GMOS Functional and Performance Requirements (1.3)

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1. Introduction

1.1. GMOS Primary Requirements

GMOS is intended to be a multi -purpose imaging spectrograph for use in the non -thermal wavelength regime. Two devices will be constructed, one for Mauna Kea, the other for Cerro Pachon.

This document expands and extends the minimum specifications for GMOS, which are contained in the GMOS Work Scope, and are listed below.

GMOS Primary Requirements

- *Overall*

Wavelength range 0.4-1.1 micron

Unvignetted field: 5.5' diameter, up to 10% vignetted at maximum field diameter of 7' (effective length of spectra 8.2' on a 4K x 6K CCD)

Image scale 0.08" per 15 micron pixel

The image quality specs for each mode of operation are given as a set of tables in the GMOS Functional Requirements Document. The GMOS optics excluding the AtmDC should not degrade the on-axis images delivered at zenith by the telescope, including the atmosphere and telescope optics, by more than 10%.

2 filter wheels, at least 11 positions each

Grating turret: 3 grating + 1 mirror (imaging) position

Field of view imaged by camera suitable for 4K x 6K (15 micron pixel) CCD

The design has a pupil diameter of 100 mm and an f/4.8 camera.

- *Spectroscopic*

The throughput in spectroscopic mode will obviously strongly depend on the efficiency of the gratings. It is anticipated that the gratings will be silver coated and have a efficiency at blaze of up to 80%.

Minimum slit width 0.20" (2.5 pixels)

Maximum slit length 5.5', masks 5.5 x 5'

Mask cassettes will be designed to accommodate combinations of masks and up to two IFUs. Only one cassette per instrument will be delivered.

Only 3 gratings included with each instrument

With appropriate (standard) reflection gratings, dispersions from 8Å/mm to 250Å/mm (R=10000 to R=500) will be possible.

- *Integral Field Unit (IFU):*

An IFU with 0.2" elements covering 45 to 55 square arcsec.

- *Direct Imaging:*

Field 5.5' x 5.5'

The basic requirement is that the 8-m aperture advantage should be retained. Based on experience with similar instruments on 4-m telescopes, and those planned for 8-m class telescopes, we expect to achieve a typical transmission of 80% (no filter). In imaging mode, the efficiency of the telescope + GMOS + filter is estimated to be 67% at 600 nm.

Only 7 filters will be delivered with each instrument

- *Mask Maker:*

The mask maker will be specified in sufficient detail to be capable of producing slits as small as 0.2" with as much versatility (width, length, orientation, curvature) as possible. The procurement of a Mask-maker is not included in the GMOS budget.

- *Fiber feed:*

A conceptual design will be developed to accept a fiber feed from GMOS to other instruments (e.g., HROS). No other work in this area beyond the conceptual design will be included in the Work.

We can compare the above Primary Requirements with those scientific requirements recommended to IGPO for GMOS by the Gemini Science Committee and contained in GSC resolution 8.5 of April 1996:

<u>GSC Resolution 8.5</u>

REVISED GMOS REQUIREMENTS

- Two spectrographs: one with red optimized coatings for GN, the other with blue optimized coatings for GS; the intent is to have competitive scientific performance at 3727 Å at Gemini-S.
- Wavelength Coverage: 0.4 - 1.1 μm
- Detector: 4096 x 6144 CCD mosaic
- Image Scale: 0.08 arcsec/15 μm pixel
- Minimum slit width: 0.2 arcsec (i.e. 2.5 times spatial resolution element)
- Imaging Mode: adequate to support mask construction
- Maximum Spectral Resolution: 10,000 with 0.25 arcsec slit width

- Integral Field Module: Sub-apertures with 0.2 arcsec width, giving total sky coverage of 50 square arcsec, including sky

- Flexure: spectrograph flexure will introduce systematic radial velocity errors no greater than 1 km/s/hr for zenith distances greater [should read "less"] than 60 deg at a spectral resolution of 5,000

Desirable Options:

- Wavelength coverage over 0.36 - 1.8 μm

- IFUs with finer spatial sampling for wavelengths longer than 0.7 μm

The GSC is satisfied that the design presented at the PDR is consistent with the Scientific Requirements.

A direct comparison shows that the minimum contractual GMOS Primary Requirements meet or exceed the above GSC recommendations in every area except for flexure. The GMOS team has adopted a velocity stability of 2km/s/hr as a "secondary" requirement; see below for a definition of this term. This level of performance agrees directly with the Gemini Science Requirement Document general requirement of 0.2 pixels/hr.

The GMOS team is obligated to develop and deliver two instruments which demonstrate during acceptance that they fully meet the GMOS Primary Requirements described above and as identified elsewhere in this document.

1.2. The purpose of the Functional Requirements Document (FRD)

The current document expands and extends the functional requirements for GMOS. When considering the following sections, the reader should keep in mind that Gemini will operate in a fashion very different from traditional telescopes in that, based on resolution #5.4 passed by the GSC during its October 1994 meeting, at least 50% of the observing time will be dedicated to queue-based observing so that the inherent site characteristics of Mauna Kea and Cerro Pachon can be fully exploited. This capability places stringent requirements on many aspects of the instrument design. In the second section of this document we review the general functions of GMOS, and describe the broad requirements that these place on instrument characteristics. An overview of the GMOS components and the top -level requirements that relate to them is given in the third section, while in the fourth section we give a summary of the functional requirements. In the fifth section we present top-level optical image quality specifications. In the sixth section we present our requirements on other telescope systems.

1.3. Classification of Requirements

This document presents performance and functional requirements for the Gemini Multi -Object Spectrograph (GMOS). These requirements are categorized according to their source. They are collected into a table in Section 4, where they are clearly categorized according to the following scheme:

Primary requirements: these were originally stated in the GMOS Work Scope, and they meet or exceed the 1996 recommendations of the Gemini Science Committee as accepted by the Gemini Board, except as noted above in the case of instrumental stability. NRC and PPARC are contractually bound to meet the primary requirements.

Secondary requirements: these requirements have been set by the GMOS team, and are of two types:

(a) **Flow-down requirements** are derived from the primary requirements; the GMOS team believes these must be met if the primary requirements are to be met.

(b) **Additional requirements** which the team believes to be necessary to meet the scientific goals of GMOS, even though they are not included in the GSC recommendations or the minimum system specified in the GMOS Work Scope. They will be treated as firm requirements by the GMOS team even though they are not contractually required to do so.

Goals: a few goals were included in the GSC recommendations, while others have been developed by the GMOS team. The team will try to reach the goals if this can be accomplished within the budget.

Additional Functionality: if the requirements and goals can be met within available funding for GMOS, additional functionality will be provided, e.g. additional gratings. The GMOS team will require IGPO approval of the specific items of additional functionality to be provided. Some suggestions are included in this document.

2. Functional Definition

In this section, the overall functionality of GMOS is described and several requirements are identified. The requirements are summarized in tabular form in Section 4.

2.1. Top-Level Functions

The GMOS will provide three distinct capabilities:

a. Imaging: The GMOS's will provide the only wide -field optical imaging capabilities at the Mauna Kea and Cerro Pachon sites during the first few years of operation. The primary purpose of the imaging mode is to provide data suitable for spectroscopic mask production. This implies that efforts should be taken to achieve good, uniform image quality across the GMOS science field. The imaging capability is essential for slit mask design, as the spectrograph optics will produce subtle (but not insignificant) distortions over the field of view that will be very difficult to model; hence, even if deep images of a field recorded with another instrument already exist, it will still be necessary to obtain an image through GMOS to measure slit locations at the detector focal plane. A second support role for imaging is to check the alignment of objects on slits, a task that is of critical importance given the narrow slit sizes that will be used to exploit the Gemini telescope's superb image quality. However, aside from tasks dedicated to spectroscopic support, as the only optical instruments with imaging capabilities, it can be anticipated that the GMOS's will also be asked to provide science images. In addition, with imaging, the GMOS's can also serve as acquisition cameras. For all of these reasons, it can be anticipated that the imaging capability will be used in combination with the two spectroscopy modes during the course of a normal night of operations.

b. Slit Spectroscopy: The most fundamental requ irement for the GMOS's is that they provide a capability for slit spectroscopy at optical wavelengths over a significant fraction of the f/16 science field. Two modes of slit spectroscopy are likely to be used: (1) long-slit, in which a single slit is placed on one, or possibly two, objects; and (2) multi-slit, in which slitlets are placed on objects at various locations in the field. The slits will be cut or etched on a stable surface (the slit 'mask'), which will be positioned at the telescope focal plane. There will be applications where the slits will not be straight; for example, studies of gravitational arcs will require curved slits. Moreover, given that the Gemini telescopes are being constructed to exploit the inherently good image quality of the Mauna Kea and Cerro Pachon sites, it is anticipated that the GMOS will use slits which are much narrower than have traditionally been employed. This means that it will be necessary (1) to produce clean, narrow slits (i.e. slits of uniform width, and free of jagged edges), and (2) position the slits very accurately. The slit spectroscopy mode will be used in conjunction with the imaging and integral field modes during the course of a single night's observations.

c. Integral Field Spectroscopy: A major shortcoming of traditional slit spectroscopy is that only a small fraction of an extended object can be observed at any one time - more specifically, slit spectroscopy can be used to study only a slice through an extended object, and a tacit assumption is that this slice samples a representative part of the object. In addition to loss of spatial detail, there are uncertainties associated with the placement of slits; for example, dynamical studies of galaxies require very accurate centring of the slit. One way to overcome these shortcomings is to record spectra of individual spatial elements (i.e. obtain spectra of an entire "integrated" field). The integral field mode that will be incorporated in the GMOS will give the Gemini telescopes a unique capability, and make it possible to obtain spectra of faint, extended objects over a ~ 50 square arcsecond field. Light from the integral field focal plane will be reformatted to feed the slit area of GMOS with an f/16 beam. The integral field capabilities will be used on the same nights as slit spectroscopy and imaging.

2.2. Generalized Requirements

To perform these functions, the GMOS will have to meet the following *general* requirements:

a. Versatility: Given that there will be occasions when the imaging, slit spectroscopy, and integral field modes will be used on the same night, the GMOS must be capable of changing modes in an automated fashion. Moreover, these changes in operational capability must be made without affecting the basic set -up and internal alignment of the spectrograph.

b. Efficiency: Given that the GMOS will be reconfigured during the night, and will be asked to record numerous set -up and calibration images, it is critical that any time lost due to these functions be minimized. We require that 95% of all time that GMOS is in operation be available for on -sky observations. The remaining 5% of the time will be taken up by detector read out, the duty cycle for instrument reconfiguration, telescope motions, and guide star setups. It is difficult to divide the time lost between these four sources, as some of the functions can be performed simultaneously (e.g. the detector could be read out while the telescope is slewing, etc). However, this will not always be the case. For example, it will be necessary to await the detector readout after image acquisition through the slit before adjusting the guide probe positions and beginning a spectrographic observation. We require that the instrument reconfiguration be responsible for losses not to exceed 2.5% of the available observing time, and that the detector readout and display also consume no more than 2.5%, with the understanding that these two must operationally overlap. By 'instrument reconfiguration', we refer not only to changes in individual components, such as, for example, the dispersing elements or filters, but also to a major reconfiguration from, say, imaging to slit spectroscopy modes.

An upper limit to the time required for any reconfiguration can be estimated as follows. We assume that GMOS will be used to study faint objects, and that typical integration times for spectroscopic applications will be ~ 1 hour. To prepare for spectroscopy, there typically will be a need for *at least* two reconfigurations (e.g. from imaging to spectroscopy and back to imaging mode - this latter change is required to prepare the instrument for the next target field). If two reconfigurations occupy 2.5% of each hour's observation then each reconfiguration should take *on average in a typical observing sequence* no longer than ~ 50 seconds; a goal is to have any instrument reconfiguration completed *on average* in half this time. It is reasonable that complex but less frequent changes such as selecting a new mask and inserting it into the focal plane may take slightly longer, as long as the average reconfiguration time can be preserved.

c. Stability: One of the main motivations behind the construction of 8 meter telescopes is that they will permit the study of objects that are too faint to be observed in realistic exposure times from 4 meter -class facilities. Given the tendency for astronomers to push the limits of available facilities, it can be anticipated that the GMOS will be required to observe fields for lengthy periods of time. Indeed, experience with 4 meter facilities indicate that total integration times of ~ 3 hours or more on a given night are not unreasonable. Even though such lengthy integrations will be obtained by co -adding a sequence of shorter exposures (e.g. 3 x 1 hour, say), it is inefficient to break the observing sequence and pause to check and re -position the location of objects on the focal plane or to recalibrate the instrument after each integration. Hence, the GMOS must meet the flexure requirements derived here during normal operations over periods of 1 hour in any range of zenith angles between 0 and 75 (i.e. air masses 1 - 2), with a goal of meeting all flexure specifications over periods of 3 hours.

The requirement for the level of stability can be derived by considering the most demanding case, which is spectroscopy with R ~ 10000 intended to measure radial velocities to accuracies of a few km/sec. At R ~ 10000 a centring accuracy of 1/15 of a spectral resolution element is required to obtain a velocity accuracy of 2 km/sec. For a resolution R ~ 10000 and with 0.25 arcsec slits, each spectral resolution element will be sampled by 3 pixels at the detector, and the centring accuracy to achieve this radial velocity accuracy must be 3/15 x 0.08 = 0.016 arcsec. This number corresponds to about 10 μm at the telescope focus and 3.0 μm at the detector focus. We emphasize that this specification refers to *motion during an exposure* - the *absolute* position of the slit imaged onto the detector does not have to be known to this accuracy, as arcs recorded before and after an exposure can be used to calibrate the wavelength scale in an absolute sense.

d. Throughput: Given that 8 meter telescopes are being constructed to study objects that are beyond the reach of existing facilities, it is critical that the aperture gain not be frittered away with instruments that have low throughput. We require that the overall efficiency of the GMOS be such that the aperture advantage of the Gemini telescopes be maintained with respect to the most efficient multi -object spectrographs on 4 -meter class facilities. To the best of our knowledge, the most efficient spectrograph of this nature is the CFHT MOS/SIS, which has an optical throughput in imaging mode (i.e. without a dispersing element *and not considering the detector, AtmDCC and slit losses*) of ~ 80% over the base science wavelength range. We therefore require that GMOS also achieve a throughput of ~80% in the base science wavelength range of 0.4 to 1.1 μm, with a goal of meeting this throughput from 0.36 to 1.8 μm. Assuming that the imaging flat has a reflectivity of ~ 98%, then the throughputs of the collimator and camera optics should each be roughly 90%.

e. Image Quality: The Gemini telescopes are being designed to deliver exceptional image quality, and it is imperative that instruments be capable of exploiting this unique capability. Image quality specifications for GMOS were investigated in the document "*Top-Level Image Quality Specs For GMOS* " by Davidge, dated 22 February 1996, and are reproduced in Section 5. Specifications were developed for the imaging performance of GMOS, both on axis and at the edge of the field, as a function of wavelength Separate specifications are presented for the pre-slit optics, considering slit throughput, and also for the image quality necessary for the spectrographic detector to be able to image the slit. In the case of spectroscopy, light from a perfect point source placed *at the telescope focus* should produce a response function at the detector surface with 50% of the encircled energy falling within a 0.11 arcsec diameter circle, and 85% of the encircled energy falling within 0.18 arcsec diameter. As for imaging, *a point source at infinite distance viewed through the 10th percentile best atmosphere and entire telescope system pointing at the zenith* , may be degraded at any particular wavelength by 10% on axis and 15% at the edge of the field. The image quality specifications are presented in more detail, and over both the required and goal range of wavelengths, in section 5.

f. Reliability: Given that the GMOS's will be the only optical faint object instruments available on the Gemini telescopes during the first few years of their existence, it can be anticipated that these instruments will be used frequently, and will be heavily scheduled. Hence, the GMOS's must be extremely reliable. The Gemini Science Requirement Document specifies that no more than 2% of scheduled observing time be lost due to equipment failure of any kind. Clearly, only a portion of this time can be allocated to instrument failure. GMOS developers will have to pay careful attention both to techniques which minimize the rate of failure and techniques which make the recovery from failure as rapid as possible. GMOS will require a comprehensive preventative maintenance schedule as well as any specialized tools or equipment required to perform that maintenance. The instrument should be designed with as complete self-diagnostic capability as reasonably affordable. Wherever possible, mechanisms and functional units within GMOS must be designed to be electrically and mechanically modular, so that they can be removed, examined, bench tested and replaced with a minimum of down time. The control system must provide sufficient logging of hardware and software activity that information is available to diagnose a system failure or fault, especially an intermittent one. Software tools must be available at the telescope that quickly and easily process the logged information in a manner appropriate to fault diagnosis. The control system must allow remote operation and telemetry of the instrument by instrument specialists so that they might be able to quickly diagnose a fault without having to travel to the observing site. The GMOS instrument enclosure should be designed with a goal of providing easy access to as many internal mechanisms as possible.

3. Descriptive Overview of GMOS

In the following, we discuss the general components of the GMOS, and identify the *top-level* requirements that relate to each of these. In some cases, these requirements affect more than one component; for example, motions of the slit image on the detector involve not just the mask assembly (the section in which it is discussed), but also the support structure, opto-mechanical assemblies, and the detector

3.1. Support Structure and Instrument Enclosure

The GMOS will require a structure to support and an enclosure to protect the various components of the instrument. In addition, the enclosure must offer a light-tight environment for the optical elements. The structure, which may be mounted on any of the five ports on the Instrument Support Structure (ISS), must be designed to minimize the lever arm for flexure, and offer a rigid platform on which to hang mechanical components and the optical bench. Present Gemini specifications dictate that the instrument weigh 2000 kg. with a center of gravity located on the optical axis 1m from the ISS, and with a precision in these two such that the mass moment error is less than 400 N m. Finally, the basic design of the support structure and enclosure must also offer ready access to all configurable portions of the instrument, such as the detector/dewar/controller assembly, grating, filter, and slit mask assemblies, to facilitate set-up and maintenance.

3.2. AtmDCC

An atmospheric dispersion compensator and field corrector (AtmDCC) is required to correct for atmospheric refraction and field curvature.

The atmospheric dispersion compensator will control smearing which would otherwise occur in broad-band images, especially those near the blue limit of the instrument optics, as well as in exposures recorded over a range of zenith angles. For spectroscopy, atmospheric dispersion will introduce wavelength-dependent slit losses at wavelengths different from those used for guiding or set-up. The results are (1) a reduction in the photometric quality of the data, and (2) a loss in slit throughput. The degradation in image quality can be substantial, measured in arcsecond scales in extreme cases, depending on the wavelength coverage and airmass. Unfortunately, the AtmDCC will also introduce a complex field distortion as a function of rotation setting.

The field corrector will control the point spread function variation as a function of radial distance off axis which would otherwise occur as a result of the mismatch between the curved telescope focal plane and the flat input plane to the spectrograph (see "*Field Curvature and PSF Variations in GMOS*" by Davidge, dated 31 January 1996).

There are four general requirements for the AtmDCC. First, its optical quality and system performance (e.g. ability to rotate, etc.) must be very high, so as not to degrade the image quality. Second, it is necessary that the change in the AtmDCC distortion during any hour from 0 to 60 degrees not degrade the 0.25 arcsecond slit throughput significantly. Thirdly, the AtmDCC must be removable from the light path (i.e. it cannot be permanently fixed in place); however, the AtmDCC does not have to be remotely deployable. Fourth, and finally, the GMOS will be used with the AO module, which will have its own dispersion compensation and field flattening, with image quality specifications appropriate for near diffraction -limited conditions. Consequently, if it is not possible to implement the preferred option of remote removal of the GMOS AtmDCC, then its optical performance must be such that GMOS is able to meet its image quality primary requirement with the AtmDCC in place.

3.3. OIWFS + Feed optics

Both the Mauna Kea and Cerro Pachon telescopes will have secondary mirror assemblies capable of correcting focus and tip -tilt aberrations. In addition, the Mauna Kea telescope will have an Adaptive Optics (AO) module that will be capable of producing on-axis Strehl ratios of 0.4 at 1.6 μm. The reference signals used to compensate for atmospheric affects and guide the telescope will be provided by the various wavefront sensors. In order to minimize differential flexure between the instrument and OIWFS and to provide instrument builders with a flexible means of obtaining guiding information, all instruments must incorporate OIWFS's that, at a minimum, produce information necessary for tip -tilt and focus compensation.

The OIWFS camera head and any electronics associated with operating that head will be provided to GMOS from another work package, and are functionally and logically part of the Acquisition and Guiding system. It is the responsibility of GMOS to provide any optics and mechanics necessary to direct light from the guide object to the camera head aperture. Hence, the GMOS design must include space for an OIWFS.

A system will be required to direct light from the reference star to the GMOS OIWFS. The feed optics should be designed so as (1) to direct as much light as possible from the reference star to the OIWFS (an important consideration as the ability to compensate for atmospheric effects depends critically on the number of photons detected from the reference source); (2) to minimize vignetting of the science field (this refers not only to the pick -off mirror, but also to any support structure); (3) to be mechanically rigid with respect to the telescope focal plane and OIWFS so as not to degrade the image quality delivered to the telescope focal plane by mechanical flexure; and (4) to patrol a field sufficiently large to produce reasonable likelihood's of finding natural guide objects. The latter requirement is important as there are some fields in which the number of possible reference sources may be small (e.g. the Galactic Poles or dark cloud sites). Moreover, given that the isoplanatic patch for moderately high orders of correction is small, the OIWFS pick-off system must be capable of working close to the center of the science field, where the integral field unit will be located.

We require that the throughput of the OIWFS pick -off system be no worse than 90%, and that the shadow produced by the OIWFS pick -off mirror assembly (i.e. mirror and support arm) occult no more than 5% of the GMOS science field of view. The pick -off mirror must be capable of patrolling a region of sufficient area to give 90% probability of finding a guide object at the North Galactic Pole (the sensitivity and noise of the OIWFS should be such that this area is less than the tip-tilt corrected atmospheric isoplanatic patch) with a goal of obtaining 99% coverage at the North Galactic Pole.

3.4. Slit assembly

It is likely that multi -object slit spectra will be obtained of a number of fields on each night. Each field will have its own unique arrangement of slits, based on factors such as the position of objects on the sky, the characteristic widths of sources, and environmental conditions (e.g. seeing). Consequently, the GMOS will need an automated system for removing and introducing slit masks into the telescope focal plane during the course of each night. Many studies will be conducted with moderately narrow slits over much of the entire science field, and a goal is that calibration information for each mask be obtained during daylight hours to maximize observing efficiency at night. (We note that there will be circumstances, such as high resolution spectroscopy, when this goal will be difficult to achieve; hence, some calibrations may have to be recorded at night - see Section 3.7). In any event, if there is to be any hope of realizing this goal, the slit mask deployment mechanism must be capable of positioning masks with great accuracy, and without significant differential rotation.

In an effort to minimize time lost during the night, a goal is to record calibration information, such as flat-fields and arcs, during the day. If these calibrations are obtained after the science data have been recorded, then the effects of flexure can be reduced by positioning the telescope and instrument rotator at the same settings as during sky observations. However, the absolute positioning accuracy of masks still remains a concern and the results depend on the velocity accuracy desired. Following the arguments presented in the previous paragraph for velocity accuracies of 2 km/s, then the slit masks would have to be positioned with a combined (x,y) accuracy of 2.5 μm. However, for velocity accuracies of 100 km/sec with spectral resolutions of ~ 1000, such as might be expected for faint object surveys, the absolute positioning requirements are much less stringent. In this case, the centring accuracy is a third of each spectral resolution element, which for 0.25 arcsec slits is 0.083 arcsec, or 46.88 μm at the f/16 focus. The mask positioning accuracy perpendicular to the optical axis, then, need be such that every point on the mask is positioned to within ±25 μm of the commanded position, this specification including the effects of rotational and translational error. We anticipate that a significant fraction of the GMOS observing time will be devoted to studies of faint objects, and hence adopt the latter specifications for absolute positioning accuracy of the slit mask.

Given that much of the observing time will be dedicated to queue -scheduled observing, and there may be a number of GMOS proposals in the queue at any one time, the GMOS must be capable of holding a number of masks for potential target fields on any given night. Queue observing places the most demanding requirements on mask capacity, and the number of slit masks that must be available during a given night can be estimated as follows. We assume that one fifth of all observing time will be dedicated to GMOS in slit -observing mode, and that each proposal will require 4 nights to complete. Based on these assumptions, during each year there will be ~ 9 scheduled GMOS slit spectroscopy proposals per semester. If half of these are scheduled for queue observing (i.e. 5), and a typical exposure time per field is 3 hours, then ~ 60 fields would be observed each semester during queue observing. However, not all of these masks would have to be available at one time. If each program has three masks mounted each night (i.e. a mask covering a field for the beginning, middle, and end of the night), then 5 x 3 = 15 masks would have to be available for the GMOS during any one night of queue observing to achieve maximum queue flexibility. This is similar to the number of masks required for a single 4 night observing run, which will require 4 x 3 = 12 masks. It is worth noting that these estimates do not include so-called 'generic' masks, such as long-slit configurations, that may be required for standard star observations, and masks for instrument set-up. Nevertheless, the estimates given above indicate that GMOS should have the goal that it be capable of holding a large number (i.e. 15) of masks at one time. As an absolute minimum, GMOS is required to hold the observing needs for one night, or three masks in the instrument at one time. An automated identification scheme to identify and keep track of the masks installed in the instrument should be considered a design goal.

We close the discussion of the slit environment by considering the placement of the slit mask with respect to the telescope focus. The telescope focal surface is not flat, and a choice must be made as to where the flat slit mask is positioned. Unless the focal surface is flattened within GMOS, the image quality will change quickly as a function of radius on the field; a focus setting which gives best on-axis images will also give degraded images at the field edge. For any field size of interest a best compromise focus can be selected to give optimum average image quality. Therefore, it is necessary that either by means of telescope focus or mask position, the slit mask can be placed in the best compromise focus for any field size of interest, from on-axis only through to full field.

3.5. Integral Field

The integral field module will provide unique spectroscopic capabilities for both telescopes at optical wavelengths. The spatial scale of the integral field resolution elements (0.2 arcsec diameters) is a compormise between the median and best natural seeing conditions at both sites. For this reason, the integral field mode will see much use during queue-based observing situations, and this implies that the system be deployable remotely.

Given that this and smaller entrance aperture variants of the integral field unit will be used with the AO system, it is necessary that the OIWFS pick-off system used for this mode be capable of acquiring sources very close to the primary science field of the integral field module; indeed, a goal is to use objects in the field of view as reference source to minimize isoplanicity effects.

Aside from the constraints imposed by the desire to exploit the superb image quality planned for the Gemini telescopes, practical considerations associated with the day-to-day use of the integral field unit define additional requirements for this system. First, the integral field system is mainly intended for the study of extended, faint objects, so provisions must be made to measure background light. Given that telescope time will be at a premium, the sky level must be measured simultaneously with the science observations. In particular, it is unacceptable to simply offset the telescope and measure background levels after a long integration on a science object; not only will this consume valuable observing time, but the sky level can also change with time. Therefore, it is required that the background be measured in a *sky field* which is separate from the *object field*.

Second, the reduction of data produced by the integral field unit will be greatly simplified if the response characteristics of each spatial element are well calibrated, and remain stable with time. Both the object and sky fields will be reformatted to inject light at f/16 into the main spectrograph, and this will be done using fibers. Stability of response characteristics requires that these fibers not move or bend with time, as these motions can alter fiber characteristics. We require that the throughput of each fiber remain stable to within 1% during the course of one night.

Third, the integral field unit is required to have an object field of ~50 square arcseconds. This corresponds to ~1500 sub-apertures.

Fourth, although intended primarily for spectroscopy, there will be circumstances when it will prove scientifically useful to obtain broad-band images through the integral field system - for example, this would be useful for dynamical studies intended to measure galaxy mass-to-light ratios, or simply for checking the placement of objects on the integral field unit; consequently, it is required that the integral field system have simple imaging capabilities.

Fifth, the IFU assembly is in principle an optical assembly which can be designed differently to suit many different scientific requirements; the design requirements here are for a general purpose device suitable for initial use with GMOS. Since it can be expected that other IFUs will be developed during the life of GMOS to meet special scientific needs, it is required that although each initial instrument will be delivered one IFU, it be capable of holding and remotely deploying up to two IFUs. Since IFUs would replace observing time which might otherwise be consumed by slit spectroscopy in a night, it is not necessary to try to meet the goal of accommodating multiple IFUs and the goal of 15 slit masks at the same time.

The positional stability of the integral field unit is set by the size of each sub-aperture. We require that differential flexure between the integral field unit and the OIWFS pick-off not exceed one-tenth of these elements, or 0.02 arcsec at f/16 which corresponds to 12 μm, for each hour of observation. As for absolute positioning of the integral field unit, we require that it be deployed with an accuracy such that the overlap in object field size not be degraded by more than 5%. This implies a positioning accuracy and repeatability of one sub-aperture, or 120 μm at the f/16 focus. These requirements hold for all zenith angles between 0 and 75 (i.e. between 1 and 2 air masses).

3.6. Collimator

Collimating optics are required to produce a parallel beam for subsequent dispersion by the dispersing element. For operational efficiency, it is desirable that the image quality and wavelength coverage requirements be met with a single set of collimator optics. In addition, to minimize mechanical flexure and keep the instrument within the space envelope, the collimator design should also be relatively short, although the number of elements should not be so great as to compromise the throughput requirement.

3.7. Dispersing elements

The GMOS will be used to obtain spectra of a variety of targets, ranging from faint objects that are near the limits of detection, for which only low spectral resolution data can be obtained, to those that are relatively bright, for which high spectral resolution data can be recorded. Given this diversity of targets and spectral resolutions, the GMOS will need a large arsenal of dispersing elements covering the entire parameter space defined by wavelength range and spectral resolution. To facilitate operations, a number of remotely deployable dispersing elements must be mounted in the instrument at any given time. Moreover, a goal is to record calibration information for a variety of different programs during day light hours, so the mounting mechanism for the dispersing elements must be very stable against, for example, gravitational flexures (since the telescope may be parked at zenith during the day), and be capable of delivering highly reproducible wavelength settings after configuration changes.

The absolute positioning accuracy is specified to allow the measurement of calibration images during the day. If, as in Section 3.4, we restrict this to programs that require velocity accuracy of 100 km/sec, then the dispersing element must be deployable in an absolute sense such that the wavelength setting is repeatable by better than 0.04 arcsec at the detector. These specifications must be met over zenith angles from 0 to 75 degrees.

What number of dispersing elements should GMOS be capable of carrying at any one time? Inspection of grating response curves suggests that a single dispersing element will not be able to cover the entire 0.4 to 1.1 μm wavelength range with reasonable efficiency; rather, it is likely that two dispersing elements, with 'blue' and 'red' blaze wavelengths, will be required for each spectral resolution. If programs are simply grouped into three resolution categories (high, medium, and low spectral resolutions), then the availability on the instrument of two dispersing elements is required but 2 X 3 = 6 dispersing elements would be desired for queue observing. The primary requirement is for 3 dispersing elements.

A final selection of gratings will be made in the future. However, it is important to know that a wide selection of appropriately sized blanks are commercially available. To demonstrate this, in Table 1 we provide a sample of gratings which would meet the spectral resolution and wavelength requirements and which are now available from the Milton-Roy company. This is not meant to be a definitive list of gratings for GMOS.

TABLE 1 - POTENTIAL GRATING CHOICES FOR GMOS

Catalogue[a] Number	Grooves per mm	λ_{Blaze}[b] (nm)	$R_{0.25}$[c]	$R_{0.50}$[d]
35-53-*-240	2400	300	7400	3700
35-53-*-290	1800	500	9300	4600
35-53-*-330	1200	400	4900	2500
35-53-*-340	1200	600	7400	3700
35-53-*-530	1200	1000	12400	6200
35-53-*-080	600	400	2500	1200
35-53-*-267	600	650	4000	2000
35-53-*-351	600	800	4900	2500
35-53-*-270	300	500	1500	770
35-53-*-180	300	750	2300	1200
35-53-*-510	300	1000	3100	1500
35-53-*-201	150	500	770	390
35-53-*-426	150	800	1200	620

Notes: Gratings were selected from the list of master blanks quoted in the Milton-Roy Diffraction Grating catalogue. It is possible that some of these gratings (i.e. those blazed at 750 nm and longward) could be used in second order. However, this will result in lower efficiencies, and could introduce additional optical aberrations.

a Milton-Roy catalogue number

b First-order Littrow blaze wavelength

c, d Spectral resolutions at λ_{Blaze} for 0.25 and 0.50 arcsec slits

3.8. Camera

Optics are required to image the dispersed spectra onto the detector, and the requirements imposed on the collimator optics also hold for those that constitute the camera. In particular, the image quality and wavelength coverage specifications of the camera must be met with a single set of optics, while the design must also be relatively compact. An additional requirement is that the camera optics permit focusing onto the detector focal plane. The range of focus motion must cover the full chromatic range of the optical design, while the accuracy of the focus must be sufficient to not degrade the top -level image quality specification (the uncertainty assigned to this figure will ultimately be determined from an error budget).

An important design issue is the relative sizes of the camera and collimator fields of view. If the two fields of view are identical in size, then, in the multi -slit case, it is not possible to obtain spectra of objects near the edges of the field, as the light is dispersed outside of the imaged portion of the sky. This problem can be solved by enlarging the field of view of the camera with respect to that of the collimator. It is worth noting that an enlarged camera field will also permit greater wavelength coverage for integral field applications (alternatively, spectra could be recorded for a larger number of spatial elements). One implication of implementing an oversize camera system is that a larger detector than that suitable for just the imaging field would be required. The Gemini optical detector program is based on 2048 x 4096 pixel detectors, so the increase in field size is quantized. The smallest detector array size which takes full advantage of the science field, then, is composed of three elements, resulting in a detector array of about 4096 x 6144 pixels (each of 15 μm) and we require that the camera optics illuminate a detector array of this size.

3.9. Shutter

GMOS will need a shutter to control the light arriving at the science detector. One of the important characteristics of the shutter is its ability to operate uniformly: so that every part of the field obtains the same length of exposure. Deviations in exposure time uniformity will manifest themselves as calibration errors. The GMOS shutter should not create flat field calibration errors greater than 1% for the shortest anticipated exposure. The limiting short exposure time will be set by bright photometric standards and we require the shortest exposure time to be 1 second. Hence, the non-uniformity of exposure time over the detector focal plane must be less than 10 msec.

3.10. Filters

There is a need to filter the light from the telescope in all three operating modes. In the particular case of imaging, filters are required to restrict wavelength coverage to standard passbands, so that the brightness of sources can be measured in a standard system, or to limit wavelength coverage to small intervals around features of astronomical significance, such as H α or [OII] λ3727. As for spectroscopic applications, filters are required to limit wavelength coverage to suppress signal from higher orders (i.e. order -sorting filters), and prevent overlap between spectra of objects located at different positions in the science field. Given that many calibration sources, such as radial velocity standard stars, are moderately bright, it may also be necessary to use neutral-density filters to reduce the amount of light incident on the detector. The GMOS filters must be deployable remotely and quickly within the reconfiguration time derived earlier. Filters must be situated in and not vignette the collimated beam. They must be AR-coated to minimize reflective losses. GMOS mechanical and control design must make it easy and safe to manually access the filter-holding mechanism to remove or add filters, as custom filters and user-supplied filters will be required for many applications.

How many filters should the GMOS be capable of holding? For imaging applications, *B, V, R* and *I* broad band filters are essential; however, there may be programs which require narrow band images, the filters for which may come in pairs (e.g. on -feature and continuum), as well as other 'standard' filters (e.g. Gunn *g, r, i,* and *z*). Hence, if GMOS is to offer two standard filter sets, and have room for two pairs of narrow band filters, then the device must be capable of carrying 12 filters for imaging at any given time. We recommend that the base GMOS instrument be delivered with a complete *BVRI* filter set.

A number of filters must also be available for spectroscopic applications. Four order -sorting filters will be required for general applications. In addition, custom filters, which define non-standard passbands, will be required for some programs to limit wavelength range so that multiple tiers of spectra can be recorded. In Section 3.4, it was argued that at any one time there will probably be ~5 slit spectroscopy programs scheduled for queue observing; if we assume that another 3 programs will be in the queue for integral field work, then the total number of queue-scheduled GMOS spectroscopy programs will be 5 + 3 = 8. If half of these use standard broad-band filters to define wavelength coverage, then this implies that GMOS must be capable of holding ~4 custom spectroscopy filters at any one time. It is likely that neither the order sorting nor the custom filters would be deployed in combination with the broad -band imaging filters.

In summary, the total number of filters that GMOS must be capable of carrying for a given night of observing is 12 + 4 + 4 = 20. Further, in some cases it will be necessary to place two filters in series along the light path; for example, it will be necessary for bright sources to pair spectroscopic band-limiting filters with neutral density filters. We require that the 20 or more filter positions be available in two wheels, such that two filters can be placed in the light path at the same time. The primary requirement is for 2 filter wheels with at least 11 positions in each wheel.

3.11. Mask Maker

In addition to the components traditionally associated with a spectrograph, the GMOS system must include the capability to design and fabricate slit masks in a quick and automated fashion. The software requirements to perform this task are discussed later.

There will be occasions, such as during exceptional seeing conditions, when it may be desirable to obtain spectra of a field on the same night that an image for mask design was recorded. Hence, the turn-around time for mask production must permit this. Experience with MOS/SIS on CFHT suggests that fabrication time-scales of one hour are possible. It is a goal that GMOS achieve similar mask fabrication times. As a minimum requirement it is necessary that the mask fabrication times be such that the typical night's mask set be fabricated during one daytime work shift. In 3.4 we argued that a mask would be used for 3 hours of observation in one night. Hence it is necessary to fabricate the 4 masks needed for one night during the 8 hour day shift, resulting in a minimum average fabrication time of 2 hours per mask.

The slit masks must not degrade spectrographic performance as a result of changes in environment (e.g. temperature or humidity), and gravity. Moreover, the slits will not be restricted to traditional rectangular shapes. For example, curved or irregular slits may be required for studies of gravitational arcs, or of shells and filaments in HII regions. Although the slit width for which R=10000 must be met is 0.25 arcsec, the mask maker should not limit observers who may wish to achieve even greater spectral resolution at the expense of throughput. The detector pixel scale will be able to adequately sample spectral lines for slits as narrow as 0.2 arcsec, and we feel that this is the smallest slit for which the mask maker must satisfy all its requirements. The fabrication process must be capable of producing slit edges that are very smooth and free of jagged features.

Two factors contribute to uncertainties in slit location: the positioning accuracy of the fabrication unit, and temperature differences between the fabrication area and the telescope (which could be as great as 20 - 25C on Mauna Kea, depending on the sitting of the mask maker). What tolerances should be assigned to these? To answer this question, it must be realized that the most important consideration is not absolute slit location, as the telescope can be offset or the field rotated to position objects on the slit. Rather, the most critical factor is the relative position of slits on the mask. In particular, if slits are not located with the correct distances between them, then if some sources are centered on their slits, others will be off-center. This will result not only in loss of throughput, but also in systematic velocity errors, as line profiles will vary from slit to slit.

Throughput and velocity accuracy define identical specifications for relative positioning accuracy of slits. The specification for the former can be estimated using the 0.25 arcsec slit width. To prevent substantial losses in throughput across the field, we require that the slit-to-slit positional accuracy in the dispersion direction be no greater than one tenth the minimum slit width, and this corresponds to 0.25 x 0.1 x 620 = 16 μm at the telescope focal plane. As for the requirements placed by velocity accuracy, if a velocity accuracy of 2 km/sec is specified then for R=10,000 a positioning accuracy of 1/15 of a spectral resolution element (i.e. one slit width) is required. Hence the positioning accuracy is 0.25 arcsec / 15 = 0.016 arcsec, which corresponds to 10.35 μm at the telescope focus. We note that this degradation is not considered as part of the error budget in Section 3.4, as these positional errors are *systematic*, and not *random*. These errors include both the internal accuracy of slit fabrication and temperature effects.

The specifications derived in the previous paragraph refer to the relative location of slits on the mask. However, the properties of individual slits are also of critical importance, especially for faint objects, where sky subtraction is of paramount importance. Although variations in throughput can be compensated by flat -fielding the data, this nevertheless introduces a source of noise. To minimize this effect, we require that the width of the narrowest slit not vary on pixel-to-pixel scales by more than 1% along the spatial direction, which corresponds to ~ 1 μm. Although cast in terms of a traditional rectangular slit, this specification must also hold for irregularly shaped slits as well. Width variations which must be controlled are not only those introduced during fabrication, but also those due to flexure and temperature changes.

It is also important for the mask to be able to completely block potentially bright objects in the field, over the full detection range of the detectors. Band pass filters often have some significant amount of out-of-band leakage, and cannot be relied on to block any unwanted transmission through the masks. Infrared detectors used for GMOS will either have a long response cutoff at about 2.5 μm or the dewar aperture will be filtered to prevent radiation longward of this limit from reaching the detector. We therefore require that the mask material used for GMOS be opaque over the wavelength range 0.3 - 2.5 μm.

3.12. Software Systems

3.12.1. Control System

A control system is required to operate the various automated functions and monitor the status of the instrument. This applies not only to mechanisms permanently mounted in the instrument, but also to components that are interchangeable, such as gratings, slit masks, and filters. The control system will require deterministic knowledge of these components, and provisions for storing this information must be considered during its development. In addition, the control system will keep a log of the instrument configuration and conditions at the telescope. Not only will this information be used for data reduction, but GMOS will have an active control system to compensate for flexures and gravitational deformations, and these data will be used to derive corrections for instrument components.

Given the emphasis on image quality, it is likely that the thermal environment of the dome will be strictly monitored, and activity in the dome during daylight hours will be kept to a minimum. Therefore, the control system should be designed to provide ready access to all components to minimize maintenance time when the GMOS is mounted on the telescope. Indeed, it can be anticipated that daily access will be required to change filters, slit masks, and gratings. The control system must make such daily maintenance as easy to perform as possible. One example is to provide local control for any functions which need it, such as rotating the filter wheel to load filters. Major instrument setups will be done in a special preparation room, and the GMOS control system must be designed so that the instrument is fully functional when not mounted on the telescope (i.e. it must have a 'stand -alone' mode). The control system should also include self-test and diagnostic capabilities.

A user-friendly engineering interface must be provided that permits rapid assessment and easy manipulation of the instrument mechanisms.

The control system must provide sufficient logging of hardware and software activity that information is available to diagnose a system failure or fault, especially an intermittent one. Software tools must be available at the telescope that quickly and easily process the logged information in a manner appropriate to fault diagnosis. The control system must allow remote operation and telemetry of the instrument by specialists so that they might be able to quickly diagnose a fault without having to travel to the mountain top.

3.12.2. Data Handling and Reduction System

GMOS will make use of the Observatory Control System and the Data Handling System (developed outside of GMOS) to provide the user interface for the observer and a quick -look display and data reduction capability. The purpose of the data reduction capability at the telescopes is to permit the rapid assessment of data quality during observations, and to process data as part of the cycle of mask making. In addition, these control systems will coordinate GMOS with other telescope functions. The nature and complexity of an on -line data reduction system depends on the application. For imaging applications simple bias subtraction and flat-fielding, using 'typical' calibration frames, will be sufficient. However, more complex algorithms are required for spectroscopic applications, as the flat -field depends on parameters such as wavelength region, slit location and width, and filter response. Moreover, the ability to perform simple wavelength calibration and sky subtraction is also required.

The GMOS control system will incorporate the detector controller, but is not responsible for saving the data on any permanent media. Data and any appropriate header information will be passed to the data handling system for display and for assembly into standard image files with appropriate header information.

Part of the data processing system for GMOS must include the capability to design and fabricate slit masks in a quick and automated fashion. The software intended for mask design would be supplemented by versatile photometric reduction routines capable of measuring, for example, the brightness of extended objects and point sources, as well as performing star -galaxy separation. These latter functions could be integrated with the data reduction system. It is necessary to be able to design masks with recent imaging data and also with previously taken data which has now become part of the permanent data store.

The data processing system must provide the functionality to be able to reassemble and view images taken with the IFU.

Finally, the control system should have a instrument simulation mode. Such a mode would allow the potential user of the instrument to see simulated detector data taken by GMOS while manipulating slit positions, cassegrain rotation, filters, guide objects, etc. This capability would be useful for planning observations, especially those that might be scheduled for the observing queue. Such a system would also permit modeling of observations, so that observers could optimize acquisition parameters to best achieve their scientific goals. There is large scope for the possible functionality (and development effort required) of such a tool, and as such it must be considered desirable but not essential to the operation of GMOS.

3.13. Handling Cart

The GMOS must come with a handling cart that will, in conjunction with facility handling equipment, be used to transport the instrument around the telescope and support buildings. It will also provide a rigid support structure for when the instrument is used in stand -alone mode. The purpose of the cart is to move GMOS safely between the instrument storage and preparation areas and the telescope ISS. The handling cart must be capable of fitting into all main loading entrances and elevators in and around the Gemini domes. It must be able to offer the instrument to both the up-looking and the side-looking ports of the ISS. Further, the handling cart will support the instrument during off-telescope maintenance, preparation and tests. The cart must allow access to all routine service ports and must accommodate any specialized calibration or alignment instruments.

3.14. Other Deliverables

In addition to an instrument which meets all of the above performance and functionality, the following are a minimum set of components which must be delivered with *each* instrument to meet the commissioning goals:

- Three gratings appropriate for commissioning test and observations.
- Five filters, including B, V, R and I.
- Any masks or other hardware necessary to perform instrument calibration and focusing (i.e. grid masks or Hartmann masks, as appropriate to the method used).
- One mask cassette capable of holding one IFU and a number of slit masks.
- At least 15 mask frames.
- Protective covers for any optics which are exposed when not on the telescope.

4. Summary of Requirements

In this section, all the requirements and goals are summarized. The type of requirement is identified in accordance with the definitions in 1.3 above as P (primary), Sa (Secondary requirements which flow down from primary requirements), Sb (Secondary requirements which the team believes are necessary to meet the scientific goals), G (goal), E (external) or A (additional functionality). The numbers in brackets indicate the section of this document in which the requirement is discussed.

4.1. General Optical:

4.1.1. Wavelength Coverage Requirement: To meet the primary image quality specs (4.1.6 below) and throughput specs over 0.4 - 1.1 μm **[1.1, P].**

4.1.2. Wavelength Coverage Goal: To meet the image quality and throughput specs from 0.36 to 1.8 μm. **[1.2, G]**

4.1.3. Image scale is 0.08 arcseconds per 15 μm pixel **[1.1, P]**

4.1.4. Field: 5.5 arcmin diameter unvignetted; 7 arcmin diameter with no more than 10% vignetting **[1.1, P].**

4.1.5. Spectral Resolution: up to 10000 with 0.25 arcsec slits, and 5000 for 0.5 arcsec slits **[1.1, P].**

4.1.6. GMOS (excluding ADC) pointing at the zenith should not degrade the on-axis image quality delivered by the telescope by more than 10% **[1.1, P]**

4.1.7. Optical throughput in imaging mode (i.e. without a dispersing element) and not considering the detector, filter or AtmDCC of ~ 80% over the base science wavelength range of 0.4 to 1.1 μm, with a goal of meeting this throughput from 0.36 to 1.8 μm.**[2.2.d, P/G]** .

4.2. General Instrument:

4.2.1. GMOS must be capable of reconfiguration in an automated fashion **[2.2.a Sb].**

4.2.2. Each reconfiguration should take *on average* no longer than 50 seconds; a goal is to have any instrument reconfiguration completed *on average* in half this time **[2.2.b, Sb].**

4.2.3. GMOS must meet the flexure requirements of an image stability of 10 μm or less at the telescope focal plane (which corresponds to a radial velocity of 2km/s at

R=10,000) during normal operations over periods of 1 hour in any range of zenith angles between 0 and 75 (i.e. air masses 1 - 2), with a goal of meeting all flexure specifications over periods of 3 hours **[2.2.c, Sb/G].**

4.2.4. As complete a self-diagnostic capability as reasonably affordable **[2.2.f, G].**

4.2.5. A goal is that subsystems are electrically and mechanically modular **[2.2.f, G].**

4.2.6. The basic design of the support structure and enclosure must offer ready access to all configurable portions of the instrument, such as the detector/ dewar/ controller assembly, grating, filter, and slit mask assemblies. Instrument enclosure should be designed with a goal of providing easy access to as many mechanisms inside as possible **[2.2.f, Sb/G].**

4.2.7. Instrument enclosure must provide a light -tight environment. **[3.1, Sb].**

4.2.8. Total instrument in full operational configuration (i.e. including OIWFS and detector) must weigh 2000 kg with a center of gravity located on the optical axis 1m from the ISS, and with a precision in these two such that the mass moment error is less than 400 N m. **[3.1, P].**

4.3. AtmDCC:

4.3.1. Should be removable, but there is no requirement to have it remotely deployable **[1.1, G].**

4.3.2. It is necessary that the change in the AtmDCC distortion during any hour from 0 to 60 degrees not degrade the 0.25 arcsecond slit throughput significantly **[3.2, Sb]**.

4.3.3. If it is not possible to remove remotely the GMOS AtmDCC, then its optical performance must be such that GMOS is able to meet its image quality primary requirement with the AtmDCC in place. **[3.2, Sb].**

4.3.4. The optical quality and system performance (e.g. ability to rotate, etc.) must not degrade the image quality **[3.2, Sb].**

4.4. Wavefront Sensor:

4.4.1. Throughput of the OIWFS pick -off system must be no worse than 90% **[3.3, Sb].**

4.4.2. The shadow produced by the OIWFS pick -off mirror assembly (i.e. mirror and support arm) occult no more than 5% of the 5.5 arcmin diameter science field of view **[3.3, Sb].**

4.4.3. The pick-off must be capable of patrolling a region of sufficient area to give 90% probability of finding a guide object at the North Galactic Pole (the sensitivity and noise of the OIWFS should be such that this area is less than the tip-tilt corrected atmospheric isoplanatic patch); the goal is to obtain 99% coverage at the North Galactic Pole **[3.3, Sb/G].**

4.4.4. Must be capable of working close to the center of the science field, where the integral field unit will be located **[3.3, Sb/G]**

4.5. Integral Field Unit:

4.5.1. 45 - 55 square arcsecond (0.20 arcsec/element) field coverage **[2.1.c, P].**

4.5.2. The sky level must be measured simultaneously with the science observations **[3.5, Sb].**

4.5.3. Throughput of each fiber-lenslet combination (both in the primary science and sky fields) must remain stable to within 1% during the course of one night **[3.5, Sb].**

4.5.4. Ability to reconstruct images as viewed through the integral field system **[3.5, E].**

4.5.5. Automated deployment and retraction of all related components **[3.5, Sb]**

4.5.6. It is a goal that GMOS hold up to 3 IFUs for deployment **[3.5, G].**

4.5.7. It is necessary that the OIWFS pick -off system used for IFU mode be capable of acquiring sources very close to (but not necessarily in) the primary science field of the integral field module; however, a goal is to use objects in the field of view as reference sources **[3.5, Sb/G].**

4.5.8. Differential flexure between the integral field unit and the OIWFS pick -off will not exceed one-tenth of a resolution element, or 0.02 arcsec at f/16 per hour **[3.5, Sb].**

4.5.9. Be deployed with an accuracy of 120 μm at the f/16 focus **[3.5, Sb].**

4.6. Slit Masks:

4.6.1. Mask cassettes can accommodate combinations of masks and up to two IFUs. Only one cassette per instrument will be delivered. **[1.1, P].**

4.6.2. GMOS must be capable of holding at least 3, with a goal of 15 or more masks at one time **[3.4, Sb/G].**

4.6.3. An automated identification scheme to identify and keep track of the masks installed in the instrument should be considered a design goal **[3.4, G].**

4.6.4. The mask positioning accuracy perpendicular to the optical axis needs be such that every point on the mask is positioned to within ±25 μm of the commanded position **[3.4, Sb].**

4.6.5. The mask material must be opaque from 0.3 to 2.5 μm **[3.11, Sb].**

4.6.6. It is necessary that either by means of telescope focus or mask position, the slit mask can be placed in the best compromise focus location for any field size of interest, from on-axis only through to full field **[3.4, E].**

4.7. Mask Maker

4.7.1. An average fabrication time of two hours or less is required, one hour is a goal **[3.11, E/G].**

4.7.2. The mask maker must be able to cut irregular or curved slits **[3.11, E].**

4.7.3. The slit-to-slit positional accuracy in the dispersion direction must be less than or equal to 5 μm at the telescope focal plane **[3.11, E].**

4.7.4. The mask maker needs to fabricate slits as narrow as 0.2 arcsec **[3.11, E].**

4.7.5. Width of the narrowest slit should not vary on pixel-to-pixel scales by more than 1% along the spatial direction **[3.11, E].**

4.8. Spectrograph Main Optics:

4.8.1. Detector Size: 4096 x 6144 CCD mosaic, with 15 μm square pixels **[1.1, 3.8, P,E].**

4.8.2. camera with 100 mm pupil diameter and a camera field of view appropriate for a 4096 x 6144 x 15 μm detector mosaic **[1.1, P].**

4.8.3. A goal is to meet all requirements with a single set of optics for each spectrograph **[3.6, G].**

4.8.4. At least 3 dispersing element positions available on the instrument **[3.7, P].**

4.8.5. Range of focus motion must cover the full chromatic range of the optical design **[3.8, Sa].**

4.8.6. Filters must be deployable remotely and quickly within the 50 second average **[3.10, Sb].**

4.8.7. Filters must be situated in and not vignette the collimated beam **[3.10, Sa].**

4.8.8. Filters must be AR-coated to minimize loss **[3.10, Sb].**

4.8.9. Total number of filters that GMOS must be capable of carrying is at least 22, in two filter wheels **[1.1, 3.10, P].**

4.8.10. Manual access to filters, gratings, slit masks **[3.10, 3.12.1, Sb]** .

4.8.11. Shortest exposure time is 1 second, and the non-uniformity of exposure time over the detector focal plane must be less than 10 msec **[3.9, Sb].**

4.9. Control and Data Handling Systems:

4.9.1. Provide sufficient logging of hardware and software activity to perform corrective maintenance on faults **[2.2.f, 3.12.1, Sb,E]** .

4.9.2. GMOS mechanical and control design must make it easy to manually access the filter-holding mechanism to remove or add filters **[3.12.1, Sb].**

4.9.3. Stand alone operation of GMOS control functions (i.e. isolated from the rest of the telescope and control system) **[3.12.1, Sb].**

4.9.4. Integrated process of mask design and fabrication **[3.12.2, E].**

4.9.5. Instrument simulation mode is a goal **[3.12.2, G].**

5. Image Quality Specification

It is likely that the GMOS's will see extensive use for both narrow -field on-axis (e.g. with the integral field unit and/or adaptive optics system), and wide -field off-axis (e.g. for imaging or multi-object spectroscopy) applications. Therefore, specifications are derived for both of these situations. Specifications for the entire GMOS optical system, including both pre - and post-slit optics, and at fixed wavelengths representing the entire range of GMOS's requirements and goals, are derived in Section 5.1. The specifications here should be interpreted as the image quality required at a single wavelength at zenith, when focused for that wavelength.

For the purposes of developing an error budget it is also necessary to develop independent top-level specifications for the pre - and post-slit environments, and these are discussed in Sections 5.2 and 5.3. These specifications must be met in normal operating configurations: typical bandpass values with a single focus setting for that band.

It should be noted that the specifications derived here supersede those presented in earlier documents.

5.1. Top Level Global Image Quality Specifications

5.1.1. On-axis case

Image quality specifications for the telescope optics were defined by assuming that they not degrade the tip-tilt corrected atmospheric image quality during good (10 percentile best) seeing conditions by more than 15%. A similar approach is adopted to compute image quality specifications for GMOS and our primary requirement is that GMOS optics (without AtmDCC) not degrade the on-axis images specified to be delivered by the telescope, which include the atmosphere and telescope optics, by more than 10%.

The starting points for this exercise are the 50 and 85% encircled energy diameters predicted for on-axis tip-corrected images not degraded by telescope optics, and these are listed in the first rows of Table 2 (50% ee) and 3 (85% ee) in units of arcsec. The values used here were supplied by Jim Oschmann and Rick McGonegal, based on an atmospheric model devised by Charles Jenkins. These diameters were then degraded by 15% to account for telescope optics, and an additional 10% to account for the GMOS optics. The contribution from the instrumental error function could then be computed. The results, corrected for diffraction, are shown in the last row of each Table.

TABLE 2: GMOS without AtmDCC: on-axis image quality (50% encircled energy diameters, in arcsec) [1.1, P]

Wavelength (μm)	*0.37*	*0.55*	*1.0*	*1.6*

Tip-corrected Atmosphere	0.274	0.245	0.209	0.183
With 15% Telescope Degradation	0.315	0.282	0.240	0.210
With 10% Instrumental Degradation	0.347	0.310	0.264	0.231
Instrumental Error	0.127	0.113	0.097	0.085
Instrumental Error when measured with Diffraction	0.127	0.114	0.100	0.094

TABLE 3: GMOS without AtmDCC: on -axis image quality (85% encircled energy diameters, in arcsec) [1.1, P]

Wavelength (μm)	*0.37*	*0.55*	*1.0*	*1.6*
Tip-corrected Atmosphere	0.558	0.512	0.467	0.437
With 15% Telescope Degradation	0.642	0.589	0.537	0.503
With 10% Instrumental Degradation	0.706	0.648	0.591	0.553
Instrumental Error	0.258	0.237	0.216	0.202
Instrumental Error when measure with Diffraction	0.260	0.242	0.233	0.247

Tables 2 and 3 are the primary GMOS image quality requirements. All of the subsequent requirements derived here are secondary (category Sb) requirements.

5.1.2. Off-axis case

The approach adopted here is identical to that used for the on -axis case, but with two important differences. First, the specifications are based on images delivered by the telescope 4 arcmin off-axis (this is slightly larger than the 3.5 arcmin GMOS field, but at the time of writing these were the only numbers available). The values listed in the first rows of Tables 4 (50% ee) and 5 (85% ee) are based on numbers supplied by Jim Oschmann, interpolated to match the wavelengths used in the on -axis error budget. Second, when used in wide -field mode, it is assumed that the GMOS optics not degrade the delivered images by more than 15%. The resulting top -level specifications are listed in the last rows of Tables 3 and 4.

TABLE 4: GMOS off -axis image quality (50% ee)

Wavelength (μm)	*0.37*	*0.55*	*1.0*	*1.6*
Telescope and Atmosphere	0.353	0.315	0.260	0.254
With 15% Degradation	0.387	0.347	0.286	0.280
Instrumental Error	0.141	0.127	0.104	0.102

Instrumental Error when measured with Diffraction	0.142	0.127	0.107	0.110

TABLE 5: GMOS off-axis image quality (85% ee)

Wavelength (μm)	*0.37*	*0.55*	*1.0*	*1.6*
Telescope and Atmosphere	0.676	0.626	0.576	0.542
With 15% Degradation	0.744	0.688	0.634	0.596
Instrumental Error	0.272	0.251	0.231	0.218
Instrumental Error when measured with Diffraction	0.274	0.256	0.248	0.260

5.2. Top-Level Image Quality Specifications for the Pre -Slit Optics

5.2.1. On-axis case:

The basic criterion for setting the top -level image quality specifications for the GMOS pre -slit optics is the preservation of slit throughput. We require that the pre -slit optics not degrade the amount of light passing through a 0.25 arcsec wide on -axis slit viewed at the zenith by more than 10% of that which would result with no pre -slit optics. To determine the 50 and 85% ee diameters of the pre-slit optical error function, a series of Moffatt functions, with 50% ee diameters identical to those in the second row of Table 2 and Beta=3, were created. These model stellar images were then convoluted with a suite of Gaussians, and the function that produced a 10% light loss within a 0.25 arcsec wide slit was determined. The resulting specifications are listed as 50 and 85% ee diameters in Table 6.

TABLE 6: Pre-slit on-axis image quality specifications

Wavelength (μm)	*0.37*	*0.55*	*1.0*	*1.6*
50% Encircled Energy	0.19	0.15	0.12	0.10
85% Encircled Energy	0.31	0.26	0.20	0.16

5.2.2. Off-axis case:

The procedure is the same as for the on -axis case except that the 4 arcmin off-axis image quality figures listed in second row of Table 4 were used to generate the stellar profiles, while the slit throughput is allowed to degrade by 15% off -axis at the zenith. The resulting specifications are listed as 50 and 85% ee diameters in Table 7.

TABLE 7: Pre-slit off-axis image quality specifications

Wavelength (μm)	*0.37*	*0.55*	*1.0*	*1.6*
50% Encircled Energy	0.45	0.36	0.25	0.24
85% Encircled Energy	0.74	0.59	0.41	0.40

5.3. Top-Level Image Quality Specifications For The Post -Slit Optics

An important criterion for judging spectrograph image quality is the ability to image slits at the detector. A compact and uniform slit response is critical, as smearing of the slits will degrade spectral resolution. Uniformity of optical quality across the field is also essential, otherwise spectral resolution will depend on focal plane location, a potentially catastrophic problem for science programs such as dynamical studies of stars in clusters and nearby galaxies.

The top-level requirement for the post -slit GMOS optics is that they not introduce more than a 15% light loss in the image of a 0.25 arcsec slit, when compared with the perfectly imaged case. The specifications were determined by smoothing a top -hat function of width 0.25 arcsec by a suite of Gaussians, and the standard deviation that caused a 15% loss in slit energy was computed. The 50 and 85% encircled energy diameters of the resulting function are shown in Table 8. Note that these requirements are panchromatic - they hold for all wavelengths. Moreover, this caliber of image quality is required over the entire field of view.

TABLE 8: Post-slit image quality specifications

Encircled Energy	*Diameter*
50%	0.11
85%	0.18

6. Requirements on External Systems

To be able to deliver astronomical data of acceptable quality GMOS relies on the performance of many telescope systems which are outside of the GMOS work scope. Described here are some of the requirements which must be placed on other non-GMOS telescope systems.

6.1. Optical Detectors and Controllers

The GMOS's will require state of the art CCD detectors to fully exploit their unique capabilities. In terms of spatial coverage, the CCDs must cover the full 5.5 arcmin diameter science imaging field, as well as the oversized camera field which permits spectroscopic coverage of all objects in the science field.

It is a GMOS primary requirement that the detector array by 4096 x 6144 x 15 μm pixels. It is a goal that the gaps between imaging pixels on the mosaic elements remain less than 500 μm.

The principle science use for GMOS will be faint object spectroscopy. In that mode, we find that the sky contribution to the detected signal after one hour at R=10,000 is 25 e- per pixel. We require that the CCD read noise not increase the sky noise by more than 10%, which is a read noise of 2 e- RMS.

The detector dark current must be such that it increases the detector noise floor in a one hour exposure by no more than 25%. For a read noise of 2 e-, and assuming a gaussian distribution of dark current, this results in a dark current rate of less than or equal to 1 e- per pixel per hour.

Fringing is also of critical importance for faint spectroscopic applications. We require that at 0.9 μm the fringing under monochromatic illumination be no greater than 3% (with a 1% goal), with a spatial period of ∫200 pixels.

The entire mosaic detector array should be flat to within ±15 µm over the entire focal plane.

In Section 2, it was stated that no more than 5% of each night should be lost due to instrument configuration and detector read out, resulting in a mean detector readout and display time requirement of 50s. If we assume that detector readout happens at the same time as other instrument configuration, and we allow some amount of time - say, 10 s - to complete the data transfer and display at the conclusion of detector readout, then we require that the controller and CCD perform a full frame readout time of 40s for the 2e- noise science frame.

In addition, there are many cases where it is of advantage to read the CCD more quickly at the expense of noise. Such cases include taking bias frames, photometric standards, wavelength calibration and dithered twilight sky flats, where time is at a premium but photons are relatively plenty. We will assume that in all cases we have many more than 100 photoelectrons and can tolerate a read noise up to 10e- without degrading performance. Although it is desirable to read out the detector as quickly as possible, a firm requirement evolves from the case of needing to take five dithered sky flats in each of four photometric filters during the 600 seconds of twilight suitable for this calibration. In this case we must maintain an average expose + readout time of less than 30 seconds. We therefore require that the CCD and controller read out full frames with 10e- noise in 20 seconds, with a goal of 5 seconds. We also require that data taken in this faster mode be linearly applicable to science data gathered in the slower mode with an accuracy of 99.5%.

It must be possible to define multiple sub -rasters of any size over the entire detector surface To check differential rotation between the slit mask and telescope focal plane will require ~ 4 sub-rasters, which we consider to be the minimum number acceptable. The subrasters need not overlap and may be constrained to have the same binning and speed parameters.

Certain applications may be compromised by the need to separately calibrate the data from different output ports on one device. We therefore require that it is possible to read out each CCD from one port only (recognizing that the above read speed requirements of 20s and 40s may not be met in this case).

The detector controller subsystem should provide as complete a self-test and self-diagnostic ability as is reasonable. It must be able to report to the GMOS ICS any relevant operating conditions including shutter state, detector temperature, software revision level, operating voltages and some indication of cryogen fill state (such as fill tube neck temperature, cryogen vessel temperature,...).

6.2. Other Telescope Systems

Interactions with other Gemini systems must also be considered when designing GMOS.

- Instrument Support Structure: When deployed, the GMOS will occupy no more than a single face of the Instrument Support Structure (ISS). Moreover, for operational versatility, the GMOS must be capable of being mounted on any face of the ISS dedicated to instruments. The physical dimensions of the GMOS must fit within those specified in the document "*Available Space Envelopes for Gemini Instrumentation*" by Dave Montgomery; however, portions of the GMOS can extend inside of the ISS, to the inner surface of the walls. We require the ISS to be rotateable such that any sky orientation can be obtained; this capability is essential for alignment of targets on slit masks.

- Calibration Unit: The GMOS will require access to continuum and emission arc calibration sources, and at present it is assumed that this capability will be supplied by a module external to the GMOS. A continuum source is required to calibrate pixel-to-pixel sensitivity differences on the detector, and also to correct for variations in throughput across the science field introduced by optical components. Arc spectra are needed to determine the wavelength scale of spectroscopic observations. To maximize the use of available observing time for scientific observations, a goal is to record calibration data during the preceding or subsequent day; hence, the overall stability of the GMOS must be very high, both in terms of repeatability of mechanical motions and minimizing flexures due to changes in instrument orientation. For some programs, such as those involving high -resolution spectroscopy, it may be necessary to record calibration data during the night immediately following observations. In this case, read -out efficiency of the detector will be critical.

The calibration requirements for GMOS have been evaluated by Davidge in " *GMOS Science Calibration Issues*", dated November 3, 1994. The flat -field stability requirements for GMOS applications were found to be (1) 0.1% variation over scales of 20 arcsec; (2) 0.2% variation over scales of 100 arcsec; and (3) 1.0% variations over the entire science field. The first two specifications are based on the need to obtain accurate sky subtraction for faint object spectroscopy and hence are considered firm requirements on the calibration system, while the third is set by photometric stability and is considered to be a goal. It is also required that the flat -field calibration light be capable of passing through the AO system when it is in use. This is a critical issue since the AO optics will contribute to the overall flat -field pattern and possibly introduce wavelength -dependent deformations.

- Adaptive Optics: The high -order adaptive optics (AO) system will give the Mauna Kea telescope unique capabilities and, as the primary optical instrument on this telescope, it is important that the GMOS be capable of working with the AO system in all modes. Moreover, given that the AO system will see much use in investigations of very faint sources, it should be possible to use the AO system on GMOS with minimal loss of throughput. We require that any designs for higher order AO reference star feeds should degrade to the least extent possible GMOS throughput and wavelength coverage.

- A & G system: The Gemini telescopes will be equipped with facility acquisition and guide systems. In particular, a CCD acquisition camera will be mounted at the bottom of the ISS, while two so -called peripheral WFS's will be located near the top of the ISS. The GMOS must be capable of working with both of these systems; conversely, these systems should strive to not interfere with the operation of GMOS. For example, the patrol field for the peripheral WFS's should be designed so that most operations can be conducted without that probe occulting the GMOS science field.

  GMOS will be designed to meet the requirement that the average reconfiguration time be less than 50 s. It is important that this operational advantage is not compromised by a limiting slow response elsewhere in the telescope. The A&G fold mirror, sensor probes and control system should be designed so that they do not constrain GMOS average availability during a typical observing run.

- Gemini Control System: To meet the needs of the user of the telescope, GMOS will reply heavily on services being provided by other components of the Gemini Control

System (the GMOS Instrument Control System is one component of the Gemini Control System, and interacts closely with other components). It is assumed that the Data Handling System will be able to accept and display GMOS data as quickly as GMOS is able to deliver it, and certainly within 5 seconds of that being transmitted from GMOS. Software which will coordinate GMOS activities (such as observation, calibration, focus, maintenance) with other parts of the telescope is required from other work packages. Similarly, software to perform a minimal suite of image data processing sufficient to assess data quality or set up and calibrate the instrument or create slit masks must be developed outside of GMOS.

Although GMOS will log instrument data appropriate for fault diagnosis, it will not provide the tools to analyze or correlate the data log. It is required that these tools be provided elsewhere within the Gemini Control System. The Gemini Control System must also provide the infrastructure to be able to be able to diagnose and service GMOS as extensively as is reasonable from a remote location such as the sea level facility.

Off-Telescope Facilities Requirements

The GMOS requirements for off-telescope facilites such as the Mask Preparation Area, Cold Storage / Preparation Area and the Instrument Preparation Area have been described in GMOS document gmz0032.doc.

Appendix 1 Glossary of Terms

Accuracy	- The difference between the mechanical position at which a mechanism comes to rest and that to which it was commanded to go.
AO	- Adaptive Optics
AtmDCC	- Atmospheric Dispersion Compen sator and Field Corrector
GMOS	- Gemini Multiobject Optical Spectrograph
IFU	- Integral Field Unit
ISS	- Instrument Support Structure
OIWFS	- On Instrument Wave Front Sensor
Reconfiguration	- Any change to the mechanisms or systems within GMOS which happen abruptly and are not part of a continuous update during observation. Changing a filter, mask, grating, inserting or removing the IFU, changing the detector binning or speed are all examples of a reconfiguration. Updating the detector position or OIWFS stage position during an observation is not a reconfiguration.
Stability	- The lack of mechanical movements happening only as a function of time during normal observations. These might result from temperature changes, gravity vector changes or other causes.
Repeatability	- The difference between the position at which a mechanism comes to rest after a single placement and the mean of the positions of a large number of such placements performed under similar conditions.