabilities. Photometric studies of crowded fields will require an AO imager operating at the shortest wavelength possible. Stellar abundance work requires high-resolution spectroscopy, primarily in the visible and UV.

4.2.2.1 Imaging of Crowded Populations

Photometry of crowded regions can reveal the star formation and abundance histories of populations as a function of environment. These studies require a diffraction-limited adaptive optics system that produces a stable point spread function with a well determined, and minimal, spatial variation pattern. The required fields of view range from a few arcsec to 30-60 arcseconds depending on the application. Moderate to high Strehl ratios (> 60% at 1.6μm) are highly desirable.

4.2.2.2 Chemistry of Halo Giants in Local Group Galaxies

Chemical studies of luminous halo giants in the local group require access to a high dispersion spectrograph operating in the visible region of the spectrum. Red Giants in local group galaxies that are accessible from Chile have apparent magnitudes of R=17-19. The visible high-resolution optical spectrograph will need to be able to obtain spectra of these stars with R=50,000 and SNR > 10 per pixel in practical exposure times. Access to the 1-2.5μm region with similar resolution will allow abundance determinations of additional elements and molecules.

4.2.3 Assembly of Galaxies

Our program for understanding how galaxies are put together has three components: tracking the mass evolution of galaxies, coupling this with the changing chemical composition of stellar and interstellar matter, and examining the interplay between galaxies and the intergalactic medium. In addition to these primarily wide-field applications, we need to explore the internal structure of galaxies, determine their dynamical properties and the distribution of dark and luminous matter.

4.2.3.1 The Mass Evolution of Galaxies

Determination of the stellar mass in galaxies over a wide range of redshifts and luminosities will entail spectroscopy of large samples of faint galaxies. Sample sizes of a few thousands per bin (by redshift, luminosity, and morphological type) are required. Large fields (~ 100Mpc) or multiple site lines are needed to suppress the impact of large-scale structure. Final field sizes on the order of 2 square degrees are needed. Achieving this in a reasonable amount of observing time calls for a multi-object spectrometer with a wide-field of view. A field area of 150 sq. arcminutes would allow one to sample a 2 square degree field in 25 pointings. A large field would clearly be preferable; a smaller field quickly becomes less attractive. Deep visible and near-IR imaging over large fields is essential for photometric redshifts, stellar mass, reddening and age determinations. The imaging material may be provided by space missions or ground-based near-IR surveys with other facilities.

Spectroscopic redshifts for these objects are best determined in the visible with a MOS covering 100-300 targets. The visible MOS should have a field area of > 150 square arcminutes and a range of resolutions from R ~ 1500 for redshift determinations to R ~ 5000 for dynamical studies.

4.2.3.2 Chemical Evolution in Galaxies

Abundance determinations in faint galaxies require access to the nebular lines in the near-IR J, H and K windows. The near-IR MOS should have as large a field of view as possible: a 5′ x 5′ is the smallest practical size for this work as it will accommodate ~ 15-30 galaxies in the appropriate redshift and apparent magnitude range. Larger fields are clearly desirable. The resolving power should be sufficient to allow one to work between the OH lines in the J and H windows, or R ~ 3000. Dynamical mass determinations from rotation in either the H alpha or [OII]3727 emission-lines should be possible with the same data. Finally, internal dynamical measurements for a sub-sample of objects will require IFU observations at either GLAO or diffraction-limited resolutions, although coarse sampling may be required to obtain adequate signal to noise ratios.

4.2.3.3 Tomography of the IGM

Understanding the link between galaxies and the heating and enrichment of the IGM requires denser sampling than is possible with present instruments. Spectroscopy at intermediate resolution (R ~ 10,000) on targets as faint as R(Vega) ~ 24-24.5 is required to achieve sufficient sampling on the sky. This requires a fairly high spectral resolution mode for the visible MOS or on a multi-object echelle. Survey areas on the order of 2 square degrees are needed, just as in section 4.2.2.1. The IGM survey must be complemented by a redshift survey over the same volume. The visible MOS requirements given in 4.2.2.2 are adequate for this task, and these two programs could be combined into a single large program.

4.2.4 Black Holes

Our priorities for black hole science center on extending the BH mass-bulge sigma relation to higher and lower masses, and, where possible, to higher redshifts. This will require diffraction-limited spatially resolved spectroscopy of the central regions of galaxies and star clusters. This is likely best accomplished with an IFU coupled to an LTAO imaging system. An IFU with lenslets that somewhat under-sample the diffraction limit at 1.5μm and fields of 3″ x 3″ are desired. A 100 x 100 lenslet array with a pitch of 25mas may be a good compromise between angular resolution and sensitivity. The IFU should operate in the 0.8-2.5μm range. This may be accomplished with a single set of detectors, or it may be best done with two systems with different optics and detectors. These IFUs should feed spectrometers with resolutions from R=3000 - 5000.

4.2.5 Dark Energy and the Accelerating Universe

Our dark energy program has three components: determining the angular scale of baryonic oscillations at $z > 4$, extending and solidifying the SNe Hubble diagram at $z > 1$, and redshift determinations of LISA sources. Follow-up of LISA sources does not place any demands on the telescope or instrument that are distinct from those arising from other programs and thus they are not discussed further.

4.2.5.1 Baryon Oscillations at z > 4

Determination of the power-spectrum requires large redshift surveys covering co-moving scales > 150 Mpc. Redshifts of samples of $z > 4$ galaxies will be obtained via the Lyα line in the red end of the visible spectrum. This program, like the survey programs in section 4.2.2.2 also needs as large a field of view as possible, as roughly 50 square degrees of sky must be surveyed. Intermediate resolution in the red is desirable as it will allow effective rejection of the OH sky emission and avoid adding aliases into the power spectrum.

4.2.5.2 SNe at z > 1

Spectroscopy and light curve determinations for SNe at large redshifts are limited to a large extent by blending of the SNe and host galaxy spectra. An IFU, operating at either the GLAO or the diffraction limit, can maximize the contrast between SNe and their host galaxies. This will also allow the collection of host galaxy spectra simultaneously with the same spectral resolution. SNe spectroscopic studies will be coordinated with imaging campaigns, perhaps from LST, that discover the candidate objects. This will require some coordination in scheduling, but does not necessarily require that the SNe IFU spectroscopic capability be available at short notice. Late-time light curves, particularly in the near-IR, will require an instrument that is regularly accessible. This is likely to be a small field, possibly AO, imager located at one of the folded Gregorian stations.

Studies of the physical properties of SNe will require near-IR spectroscopy and polarimetery in the visible and near-IR. The near-IR spectra should have *low* spectral resolution (R ~ 500) and high sensitivity. This may best be achieved by observing at high dispersion (e.g. R ~ 3000) and then recombining the spectra after masking of the atmospheric OH emission. Polarimetry is often most effective in the spectral mode. A spectropolarimetric mode for the visible and IR faint object spectrometers is a goal.

4.2.6 First Light and Reionization

Our priorities for exploring the Universe at very high redshifts have two components: exploring the detailed history of reionization and probing the first galaxies via emission-line spectroscopy of faint galaxies at z > 5.

4.2.6.1 The Reionization Era

The epoch of reionization is currently best probed by spectroscopy of Lyα absorption along sight-lines to luminous distant quasars and GRBs. The number of known z > 6 quasars should increase in the next decade, although many of these may be too faint IGM studies with current facilities. Effective spectroscopy of these objects requires intermediate resolution (R ~ 10-20K) in the red end of the visible spectrum and, eventually, into the near-IR. As the surface density of these objects is tiny, small fields and single-object spectrometers are adequate.

4.2.6.2 First Light

Direct observation of the first galaxies is one of the prime science drivers for the next generation of telescopes, both from the ground and from orbit. Successful realization of this goal will require maximum sensitivity in the 0.7 – 2.5μm region of the spectrum. Spectroscopy is the highest priority in the 0.7-1.2μm region as it covers Lyman alpha at 6 < z < 9. Moderate resolving powers (e.g. R ~ 2000-4000) are required to reduce the impact of the telluric OH emission. A field area greater than 50 square arcminutes is needed to yield more than 100 z > 5 candidate objects per exposure, based on the Hubble Ultra Deep Field. Integration times are likely to be in the tens of hours, thus there is a premium placed on field area and multiplex factor.

Diffraction-limited imaging in the near-IR over modest fields will complement, and will in some cases exceed, the capabilities of JWST. An AO optimized imager coupled with an IFU operating in the near-IR without added thermal background is an important part of the instrument compliment needed for this science. A field of view of ~20″ x 20″ with 5 mas pixels would be well matched to the diffraction limit at Ks and would fill a 4k x 4k focal plane array. Narrow bandwidth searches for Lyman alpha in the darkest parts of the J-band can probe the z ~ 10 regime. This may be best carried out with very narrow filters in an imaging survey mode, with high resolution spectroscopy, or with OH suppression reimaging spectrographs.

4.2.7 Summary of High Level Science Requirements

The science requirements are summarized in terms of the primary wavelength ranges, techniques to be employed and AO modes, in Table 4-1. A more detailed breakdown of the requirements is given in Table 4-1.1 in the appendix. We shall refer to these numbered science areas throughout this chapter. Not all of the requirements can be encoded into either table. Requirements on multiplexing, time critical observations, and requirements on observing conditions are examples of constraints that will impact instrument designs and priorities, but are not listed in Table 4-1.

Table 4-1. Science Areas and Requirements.

Science Area	Wavelengths	Techniques	AO Modes
Planet and Star Formation	NIR & MIR	High-contrast imaging IFU spectroscopy High res NIR spectroscopy Mid-IR imaging & spect.	ExAO, LTAO, Seeing, LTAO LTAO, Seeing LTAO
Stellar Populations & Chemical Evolution	Visible & NIR	High res vis spect. NIR AO imaging	Natural Seeing, LTAO
Galaxy Assembly	Visible & NIR	Wide-field VIS MOS Wide-field NIR MOS NIR AO imaging	Natural Seeing GLAO LTAO
Black Holes	NIR	NIR AO IFU Spectroscopy	LTAO
Dark Energy	Visible & NIR	Wide-field VIS MOS Wide-field NIR MOS	Natural Seeing, GLAO
First Light and Reionization	Visible & NIR	Near-IR MOS NIR & VIS high res spect.	GLAO, LTAO Natural Seeing

4.3 Definition of the Telescope and Related Systems

4.3.1 The Telescope

The GMT is a multi-purpose telescope operating in the visible and infrared. The telescope and its instruments will operate from the atmospheric cutoff at ~ 320nm to a maximum wavelength of ~25μm. Optimization for a particular wavelength range will be considered curing the design development phase. The telescope will operate in a variety of modes: narrow-field natural seeing, wide-field natural seeing, adaptive optics corrected diffraction-limited, and, if practical, intermediate field partially corrected adaptive optics modes. The telescope will provide an unobstructed field of view not less than 20 arcminutes in diameter. Instruments will be deployed at two classes of focal stations: one straight Gregorian high-throughput, low-background, focus located behind the central primary mirror segment, and a number of folded ports located above the straight focus, but also behind the center segment. The straight focus will be outfitted with a removable wide-field corrector. The folded instrument ports should have access to fields of view five arcminutes in diameter.

4.3.2 Primary Mirror

The science goals for the GMT hinge upon maximizing the collecting area and resolving power of the facility within the technical and budgetary limitations. The baseline telescope will contain seven primary mirror segments, each 8.4m in diameter. A spare off-axis mirror segment and cell, needed for efficient maintenance of throughput, will be provided as part of the baseline telescope. The total collecting area, including the hole in the central mirror segment, will be 380 square meters. Science operations may commence before all seven of the segments are installed in the telescope. The largest baseline spanned by the primary segments determines the spatial resolving power of the telescope. The outer diameter will be 25.4 meters. The resolving power of the telescope, using the Rayleigh criterion, will be 5.2mas at a wavelength of 500nm. The primary mirror segments will be made from borosilicate glass and will be of the light-weighted honeycomb spun-cast design. The focal length of each off-axis segment, and the central on-axis segment, will be 18 meters. The figure specifications for the primary mirror segments will be defined by an optical prescription as described in the GMT Design Requirements Document.

4.3.3 Secondary Mirrors

The telescope will be outfitted with one or more concave secondaries giving an aplanatic Gregorian optical prescription. The Gregorian configuration is driven, in part, by the desire for effective ground-layer conjugation, an important part of dark energy and galaxy evolution studies (science goals 6 & 7, Appendix 4-1). A segmented adaptive thin-shell secondary mirror is a goal and part of the baseline telescope. The GMT project will determine, as part of its design studies, if a rigid secondary is required for commissioning and as a backup for operations.

4.3.4 Fold Mirrors

Instruments on the upper instrument platform will by addressed by pickoff mirrors. These may be provided by the facility or as part of each instrument or instrument package. The project will identify the optimal approach to feeding beams to the instruments on the upper platform as part of the phase B studies. Priority will be placed on maximum throughput and minimum backgrounds as appropriate for each class of instrument. A number of fold mirrors with coatings optimized for each instrument may be employed.

4.3.5 Coatings

It is expected that the telescope will operate with Al coatings on the primary and secondary mirrors. These coatings will be applied on-site. The fold mirror(s) may be coated with other materials to optimize their performance over particular wavelength regions. These coatings may be applied off-site. The project will explore options for advanced coatings for the secondary mirror segments as part of the phase B design studies.

4.3.6 Wide-field Corrector

Studies in the area of dark energy, galaxy evolution and first light (science goals 6, 7, & 8) either require or benefit from access to fields larger than the telescope can provide without a corrector. The project will examine the optimal corrector configuration at the straight Gregorian focus as part of the phase B studies. Options for both multi-slit and fiber-fed instruments should be considered. The image size requirements for the corrected focus are given in section 4.9.4.2 and Table 4-7. The corrector design studies will be coordinated with design work on the wide-field instruments.

4.3.7 Atmospheric Dispersion Compensation

Chromatic dispersion of light by the atmosphere degrades the quality of broad-band imaging observations and introduces slit-losses in spectroscopic observations. One or more designs for a wide-field ADC will be developed as part of the telescope design and development phase.

4.3.8 Guiders, Wavefront Sensors and Active Optics

The primary mirror segments must be supported and controlled in such a way that the telescope produces images that meet the imaging error budget (CoDR section 8.2) at all zenith distances and azimuth ranges allowed by the operation of the mount. This will require a closed-loop guiding system and will require active control of the principal optics. The telescope should have a facility-level system of guide cameras and wavefront sensors to enable the correction of tracking errors, deformations in the primary mirror segments, collimation and focus errors and other optical aberrations due to deflections in the mirrors, their supports and the mount. The facility active optics guiders, sensors, and control system are likely to be distinct from the adaptive optics systems (see Chapter 6).

4.3.9 Focal Stations

Effective use of the telescope requires that more than one instrument be available with short turn-around times. Bridging lunar phases and allowing for time-critical and target of opportunity observations require that no less than two and preferably three focal stations be made available. Each focal station shall have sufficient room for effective instruments and shall be supported with mounting platforms, guider support, data transfer ports, heat exchange ducting etc. The requirements for instrument platforms should be developed in conjunction with the instrument development. At least one of the focal stations will be available for rapid response to targets of opportunity. It is desirable that visitor instruments be supported at one of the focal stations.

4.3.10 Slewing and Tracking

The telescope must be able to reach all astronomical objects that reach elevations greater than 30 degrees, with a goal of reaching 25 degrees. The telescope should be able to track objects to within one degree of the zenith. Tracking rates for both sidereal and solar-system objects shall be provided for, along with the required field de-rotation at each supported focal station. The maximum slew time from one sky location to another should be no more than ten minutes (including settling), with a goal of 5 minutes. Response to Gamma Ray Bursters and other transient objects in less than 15 minutes from notification is a requirement for science goal 8. The telescope should be able to track non-sidereal astronomical objects while meeting the image quality requirements given in 4.9.4. The guiding systems at both the straight and folded Gregorian focal stations should be able to operate such as to produce the lowest thermal backgrounds; this may require movement of the guiders independent of the field de-rotator (e.g. tracking without field de-rotation).

4.3.11 Mechanical Stability

The telescope should meet its image size and wavefront error requirements (4.9.4) over a wide range of operating conditions. The mount tracking and servo systems should meet the same specifications as the Magellan 6.5m telescopes. The tracking errors should be less than 0.03″ rms in a 20mph wind and less than 0.1″ in winds above 20mph but below the closing speed. Other sources of image degradation due to vibrations and deflections of the mount should be small enough for the telescope to meet the image size specifications in wind speeds up to the 90th percentile operable speed while pointed away from the wind and up to the 75th operable wind speed when pointed into the wind. Image degradation at wind speeds between these limits (90th percentile away and 75th into the wind) should not exceed the specification by more than a factor of 2. The requirement for wind speeds below the 75th percentile should be met at any angle to the wind. The wind speed at which the dome must be closed will be set to ensure the safety of the telescope. The limit may be set by wind-borne dust or by risks to the telescope from wind-induced deflections. The limitations on observing time lost to high wind are discussed below (see also section 4.4.3). At Las Campanas peak the closing speed is expected to be ~ 35 mph and the 90th percentile of wind speeds below the closing speed is approximately 26 mph (11.5m/s).

4.3.12 Up-Time

Effective use of the telescope and a proper return on the partnership’s investment requires that downtime and overheads be kept to a minimum. Down-time is defined as time on a schedule observing night between dusk and dawn nautical twilight in which the telescope cannot be used to carryout astronomical observations for any reason exclusive of weather. Overhead is the time between nautical twilights which must be used to put the telescope into an operational state or to acquire targets. Tuning of the active optics system and slewing are examples of sources of overhead. A mean night is considered to last 10 hours from twilight to twilight.

Routine maintenance, via scheduled engineering time, should not consume more than twenty nights per year, or 5.5% of the time, once commissioning is completed. Telescope down-time within the scheduled observing nights should not exceed 4% of the time; the goal is less than 2%. This includes all sources of down-time related to the enclosure, telescope and other facility systems (e.g. guiders, rotators, mirror supports), but not instruments. Overhead associated with the telescope and facility systems, excluding instruments, should not exceed one hour, or 10% of a typical observing night for a representative observing program. Down-time associated with instruments should not exceed 5% of their scheduled observing time. Rapid switching between instruments should allow for mitigation of instrument down-time. Overheads associated with instrument setup are application and observer dependent. While these should be minimized, formal requirements on such overheads are beyond the scope of this document.

4.3.13 Enclosure Requirements

The telescope must be enclosed by a robust structure to protect it from the elements and to provide shielding from the wind. The enclosure should be reasonably light-tight and it should be sufficiently insulated, or actively cooled, to keep the thermal equilibration time-scale to less than one hour for typical opening conditions. Openings should be provided to maintain optimal flushing of air through the enclosure while allowing modulation of the air flow to reduce wind loading on the telescope structure. Shielding of moonlight should be provided by a movable moon-roof. Shielding from the wind should be provided by a movable windscreen or some other arrangement that keeps wind off the telescope. Dome seeing and wind-driven vibrations are explicitly included in the telescope image quality error budget (section 4.9.4). Mirror covers may be needed to maintain high throughput (requirements given in section 4.9.2).

Table 4-2. Telescope Requirements.*

Parameter	Requirement	Goal	Notes
Collecting Area	380 sq. meters	-	7 primary segments
Wavelength Range	0.4-25μm	0.3-25μm	UV w/o corrector
Image Size	0.30″ 80%EE	0.21″ 80%EE	At 500nm; see Table 4-7
Emissivity	< 10%	< 5%	@10μm, fresh coatings
Field of View	20′ diameter	>25′ diameter	At Straight Gregorian focus
	5′ diameter	-	At folded ports
Secondary	Gregorian	-	
Up Time	95%	>97%	Excludes routine maintenance
Elevation Range	89^0-30^0	89.5^0-25^0	

4.4 Site Requirements

The considerations that go into the GMT site selection and the status of candidate sites are discussed in the following chapter. These include a discussion of the rationale for a southern hemisphere site, non-scientific criteria that impact site selection, and a list of potentially suitable peaks in central and northern Chile.

4.4.1 Light Pollution and Environmental Constraints

The telescope shall be sited at a location known to be free of significant light pollution at the time of construction. Every effort shall be made to select a site with minimal prospect of increasing light pollution. The site shall be free of known developable mineral deposits and shall be as far from any industrial or commercial activity as is practical.

4.4.2 Seeing requirements

The site shall be thoroughly tested for atmospheric seeing and must have a median FWHM better than 0.65″ at 550nm at the zenith with a goal of 0.5″ or better. At least two seeing measurement techniques (e.g. Differential Image Motion, Multi-Aperture Scintillation Sensors) shall be used to characterize the site. Every attempt shall be made to characterize the ground-layer seeing component of the site, consistent with technical limitations. This may include computational fluid dynamic studies as well as direct measurements of the atmospheric turbulence profile and image motion studies.

4.4.3 Weather Conditions

Effective use of the telescope requires that conditions allow its use during a high fraction of the available nights. The fraction of photometric nights is required to be greater than 60% with a goal of greater than 70%. Spectroscopic nights (useable nights with some cloud) should, together with photometric nights, account for more than 70% of all nights, averaged over the year with a goal of greater than 80%. The fraction of clear hours expected to be lost to winds in excess of the operating limit should be less than 3%.

4.4.4 Thermal IR Performance

The site shall be selected to meet the requirements of thermal IR observing as defined by science goals 1, 2 & 3 in Appendix 4-1 (star and planet formation and solar system studies) for *some portion of the time.* This requires that for the driest 10th percentile, the column of precipitable water vapor be less than 1.5mm. The goal is to select a site that performs as well as the median Mauna Kea conditions for more than 15% of the time, averaged over the year.

4.5 First Generation Instruments

The scientific mission of the telescope cannot be advanced without a complement of instruments designed and constructed to match the unique capabilities of the GMT. An initial set of instruments shall be considered as part of the baseline facility and their construction will be counted as part of the capital cost of the facility. This first generation instrument compliment shall allow effective use of the telescope in all lunar phases and during all operable weather conditions, excepting the worst 5% of seeing conditions.

The baseline telescope design provides two classes of focal station for instruments, one port for large instruments and multiple ports for smaller instruments that will be in long-term residence. A critical part of the design development program will be the development of concepts for a set of first generation instruments. A down-select to a final set of first generation instruments will occur near the end of the design development study period, or at some other date set by the GMT Board.

4.5.1 The visible multi-object spectrograph

A spectrometer operating in the visible spectrum (0.32μm to 1μm) with the capability to observe multiple targets simultaneously is critical to our goals in the areas of star formation, stellar populations and most extragalactic science (science areas 3, 4, and 6 through 9). Maximizing sensitivity should be the highest priority for this instrument. Secondary priorities include optimizing field of view, multiplex factors, and simultaneous wavelength coverage. It is anticipated that this instrument will be used at the straight Gregorian focus and will employ the wide-field corrector.

4.5.1.1 Wavelength coverage and throughput

The spectrograph shall operate from 400nm to 980nm, with the goal of extending the coverage into the UV (320-400nm) and the extreme red (980-1100nm). The total throughput, including telescope, spectrograph and detector, but excluding slit losses, shall be greater than 25% over the 500-800nm bandpass (requirement) with the goal of a peak throughput greater than 35%. This will likely necessitate the use of a multi-slit rather than a fiber-fed system. Early universe studies (science goals 6-8) will benefit from access to the 0.8-1.2μm region of the spectrum. Consideration should be given to the use of new detector technologies (e.g. CMOS) in addition to the standard Si based CCD detectors currently in use. The optics and coatings of the spectrograph should not preclude the use of detector packages that operate in the J and H bands, unless other arrangements (e.g a near-IR channel) are provided to meet the requirements for galaxy assembly and first-light studies (science goals 7 & 8). This spectrograph should have an imaging mode and be equipped with a standard set of filters for imaging and order-separation by the time of its acceptance review. If the spectroscopic performance of the instrument can be enhanced at the expense of imaging performance, the design team is encouraged to optimize for spectroscopic performance.

4.5.1.2 Field of view and image quality

In many applications the effectiveness of the instrument scales directly with field area; thus field of view is the second priority for this instrument. Field of view is critical to faint galaxy surveys (science goals 7 and 8). The spectrograph should have a minimum field area of 60 sq. arcminutes (requirement) with a long-term goal of 150 sq. arcminutes. The precise configuration of the field area is not critical. Realization of the field area as a long-term goal may require multiple optical units that share the focal plane.

The spectrograph should not degrade the images produced by the telescope + corrector by more than 5% at the center of the field and by more than 15% at a radius of 10′. Thus the 80%EE requirement at a field distance of 10′ radius is 0.24″, and the goal is 0.16″ 80%EE (see Table 4-7).

4.5.1.3 Stability

Stability is essential for sky subtraction and velocity determinations and it impacts science goals 3 through 8. This instrument will likely be mounted on a gravity-variable platform requiring active flexure control for acceptable performance. The maximum flexure over 3 hours of continuous observation shall be less than 0.1 spectral resolution element at the detector. Allowance should be made for charge shuffling if the detectors are of the charge-coupled variety. Sources shall be provided for wavelength and flat-field calibrations.

4.5.1.4 Resolution

A range of resolving powers shall be provided along with sufficient detector area to allow wide spectral coverage. Consideration shall be given to holographic rulings as well as traditional surface relief rulings for dispersing elements. Science goals 3, 7, and 8 require modest resolutions (R~ 3000), IGM tomography requires higher resolution (R ~ 5000), while galaxy evolution studies may be better served with lower resolution and greater wavelength coverage and multiplexing. The spectrograph should have a range of resolving powers from R=500 to R=5000 (goal) with a requirement of R=1000 to R=3000, all for a 0.75″ slit-width. The range of resolving powers do not need to be available within a single night or even a single dark-time observing campaign.

4.5.1.5 Multiplexing

Simultaneous observation of many objects is critical to many of our science goals. This multiplexing is expected to be addressed via focal plane masks. It is essential that the focal plan masks be capable of taking advantage of the excellent image quality of the telescope. The masks must also be able to deal with atmospheric refraction and field distortions that it introduces. This may have implications on the operations mode for this instrument, as a particular mask may be valid for only a limited range of hour angles.

4.5.1.6 Tunable filters, IFUs, image slicers etc

Lyα and other emission searches from distant galaxies (science goal 8) require a narrow-band imaging or imaging+spectroscopic capability. This may be best accomplished with a tunable filter or Fabry-Perot system. An imaging system with a 0.5% bandwidth and greater than 10% throughput is required, regardless of how it is achieved. Phase A studies should examine how to best achieve specialty applications, such as IFUs, tunable filters, images slicers, and polarimetery. These may be accomplished as part of the baseline instruments, or they may be second-generation specialty instruments or modules.

4.5.2 Cryogenic IR Spectrometers

The need for IR spectroscopy on the GMT naturally breaks into three regimes: moderate resolution multi-object spectroscopy in the 1-2.5μm windows, high-resolution single-object spectroscopy in the 1-5μm windows, and intermediate and high resolution spectroscopy in the 5-25μm range. The first generation instrument candidates address the first two capabilities and a portion of the 5-25μm needs.

4.5.2.1 Near-IR Multi-Object Spectrometer

Many of our science goals in Appendix 4-1 (e.g. 5-8) call for spectroscopy in the 1-2.5μm windows. A substantial field of view and high multiplexing factor are essential to studies of galaxy formation and evolution (science goals 7 and 8).

4.5.2.2 Wavelength coverage and throughput

The near-IR MOS should operate in the J, H, and K atmospheric windows. Operations in the 0.9-1.1μm portion of the spectrum (z and Y bands) are also desirable. The throughput, exclusive of slit losses but including the telescope, should be optimized over the 1-2.5μm range and should be no less than 20%, averaged over the 1.4-2.3μm spectral range with the goal of a peak throughput greater than 25%.

4.5.2.3 Field of view and image quality

Many programs (e.g. science goals 3, 7 and 8) require simultaneous spectroscopy of multiple targets to be efficient. This requires both a significant field of view and the ability to employ focal plane masks for multi-slit observations. The spectrograph/imager should have a field area greater than 50 sq. arcminutes (goal) and no less than 25 square arcminutes (requirement). The exact shape of the focal plane is less important than the total area, and contiguous coverage, while desirable, is not required.

The image quality produced by the full optical train of the imaging spectrograph should not degrade the images produced by the telescope by more than 10% within a 2.5′ field radius and not more than 15% within a 5′ field radius. The image quality requirements for the telescope (Table 4-7) call for an 80%EE of 0.30″ at 500nm to meet the requirement that best quartile seeing not be degraded by more than 10%. The free-air seeing at 1.5μm is expected to be better than that at 500nm and ground-layer corrected images with FWHM ~ 0.15″ may be achievable. To avoid degrading these images by more than 15%, the instrument should produce images with FWHM = 0.08″ (80%EE = 0.15″).

4.5.2.4 Resolving power

Resolving powers of 3000 and greater are essential to the performance of near-IR spectrometers in the OH dominated region of the spectra (below 2.3μm). Resolution of R = 3000 with a 0.5″ slit is thus required; R>5000 is desired for a number of science applications. The lowest dispersion mode will be defined by the requirement to sample the full Y-H or H-K bands in a single exposure. A series of band-limiting filters shall be included in the instrument. Some of these will double as imaging filters, but others (e.g. Y-H) may be of use only as spectroscopic order sorting filters. Multiple tiers of spectra will be accommodated via the focal plane masks and band-limiting filters.

A high dispersion mode, suitable for stellar spectroscopy, is highly desirable. Resolving powers of R>10,000 are required. This may be accomplished with a cross-dispersed mode or it may be accommodated by the 1-5μm echelle.

4.5.2.5 Internal backgrounds

The instrument shall not produce internal radiation that exceeds the noise-floor set by the detector noise and darkest OH free regions of the sky spectrum. The instrument should baffle the radiation from the telescope structure and out-of-field sky regions to levels that are also below the inter-OH sky plus detector noise floors at wavelengths below 2.3μm.

4.5.2.6 Multiplexing

The conceptual design of this instrument should address the issue of focal plane masks. The focal plane masks must be manufactured or controlled to very tight tolerances, as images as small as FWHM = 0.15″ may possible in the GLAO mode. A minimum of 100 3″ long slits (requirement) should be available over the full field, with a goal of 200 slits. The goal of 300 slits may be accommodated by the use of multiple tiers of spectra and band-limiting filters.

4.5.2.7 IFUs and other modules

Integral field spectroscopy at the natural seeing or GLAO-corrected image size is likely to be an important component of studies of the evolution and internal structure of galaxies, as well as studies of embedded star clusters and other crowded regions. The IR spectrograph will have the ability to accept an IFU unit working in the Y-H bands, and possibly at longer wavelengths.

Phase A studies should examine how to best achieve specialty applications, such as IFUs, tunable filters, images slicers, and polarimetery. These may be accomplished as part of the baseline instruments, or they may be second-generation specialty instruments or modules.

4.5.3 The Mid-IR AO Imager and Spectrometer

The mid-IR imaging spectrometer is required for studies of star and planet formation (science goals 1 and 3). The instrument should be optimized to work in the diffraction-limited regime and should critically sample the PSF at 10μm. High dynamic range imaging is essential for exoplanet and debris disk studies. This may be accomplished with nulling interferometry between the GMT primary mirror segments or by high order adaptive optics corrections using the adaptive secondary mirror and/or other deformable elements. It is likely that more than one channel will be needed to effectively sample the PSF over the full wavelength range. This instrument is expected to reside on the upper instrument platform and may be closely integrated into the facility AO system.

A grism and diffraction limited 10″ long-slit will permit medium spectral resolution (R~1500-3000) spatially resolved spectroscopy, perhaps in a cross-dispersed mode. We require access to the full 8-24μm spectral range. For Nyquist sampling at 24μm, this calls for a 2048 pixel detector in the dispersion dimension. Higher resolution is desirable for some applications. Partial spectral coverage at R ~ 3000 is a goal for this instrument.

Detailed studies of dense star forming regions and disks would benefit from an IFU approach to spatially resolved spectroscopy. This capability could be provided by a focal plane module covering 3″ x 3″ with 50mas lenslets or other apertures. This spectral capability would target the same spectral range and resolutions as the slit mode.

4.5.4 Near-IR High Resolution Spectrograph

Studies of star formation and stellar physics benefit from a high-resolution spectroscopic capability in the near-IR. These include studies of the photospheres of young stars, searches for sub-stellar objects and planets, and quasar metal-line absorbers at high redshift. The near-IR high-resolution spectrograph should operate in the 1 to 5μm regime. This may be accomplished with multiple channels and different detector technologies and formats. The resolution should range from as low as ~10-20,000 for slits matched to natural seeing and as high as ~ 50-100,000 for slits matched to the diffraction limit.

4.5.5 The Visible High Resolution Spectrometer

A high-resolution optical spectrograph is required for searches of exoplanets and abundance studies in a variety of applications. Resolving powers of 40,000 or greater are required for stellar abundance and IGM work, with resolutions as high as 200,000 desired for stellar line profile and abundance studies. Full spectral coverage is required for the R=40-50k mode. This instrument need not have a large field of view, as most of the targets are point sources or have very small angular extent. A multi-object mode, using a fiber feed, could be a valuable enhancement. The high-resolution spectrograph is expected to reside at one of the folded ports and should be available at short notice. This is critical for GRB follow-up spectroscopy (science goal 8). Deployment of this instrument at the folded port would also be useful for partial bright nights when the faint-object multi-slit spectrograph is at the straight Gregorian focal station.

4.5.6 The Near-IR ExAO Imager and IFU

Many of our science goals require a near-IR imager matched to the diffraction-limit of telescope in the 0.8-2.5μm range. It should be deployed at one of the folded Gregorian focal stations to take advantage of periods of outstanding image quality. A top scientific priority is high contrast imaging of exoplanets in the J, H and K windows. Dynamic ranges of 10^7 and greater are required, while contrasts > 10^8 are the goal. This instrument is expected to use the adaptive secondary; the need for additional deformable elements will be examined as part of the instrument conceptual development study.

A modest near-IR spectroscopic capability at the diffraction-limit is highly desirable for a variety of science goals (e.g. star and planet formation, galaxy evolution, black hole dynamics). With diffraction-limited performance, it should be possible to use the camera in combination with a grism and narrow (0.02″) slit for medium spectral resolution (R~3000) AO spectroscopy. A pixel size of ~6 mas is required for proper sampling of the diffraction-limited PSF at 1μm. Field sizes of 10″-20″ can be achieved with current detector technology in either a 2048x2048 monolithic detector or in a 4096 x 4096 focal plane mosaic. The detectors should have negligible dark current and read noise below $10e^-$ per read, with achievable read-noise better than $5e^-$.

Table 4-3. First generation instrument candidates.

#	Instrument	λ (μm)	Resolution	FOV	Modes
1	Visible WF MOS	0.4-1.0	500-5000	60-150 sq. arcmin	MOS/IFU/TF/Imager
2	NIR MOS	0.9-2.5	1500-5000	25-100 sq. arcmin	MOS/IFU/TF/Imager
3	Visible Echelle	0.3-1.0	20K-100K	20″	Single Obj/MOS/I cell
4	MIR imager	5.0-24.	5-3000	2′ x 2′	AO imager/spectrometer
5	NIR Echelle	0.8-5.0	40K-100K	30″	LTAO/Natural Seeing
6	NIR imager	0.9-5.0	5-5000	30″	ExAO/LTAO imager

An integral field spectroscopic mode may provide a greater scientific capability and more effective observational strategy for spectroscopy at the diffraction-limit. The IFU should cover a significant fraction of the field produced by conventional AO (~ 10″-20″) with a pitch size in the range from 20-100 mas. Formats from 50 x 50 to as large as 200 x 200 should be considered during the phase-A design process for this instrument.

4.5.7 Matching Instruments and Science Goals

The first generation instrument candidates should address the full range of science defined by the high-level science goals summarized in Table 4-1. Some goals will be addressed by more than one instrument. Not all of the instruments in Table 4-3 will be built as part of the first generation but a subset of them will be chosen, in part, on the basis of their ability to carry out as much of the science program as possible.

Table 4-4. Correspondence between Instruments and Science Topics.

Science Area	**Sub-Area**	**Instrument**
Planet and Star Formation	Exoplanet Imaging Radial Velocity Surveys Disk Structure Star Formation & IMF	Near-IR AO Imager Vis & Near-IR Echelles NIR & MIR AO Imagers NIR Echelle, NIR & MIR AO Imagers
Stellar Populations & Chemical Evolution	Crowded Field Photometery Stellar Abundances	Near-IR AO Imager High Res Visible Spectrometer
Galaxy Assembly	Mass Evolution Chemical Evolution IGM Tomography	Visible WF MOS NIR WF MOS Visible WF MOS
Black Holes	Dynamical Surveys	NIR AO Imager/Spectrograph, IFU
Dark Energy	Baryon Oscillations at $z > 4$ SNe at $z > 1$ Follow-up of LISA Sources	Visible WF MOS NIR AO Imager/Spectrograph, IFU Visible WF MOS
First Light and Reionization	$Z > 6$ Quasars $Z > 5$ Galaxies $Z \sim 10$ Galaxies & AGN	Visible & NIR High Res. Spectrometers Visible WF MOS Near-IR AO Imager/TF/IFU

The results of this matching are shown in Table 4-4. Most of the instrument candidates cover multiple areas. The visible MOS covers 11 and the Near-IR AO imager is useful for 13 of the science topics. The utility of the visible MOS stems in part from its use as an imager as well as a spectrograph. If the imaging capability is dropped or split off as a separate instrument, the MOS itself is reduced to ~9 areas.

4.6 Adaptive Optics Capabilities

Adaptive optics is an essential part of the GMT core mission and it plays a lead role in many of our highest priority science goals. AO is still in a developmental stage; new approaches and technical innovations are being developed on 4-8m class telescopes at this time. We expect there to be considerable evolution in the approach to various types of AO and our understanding of which approaches (e.g. GLAO, MCAO, EXAO, MOAO) are most effective, between now and the time that GMT begins operations. An essential part of the design/development activities will be the creation of a long-range plan for the development of AO within the GMT consortium.

4.6.1 Sensors and Guide Beacons

The choice of sensor and guide systems for the AO instruments on the GMT may have broad implications for our ability to carry out much of the science case. In particular, the exclusive use of natural guide stars rather than laser beacons would severely restrict the area of the sky over which diffraction-limited observations are possible. We recognize that high sky coverage is an important goal for the AO system(s).

4.6.2 First Generation AO Capabilities

We envision a staged development for adaptive optics on the GMT. Our science priorities place a strong emphasis on studies of exoplanets and faint distant galaxies. These call for early capabilities in the extreme AO and ground-layer correction. For the first generation of instruments our scientific priorities for adaptive optics are:

Extreme AO: This mode will provide high contrast on small angular scales and is essential for science goal No. 1, exoplanet and debris disk studies.

Ground-Layer AO: This mode may offer significant gains in image size over modest to wide fields, a capability important to many of our extragalactic programs (science goals 6 through 8).

Laser Tomography AO: This will provide nearly all-sky coverage at the diffraction-limit with modest Strehl, an important part of a large number of our science goals (e.g. 2-8).

Multi-conjugate and multi-object adaptive optics capabilities are of considerable interest and developments in this area will be closely watched, but they are not part of the GMT baseline AO plan at this time.

4.6.2.1 High Strehl AO

Imaging and spectroscopy of faint objects near bright stars require an AO system that delivers high Strehl ratios or high dynamic range at a particular range of angular separations. This capability is critical to exoplanet detection and to studies of AGN host galaxies and environments. The system should produce contrast ratios better than 10^6 at 0.1″ radius, with a goal of $> 3 \times 10^8$.

4.6.2.2 Ground-Layer Correction

AO systems tuned to correct ground-layer turbulence induced seeing offer the possibility of significant image improvement over large fields of view. While not producing diffraction-limited imaging, ground-layer AO is expected to produce improvements in FWHM ranging from 50% to 400%, depending on the wavelength and conditions. The GMT adaptive secondary is expected to provide an effective path to ground-layer correction. Our hope is that a factor of 2 reduction in image size over a 10′ diameter field will be possible at wavelengths beyond 1μm. Our goal is to have GLAO correction provided by the adaptive secondary available at all of the focal stations. Phase B studies will examine the trade-space between natural guide star and laser beacons for GLAO.

4.6.2.3 Small Field Adaptive Optics

Diffraction-limited imaging and IFU spectroscopy are a key part of studies of debris disks, dense star clusters, SNe, faint galaxies, gravitational lenses and many diverse phenomena. Some of these programs may be possible using natural guide stars or the science targets to close the loop, others either require or benefit from laser guide beacons. The GMT facility diffraction-limited AO system should not add additional background greater than 10% of natural sky and telescope emission. The system should produce diffraction-limited images with median Strehl ratios better than 0.4 at 1.5μm with a goal of better than 0.7. The AO image quality requirements are discussed more fully in section 4.9.4.3. The system should work with natural guide stars with a long-term goal of incorporating laser beacons as they are developed.

4.6.3 Second Generation AO Capabilities

Adaptive optics has the potential to unlock the full capability of the GMT. As technology develops on the 4-8m class telescopes some techniques will mature to the level that will allow them to be incorporated into the GMT. At this time we identify two approaches that have strong scientific appeal and should be considered as candidates for second-generation AO capabilities. It is premature to specify requirements for second-generation AO capabilities; *the specifications listed below are goals* and we expect these to be revised periodically in light of progress with systems on 4-10m telescopes.

4.6.3.1 Multiconjugate AO

The use of multiple deformable elements conjugated to different levels of the atmosphere is expected to produce diffraction-limited imaging with a stable point-spread function over fields as large as 2′ in diameter. The GMT MCAO system should operate over the 0.7 to 2.5μm range and should be cooled so as not to add a background due to thermal emission from the DMs or re-imaging and relay optics that is greater than 20% of the sky and telescope backgrounds combined. Excessive instrumental backgrounds defeat the sensitivity gains that devolve from smaller image sizes in sky-limited observations. The total end-to-end throughput of the system should be greater than 25%. Delivered median Strehl ratios should be better than 20% and the PSF should be uniform and stable enough to allow (with calibration) 2% relative photometry over the full MCAO field and 5% relative photometry from field to field.

4.6.3.2 Multiobject AO

Multiple deployable IFUs may be combined with deployable wave-front sensors and multiple deformable elements to correct multiple fields of view simultaneously. As the AO plan develops in phase B and beyond, the project and the SWG will periodically revisit the case for MOAO.

Table 4-5. GMT AO Modes.

Mode	FWHM	Field	Strehl	Guide	Notes
EXAO	Diff. Limit	2″	>0.95	NGS/LGS	
GLAO	0.15″-0.25″	20′	-	NGS/LGS	
LTAO	Diff. Limit	20″	0.2-0.7	LGS	High Sky Coverage

4.7 Support Facilities

The effective use and maintenance of the GMT requires a significant level of support facilities. As these are required both for first-light and for continued operations, they must be considered as part of the baseline facility and included in the capital cost of the facility.

4.7.1 Coating and Cleaning Facilities and Spare Primary Mirror Segment

The primary mirror segments must be coated before use. They must also be cleaned regularly and stripped and recoated at regular intervals. The coating facility must be capable of applying an aluminum coating to the primary mirror segments and other small optics (e.g. secondary mirror, folding-flats etc) before first light. The ability to apply advanced coatings that maximize throughput and reduce the need for recoating to some or all of the GMT optics, is an important long-term goal for the operating facility.

The primary mirror segments must be cleaned and provision shall be made for cleaning the mirror segments in place. Recoating the segments is likely to require their removal from the telescope. To reduce the associated downtime and to provide redundancy in the case of failure, the baseline plan should include the securing of a spare 8.4m off-axis mirror polished to the same optical specifications as the other off-axis segments. A mirror cell and supports shall also be provided for this mirror so that it can be swapped with any of the other off-axis segments during recoating operations.

4.7.2 Instrument Support Laboratory

The GMT instruments will need to be stored and maintained when they are not in the telescope. A facility shall be provided for storage of the instruments that allows adequate room for routine maintenance operations as well as partial disassembly/reassembly of the instruments. Adequate support in the form of machine and electronic shops will be included in this facility or in close proximity. Space will be provided for offices for technical and scientific staff.

4.7.3 Observer Support Facilities

Sufficient dormitory and dining facilities shall be provided for visiting observers and resident support staff. In addition, space will be provided for visiting observers, both the current and recent/subsequent groups, to prepare for and complete operations associated with their observing time.

4.8 Operational Requirements

The telescope and its associated facilities should support a variety of observing modes. These include classical observing, assisted observing, service observing, and queue scheduling. The high level philosophy of the scientific facility, the details of the operational model for the observatory, and their implications for the operating budget are discussed in detail in chapter 7.

4.8.1 General Operating Principles

The GMT partner agreement and articles of incorporation define the procedure by which observing time on the GMT is distributed to the partners and other eligible parties. The observatory will be operated for the furtherance of astronomical research and will place a high priority on efficient operations. Many of the requirements on telescope performance (e.g. down-time, overhead), instrument accessibility, and site performance have implications for the operation of the observatory, and the operations plan must meet these requirements.

4.8.1.1 Classical Observing and Campaign Mode

The observatory should support observations in which an astronomer, or astronomers, travel to the site and use the telescope for a predefined period of time. The astronomers usually operate the instruments and are responsible for carrying out an efficient observing program. In campaign mode one or more groups of astronomers will travel to the observatory for long duration observing programs focused on one or more large science projects. These may involve scientists from more than one partner institution.

4.8.1.2 Assisted Observing

Some observing modes may involve instruments or systems whose operational complexities are such that visiting astronomers cannot make efficient use of them without assistance from a trained specialist. The observatory will support such assisted observing as needed and deemed appropriate by the GMT board.

4.8.1.3 Service Observing and Queue-Scheduled Service Observing

It may develop that the most efficient mode of operation will entail observing by a professional staff. Service observing can follow a strictly pre-allocated set of programs or, in the queue mode, it can be adapted to the conditions and RA distribution of targets.

4.9 Performance Requirements

4.9.1 Conventions and Metrics

Unless otherwise noted, all image quality, wavefront errors, and reflectivities are specified at a wavelength of 500nm.

Image sizes for the telescope and instruments are specified in terms of 80% encircled energy diameters.

Site surveys generally measure the seeing in terms of FWHM. We convert between FWHM and 80%EE on the basis of empirical seeing profiles, using D(80%EE) = 1.89 x FWHM. Image FWHM diameters are a factor of 1.66 times larger than rms image radii.

Telescope performance and site specifications that involve the atmosphere are referenced to unit airmass.

4.9.2 Throughput

The power of the GMT derives in large part from its great collecting area. The throughput of the telescope, determined by the reflectivity of the mirrors and transmission of lenses, should be as high as possible. We specify the reflectivity of the primary mirror segments, secondary and fold mirrors in Table 4-6. These requirements and goals refer to freshly coated surfaces. Regular cleaning of the primary and secondary mirror surfaces should maintain reflectivities that are > 85% of the initial values. The requirements are tied to fresh over-coated Al; the goals in the IR are referenced to Au. These may not be achieved in practice, as the desire for broad wavelength coverage will probably preclude the use of Au or over-coated Ag on all but the fold mirrors.

Table 4-6. Reflectivities of Mirrors and AR Coated Surfaces.

Wavelengths	**320-400nm**		**400-1000nm**		**> 1000mn**	
	Req.	Goal	Req.	Goal	Req.	Goal
Primary	0.83	0.90	0.88	0.90	0.85	0.98
Secondary	0.88	0.95	0.88	0.97	0.85	0.98
Fold Mirror	0.90	0.95	0.95	0.97	0.90	0.99
Corrector	<2%	<1%	<1%	<0.5%	NA	NA
Total			77%*	87%	w/o corrector	
			71%	85%	w. corrector	

* totals refer to the 400-1000nm region only

4.9.3 Emissivity

The emissivity of the telescope at the straight focus should be less than 10% at 10μm with a goal of less than 5%. This includes emission from the primary and secondary mirrors with recent coatings. Regular cleaning of the primary and secondary mirrors should control added emissivity due to dust and degradation of the coatings. The emissivity between coatings of the primary and secondary mirror should not exceed 150% of the nominal values.

4.9.4 Image Size and Wavefront Error Requirements

We place the highest priority on the delivered image quality from the GMT optics and support systems. This derives not only from the desire for high angular resolution, but also from the strong dependence of sensitivity on image size in sky-limited applications. We consider three regimes for image quality: narrow-field seeing limited, wide-field seeing limited using a wide-field corrector, and diffraction-limited imaging with the primary mirror segments phased. We specify the seeing limited image quality in terms of image size, both as FWHM and 80% enclosed energy diameter. We specify the diffraction-limited performance in terms of rms wavefront error.

The image quality error budget explicitly includes the following sources:

- Figure errors in the primary, secondary and fold mirrors on their supports
- Alignment errors in the primary, secondary and fold mirrors
- Mirror seeing
- Dome seeing
- Wind-driven vibrations and deflections as discussed in section 4.3.11
- Vibrations induced by other sources within the enclosure and telescope mount

The telescope is not expected to meet the image quality requirements in the first hour of operation on a typical night due to the non-zero thermal equilibration time constant in the primary mirror segments. The images produced during this settling period, or during changes in ambient temperature faster than 0.5 ^{o}K/hour, should not exceed the requirements by more than a factor of 2.

4.9.4.1 Narrow-Field Seeing Limited Image Sizes

At wavelengths shorter than about 1μm, the images delivered by the telescope are likely to be dominated by atmospheric seeing rather than diffraction effects. We place a high priority on the telescope not degrading the best natural seeing images that the site delivers. The site requirements call for the telescope to be built at a location with median seeing of 0.60″ FWHM (corrected to unit airmass and at 500mn) or better. At Las Campanas the best 10th percentile of seeing is 0.35″; it is expected that GMT site will have a similar distribution of seeing. The telescope should not degrade the best quartile seeing by more than 10%, in terms of either FWHM or 80% enclosed energy, at the center of the uncorrected field. This implies that the telescope should produce images with 80%EE < 0.30″. These are requirements; our goal is that the telescope will not degrade the best 10th percentile seeing by more than 5%. This translates to telescope image size goals of 80%EE < 0.21″. Our imaging requirement, best 10th percentile + 10%, ensures that the median seeing delivered by the site will not be degraded by more than 5%.

The spectrum of atmospheric turbulence is believed to be well approximated by the Kolmagorov spectrum and Fried's parameter, $r_{o,}$ is expected to vary as $\lambda^{5/4}$. The image quality demanded of the telescope is thus less stringent at short wavelengths. At 330nm the telescope need only produce images with 80%EE < 0.49″ to preserve the best images to 10% in 80%EE.

4.9.4.2 Wide-Field Seeing-Limited Image Sizes

Several of the science requirements call for large fields of view to enable efficient surveys of large samples of objects. The visible multi-object spectrograph in particular should be able to access fields of 16′-20′ in extent. This calls for a wide-field corrector. The image quality requirements over these large fields are not as stringent as in the narrow field case. This stems in part from the likely coarser sampling expected in wide-field instruments and the technical challenges associated with wide-field collimators and cameras. We require that the images at the edge of the corrected field, up to 10′ in radius, not be degraded from the best 10th percentile seeing by more than 15%. This places requirements on the image size of < 0.38″ 80%EE. While these are requirements, the goals are 25% more stringent: 80%EE < 0.28″.

Table 4-7. Seeing-limited image size requirements and goals.

Mode	**FWHM(″)**	**80% EE**	**Strehl Ratio**	**Notes**
Narrow-Field Seeing Limited	0.16, 0.11	0.30, 0.21	-	500nm
Wide-Field Seeing-Limited	0.20, 0.15	0.38, 0.28	-	10′ field radius

4.9.4.3 AO Image Quality, Backgrounds and Sky Coverage

Adaptive correction of the atmospheric seeing is expected to be limited to wavelengths of 1μm and longer. Some correction at shorter wavelengths may be possible but the Strehl ratios are expected to be low. The telescope should produce diffraction-limited images at the folded focal stations at all wavelengths longer than 1μm. The actual images delivered at an AO corrected focal plane will not have unit Strehl ratios, due to the finite number of actuators and imperfect information regarding the incoming wavefront. For the purposes of this document we define the Strehl ratio relative to a perfect image produced by the GMT pupil rather than that of a filled aperture. The requirements and goals for Strehl ratio at various wavelengths, and the associated wavefront error are tabulated in Table 4-8 below.

Table 4-8. AO wavefront requirements and goals.

λ(μm)	Strehl requirement	RMS (nm) requirement	Strehl goal	RMS (nm) goal
1.2	0.20	243	0.25	225
1.6	0.40	244	0.60	182
2.2	0.70	209	0.90	113
3.5	0.90	180	0.95	126
4.8	0.95	173	0.99	77

The delivered Strehl ratio should be greater than 0.2 in the J-band and equal to or greater than 0.7 in the K-band, both referenced at a nominal distance of 10″ from the center of the LGS. At wavelengths longer than 2.5μm the AO system should produce images with Strehl > 0.9, with a goal of >0.95. These requirements apply to ambient conditions with free air seeing equal to or better than 0.6 arcsec FWHM in the V-band at the zenith.

The facility AO system should not produce significant additional thermal background. The baseline telescope calls for an adaptive secondary that acts as the first, and perhaps only, deformable element in the facility AO system. This element should meet the net emissivity requirements given in section 4.9.3 above. Additional, or alternative, deformable elements or adaptive optics modules should not produce a total emissivity in excess of 20%, with a goal of less than 10%.

The LTAO system should be able to work over a large fraction of the sky to be scientifically attractive. Sky coverage near the galactic poles (|b| > 50) should exceed 80%, and should be greater than 95% for |b| < 50.

4.9.5 Applicability of the image size and wavefront requirements

It is understood that there will be some conditions under which the telescope will not be able to meet its image size and wavefront error requirements. These include high winds, as specified in section 4.3.11, times of large temperature swings, and potentially times of very low wind. In Table 4-9 below we summarize the various conditions and the image size/wavefront requirements that apply.

Table 4-9. Applicability of Image Requirements.

Conditions	**FWHM(″)**	**80EE**	**DIQ**[*]	**Source of Error**
Wind < 75th percentile, into wind	0.16	0.30	0.62	Nominal Conditions
Wind > 75th percentile, into wind	0.32	0.60	0.68	Mount Shake
Wind > 90th percentile, into wind	0.48	0.90	0.76	“ “
Wind < 25th percentile	0.24	0.45	0.64	Mirror Seeing
ΔT/Δt > 0.5 °K per hour	0.32	0.60	0.68	Mirror Figure

[*] DIQ is the Delivered Image Quality in 0.6″ free-air seeing in units of arcsec FWHM.

Appendix 4-1 – Details of the Science Requirements by Area

Table 4-1.1 – Detailed Science Requirements

#	**Science Area**	**λ range**	**FOV**	**R**	**Mode***	**AO**	**Notes**
1	Exoplanets	0.5-10	2″	5-100	I	ExAO	Direct imaging
		0.4-2.0	20″	5-100	I, S	LTAO	Disks scattering
		1.0-25	20″	5-3000	I, S	LTAO	Disk emission
		0.5-1.0	20″	100000	S	-	Radial vel. Surveys
2	Solar System	0.4-2.5	5′	5-1000	I, S	LTAO	KBOs
		0.4-10	1′	5-30000	S	-	Comets & Moons
3	Star Formation	0.8-5.0	40″	5-5000	I, S	LTAO	Embedded clusters
		0.4-2.5	8′	5-100	I	GLAO	Proper motions
		1.0-5.0	30″	5-3000	I	LTAO	Crowded fields
		0.8-5.0	30″	5-100	I	GLAO	Mass ratios
4	Stellar Pops	0.3-1.0	3″ slit	20k-100k	S	-	Stellar abundances
		0.7-2.5	1′	5-5000	I, S	LTAO	Pop. Studies
5	Black Holes	0.3-10	5′	5-5000	I, S	LTAO	AGN Environments
		0.8-2.5	3″	500-5000	S	LTAO	Velocity structures
6	Dark Energy	0.3-2.5	5′	5-5000	I, S	LTAO	SNe monitoring
		0.3-2.5	30″	500-2500	S	-	SNe physics, pol.
7	Galaxy Ass.	0.4-2.5	>8	5-3000	I, S	GLAO	Stellar mass density
		0.8-2.5	30″	500-5000	S	LTAO	Internal dynamics
8	First Light	0.4-1.0	>8′	5-100K	S	-	IGM studies
		0.8-2.5	>8′	5-5000	I, S	LTAO	First Galaxies

* I = imaging mode, S = spectroscopy

Table 4-1.2 – Detailed Match of Science Requirements and Instruments

#	Science Area	Sub-Area	Instruments*	Notes
1	Exoplanets	Direct imaging	6, 4	ExAO, Nulling
		Disks scattering	6, 4	
		Disk emission	4, 6	mid-IR
		Radial vel. surveys	3, 5	
2	Solar System	KBOs	1, 6	
		Comets & Moons	3, 5, 4	
3	Star Formation	Embedded clusters	6, 4	
		Proper motions	1	GLAO critical
		Crowded fields	6, 2, 1	
		Mass ratios	6, 3, 5	
4	Stellar Pops	Stellar abundances	3, 5	
		Pop. Studies	1, 6, 3	
5	Black Holes	AGN Environments	1, 6, 2	IFU,TF Modes
		Velocity structures	6, 1	IFU Mode
6	Dark Energy	SNe monitoring	6, 1, 2	
		SNe physics	1, 2	Polarim. mode
7	Galaxy Ass.	Stellar mass density	1, 2	
		Internal dynamics	2, 6	
		IGM Tomography	1,2,3	
8	First Light	IGM studies	1, 3, 2, 5	
		First Galaxies	1, 2, 6	

* The instrument numbers are given in Table 4-3.

Appendix 4-2 – The impact of precipitable water vapor on the mid-IR atmospheric windows.

The GMT science requirements dealing with precipitable water vapor levels were derived from consideration of their impact on the transmission of the atmosphere in the mid-IR and the background in the transparent regions. The curves in Figure 4-2.1 below show that water vapor has a moderate impact in the 4.8μm M-band, less impact in the 10μm window and dramatic impact in the 23-28μm region of the spectrum. In the 5 and 10μm windows, the difference between the transmission for PWV levels of 1 and 1.6mm are not dramatic, while at 3mm quite significant losses in transmission and increases in background are apparent, particularly in the 5μm and 25μm windows. For this reason we selected 1.5 mm as our threshold for acceptable mid-IR conditions, although there is no question that drier conditions are desirable. At high spectral resolution there are a number of applications that require conditions drier than 1mm of water. In many cases this is driven by critical transitions that produce lines very close to water lines in the atmosphere. For these lines the limiting factors are the transmission in the core of the water lines and ones ability to subtract atmospheric features with high fidelity.

In chapter 5 we discuss the site selection process and our program for monitoring PWV levels. Here we briefly point out some of the science opportunities that are negatively impacted, and in some cases entirely lost, at a low elevation site.

The unique features of the GMT (sensitivity over a wide field of view in the visible and near--infrared, unprecedented spatial resolution and high contrast ratios in the near-- and mid--infrared, and excellent performance in the thermal IR from 2-12μm) will address many of the most compelling questions facing astrophysics today. However, a GMT telescope located at a high altitude site, above 13,000 feet elevation in the southern hemisphere, would represent an opportunity to extend the reach of GMT into additional areas of discovery space.

Sited on a high dry mountain with median PWV of one millimeter or less, the GMT would be able to make high resolution (R > 30,000) spectroscopic observations over large portions of the 6-13μm and 16-25μm atmospheric windows. This would enable surveys for molecular gas throughout the protostellar collapse and planet formation phase in circumstellar disks. Such observations would trace the physical conditions and evolution of molecular abundances as cloud cores transform into stars. Resolving the Keplerian line profiles of important organic molecules would enable mapping critical densities and temperatures as a function of radius in circumstellar disks. Similar atmospheric conditions would provide unprecedented sensitivity for high spatial resolution imaging in the 16-25μm window. Such sensitivity would enable spatial resolution of important grain mineralogies, indicative of grain processing and perhaps radial mixing beyond 10 AU where ice giant planets are thought to form. Comparison of these observations for well-chosen samples of solar analogs with models for the dynamical evolution of our solar system between 10 Myr and 1 Gyr could help us infer the frequency of events responsible for the sculpting of our own asteroid and Kuiper belts as well as the period of intense giant impacts associated with the late heavy bombardment.

Other programs enabled by building the GMT at an altitude optimized for thermal IR performance include:

- Imaging of protostars in the very earliest phases resolving their multiplicity and determining the mass/radius of individual objects during the earliest stages of collapse.

- Resolving the nearest AGN accretion tori in thermal emission as well as in diagnostic emission lines.

- Resolving PAH features and tracing obscured star-formation in distant galaxies detected by Spitzer.

- Obtaining mid-infrared images of sub-arcsecond multiple-lensed quasars to distinguish between models of the brightness ratios of image pairs.

There is no doubt that a high elevation site will enable important science that is not possible under typical observing conditions at a moderate elevation site. The scientific opportunities offered by a dry site must be weighed against other cost and risk factors, as described in Chapter 5.

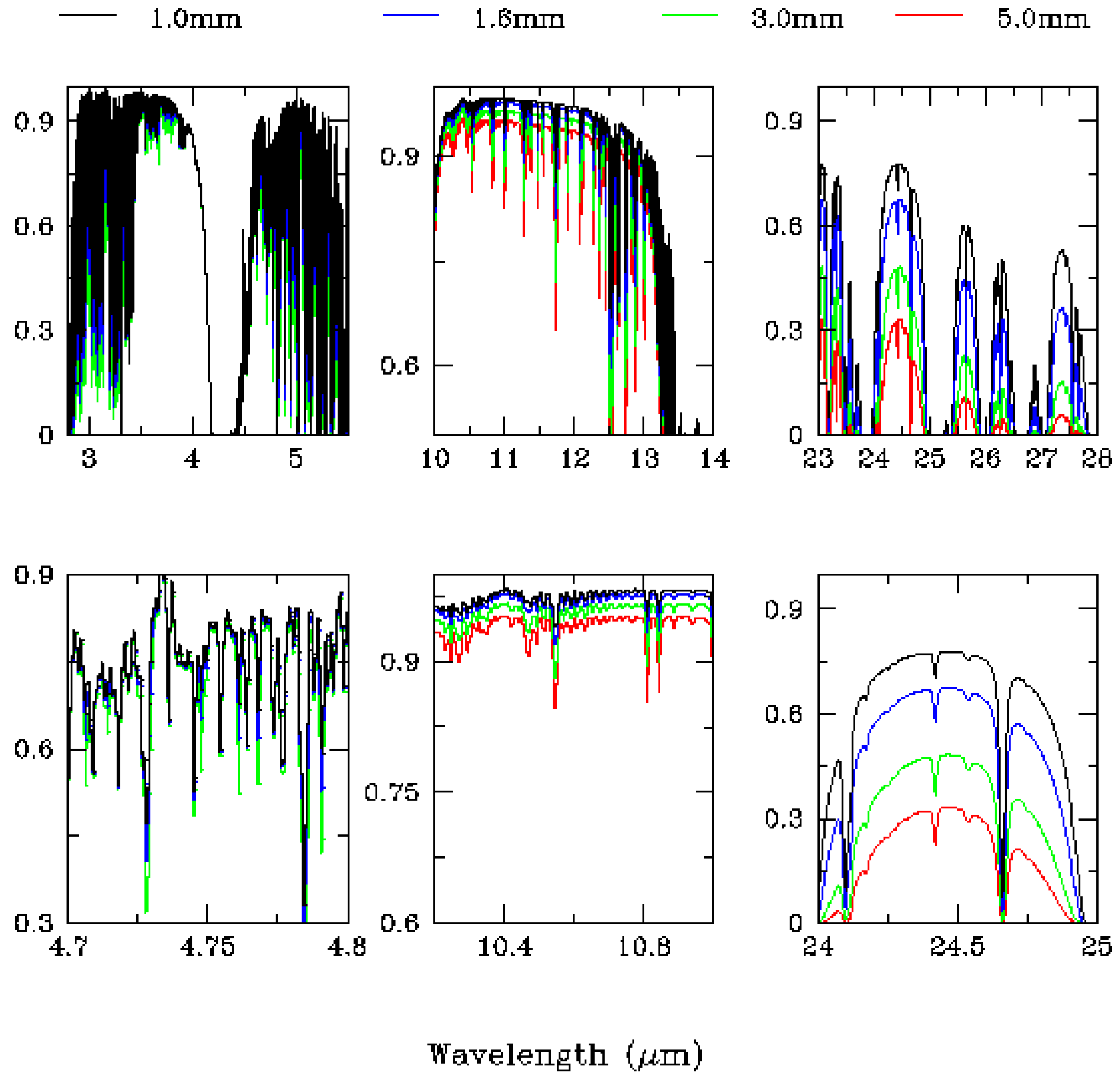

Figure 4-2.1. Transmission of the atmosphere in selected regions of the mid-IR spectrum. The top panels show broad-band regions covering the 3 and 5μm windows, the 10μm window and the 25μm window. The curves show the transmission for PWV column densities of 1 (black), 1.6 (blue), 3.0 (green) and 5.0mm (red). The lower panels show sub-regions at higher resolution to illustrate the impact of various PWV levels on water lines and continuum opacity.