GEMINI
SCIENCE REQUIREMENTS

VERSION 3.0

NOVEMBER 1996

PREFACE & HISTORY

Version 3.0 of this document, approved by the Gemini Board in November 1996, includes changes to correct typographical errors, clear up inconsistencies, incorporate Gemini Science Committee resolutions on scientific operations and archiving, and by the addition of Appendices I and II which document the initial scientific instrument complement and associated performance requirements (Appendix I), and the initial Adaptive Optics performance requirements (Appendix II) as recommended by the Gemini Science Committee and approved by the Gemini Board.

Fred Gillett
Project Scientist

Version 1.0 of this document was approved by the Gemini Board 9-11 November 1992. In version 1.2, typographical errors and inconsistencies between sections have been corrected.

Version 2.0 of this document has been amended consequent on the removal of the Nasmyth foci from the baseline Gemini Design and updating the image quality goals for the f/16 focus and the requirements for infrared chopping and nodding [off-setting].

Matt Mountain
Project Scientist

This document is a revision of the version prepared in September, 1991. At that time, the main requirements for the telescopes had been identified by representatives of the astronomical communities in the three partner countries. In the last thirteen months many of the scientific efforts in the project have concentrated on identifying the instrument requirements for the Gemini telescopes. In addition, progress has occurred on defining the needs for adaptive optics, on plans for achieving low emissivity, and on an assessment of the control issues for the telescopes. The Project Team developed a new concept for the telescope design, which promises improved imaging performance and offers an innovative way of implementing the Nasmyth focus. These developments are all reflected in this version of the science requirements document.

The intent of this document is to present the long-term science requirements for Gemini. It provides the basis for the development of the engineering design requirements and the cost estimates.

The document is the outcome of the efforts of the national science committees in the partner countries, of the Gemini Science Committee, and of the Gemini staff. It is a pleasure to acknowledge the significant contributions of Fred Gillett. I am grateful to Richard Green for his assistance. Roger Davies and Gordon Walker led the efforts in the U.K. and Canada, respectively, and their contributions were fundamental. Matt Mountain updated the Adaptive Optics section based on the input of Steve Ridgway, Richard Myers, and Rene Racine; produced the section on Instrumentation with the assistance of the Gemini Instrument Group; and checked the revision in general. As Project Scientist, Matt will have responsibility for the next version of the document.

Patrick Osmer
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I. INTRODUCTION

The Gemini Project is an international partnership to build two 8-m telescopes, one on Mauna Kea, Hawaii, and one on Cerro Pachon, Chile. The telescopes and auxiliary instrumentation will be front-line facilities open to the scientific communities of the member countries on a merit basis. The telescopes are to achieve an unprecedented combination of light-gathering power and image quality over the infrared, optical, and ultraviolet spectral regions observable from the ground.

The purpose of the Gemini Science Requirements documents is to identify the main scientific goals of the project and to provide a logical framework for the project staff to develop the engineering requirements for the telescope systems. The challenge is to do so for telescopes that will likely be used in virtually every area of ground-based infrared and optical astronomy over their lifetime.

In this document we begin by describing specific examples of research programs that drive the main parameters of the telescopes and instruments. Then we address the overall requirements and goals for the project. Finally, we present more detailed requirements for the telescopes and instruments.

Organization of the document

The organization of this document is the following:

Section II contains the top level science requirements and examples of programs that set key parameters of the telescopes.

Section III describes the general project and configuration requirements. It begins with the site properties and the top level performance requirements for the telescopes. Instrument considerations follow; then the operating requirements are given. Two telescope configurations are needed to meet the requirements.

Section IV describes illustrative instrumental capabilities for the Gemini telescopes. Appendix I documents the initial scientific instrument complement and associated performance requirements.

The document then addresses the details of the key capabilities and the telescope configurations. These are followed by a discussion of the requirements for the telescope structures and enclosures.

Section V discusses in detail the Image Quality Specification, one of the critical characteristics of the Gemini Telescopes.

Section VI contains the throughput requirements for the different wavelength ranges.

Section VII describes the Infrared Optimized Configuration.

Section VIII takes up the requirements for and impact of Adaptive Optics, which will be needed for correcting atmospheric distortions to the image beyond what can be done with wavefront-tilt correction. Appendix II documents the performance requirements of the initial Adaptive Optics system.

Section IX describes the Optical Wide-Field Configuration.

Section X discusses the properties that the telescope structure and enclosure must have to meet the overall science requirements.

This document sets the overall specifications by which the progress and eventual success of the project will be measured. As such, it must be approved by the Gemini Board.

II. TOP LEVEL SCIENCE REQUIREMENTS

The most striking gains offered by the Gemini telescopes over their 4-m class predecessors will come from the combination of the light gathering power of their 8-m diameter primary mirrors and the superb image quality of their optical systems. At infrared wavelengths, where near-diffraction-limited performance is the goal, the sensitivity gain for faint sources seen against the emission from the sky will go as the square of the diameter of the primary mirror while the exposure time to reach a given signal-to-noise ratio will decrease by the fourth power of the primary mirror diameter. At optical wavelengths, the gain in limiting sensitivity for high-resolution spectroscopic observations of photon-limited sources will be proportional to the square of the mirror diameter, as will the decrease in exposure time for a given signal-to-noise ratio.

Additional gains will come from designing the telescopes to have low emissivity and from improvements in instrumentation and detectors. For example, the gain in effective collecting area of the telescopes is inversely proportional to the emissivity of the telescope system at wavelengths where the thermal background emission dominates. The use of adaptive optics will extend the near-diffraction-limited imaging performance to shorter wavelengths. Increases in the sizes of detectors or the use of multiple detectors in a single instrument will yield higher resolution or allow more objects to be observed simultaneously.

The scientific case for large telescopes is persuasively made in the individual proposals prepared by astronomers in Canada, the U.K., and the U.S. for their respective funding agencies. Additional impetus in the U.S. comes from the recommendations of the Astronomy and Astrophysics Survey Committee (AASC) for the decade of the 1990s.

In this section we give examples of scientific programs that drive the main characteristics of the telescopes. The national proposals and the AASC report may be consulted for more details.

The main themes of the science programs are concerned with observing and understanding the origins and evolution of stars and planetary systems, of galaxies, and of the universe itself. The telescopes will be used to observe objects ranging in distance from within our own Solar System to within 10% of the observable horizon of the universe.

Examples of key research programs that set the science requirements for the Gemini telescopes, arranged in order of increasing distance, are:

Circumstellar disks and possible planetary systems

What is the nature of particle disks that were discovered by IRAS around nearby stars? Such disks are thought to be the remnants of planetary formation. Mapping the disks might reveal gaps caused by the presence of planets. At wavelengths of 10μm and beyond, it will be possible to achieve a resolution with the Gemini telescopes as good as 0.3 arcsec, which corresponds to 1-2 AU (1 AU = mean Earth-Sun distance), or the scale of the Earth's orbit, for the nearest examples.

This program will require diffraction-limited image quality and low emissivity of the telescopes at thermal infrared wavelengths.

Star Formation

How do stars form and what conditions lead to protostellar collapse? The diffraction-limited angular resolution of the Gemini telescopes will be 0.07 arcsec at 2.2 μm, which corresponds to 10 AU at the distance of the nearest star-forming regions. Achievement of such resolution will permit the study of protostellar objects down to the scale of the diameter of Jupiter's orbit.

This is an example of a program that will require near-diffraction-limited imaging at near-infrared wavelengths, where the telescopes will yield their highest resolution.

Stellar Structure

What is the internal structure of the stars? The characteristics of the sound waves trapped within the photosphere of a star are critically constrained by the star's physical structure, with the many different waves causing a complex oscillation of the visible surface. The "five minute" oscillations of the Sun have set important limits to the size and structure of its photosphere and internal rate of rotation. The velocity amplitudes associated with the oscillations are subtle, less than 1 m/s, non-repetitive, and they must be monitored for many hours. With the light gathering power of the 8-m mirrors and a spectrograph of sufficiently high resolution, it will now be possible to probe the interiors of nearby main sequence stars in an analogous fashion to the Sun.

Formation of the elements

What is the chemical enrichment history of the Galaxy and the Universe? High resolution spectroscopy of the oldest stars in the Milky Way and of gas clouds illuminated by distant quasars when the Universe was less than one quarter its present age will enable us to determine how the abundances of elements heavier than hydrogen and helium were built up over time. This program requires high-resolution spectroscopy of faint objects, which in turn requires excellent imaging at optical wavelengths, high throughput in the ultraviolet down to the atmospheric limit of transmission, and the large light-gathering power of the 8-m primary mirrors.

Formation and evolution of galaxies

How did galaxies form and evolve in the Universe? Optical observations of the individual stars and star clusters in the Milky Way and nearby galaxies will provide the key to understanding the relation between stellar populations, chemical enrichment history, and the dynamical history of present day galaxies in the Universe. The Gemini telescopes will enable observations of extremely distant galaxies at IR wavelengths, covering the same rest wavelength range as optical observations of nearby galaxies. With the light gathering power and excellent image quality of the telescopes, it will be possible to make direct observations of the morphology, content, and composition of nascent and adolescent galaxies. Optical observations will reveal properties of the youngest stars in such systems. For cases where dust is present, much of the short wavelength energy emitted by young stars is absorbed and re-radiated in the thermal infrared.

To set the scale for this problem, consider galaxies at redshift 1 in a universe of critical density and age 13 billion years (q_0= 0.5, H_0= 50 km/s/Mpc). Because of the light travel time, we are now seeing such galaxies as they were when the universe was only 4.6 billion years old, long before our own sun was born. At the distance of such galaxies, one arcsec on the sky corresponds to 8.5 kpc, or the distance from the sun to the center of our galaxy. With the 0.25 arcsec resolution the Gemini telescopes are to deliver at optical wavelengths, it will be possible to distinguish between spiral and elliptical galaxies and learn about their initial process of formation. With the 0.1 arcsec resolution expected of the Gemini telescopes in the infrared, we will be able to see in detail what forms the galaxies have and how the stars are distributed in them. This program is an example of one that requires broad band spectral coverage from the ultraviolet to the infrared. It requires excellent image quality and spectroscopic capability at optical and infrared wavelengths. It requires wide-field, multi-object capability for optical spectroscopy. Full sky coverage is also required. For example, the Magellanic Clouds, the nearest external galaxies, and the center of our own galaxy are in the southern hemisphere, while M31 and M33, the nearest spiral galaxies, are in the northern hemisphere.

Summary of science requirements

The above examples illustrate the main properties the telescopes must have. The main properties are consistent with the individual national proposals and the AASC report. The table below summarizes the properties and the relation to the science examples given in this section. Of course, many other science examples could also be given.

Program Example	**Telescope Property**
Circumstellar Disks	8-m Primary Mirrors Near-diffraction Limited Imaging Low Emissivity
Star Formation & Stellar Structure	Full Sky Coverage 8-m Primary Mirrors Near-diffraction Limited Imaging Low Emissivity
Formation of Elements	Full Sky Coverage 8-m Primary Mirrors Wide-field Coverage
Formation and Evolution of Galaxies	Full Sky Coverage 8-m Primary Mirrors Low Emissivity Broad Wavelength Coverage Wide-field Coverage

III. GEMINI PROJECT AND CONFIGURATION REQUIREMENTS

In this section we establish the main properties the telescopes must have in the long term to meet the science requirements. We also identify additional performance requirements needed to maximize scientific output during the lifetime of the project. We consider first site properties and top level performance requirements. Next a brief discussion of the relation between instrumentation and telescope parameters is given. Then operational requirements are discussed. From all these considerations we find that two telescope configurations will be needed, and they are described in summary form.

Site Properties

- **Full sky coverage.** There are to be two Gemini telescopes, one in the northern hemisphere and one in the southern. Key astronomical objects will be accessible, regardless of their location on the celestial sphere. All objects accessible to space observatories will be observable with the Gemini telescopes.

Location on Excellent Sites. The northern telescope is to be located on Mauna Kea, Hawaii, which is regarded as the best available site in the world for an infrared-optimized telescope in terms of its 0.4 arcsec median seeing, 4200m elevation, and 1 - 2 mm typical level of water vapor. It also is the best site for ultraviolet observations. The southern telescope is to be located on Cerro Pachon, Chile, an outstanding site with over 60% of nights being photometric and 77% spectroscopic, 0.5 arcsec median seeing, and water vapor comparable to Mauna Kea during the winter months.

Top Level Performance Requirements

A. Telescopes

- **8-m Diameter Primary Mirrors.** The Gemini telescopes will have a minimum usable primary mirror diameter of 8.0 meters. The 8-m mirrors will have four times the light gathering power of 4-m telescopes and, at wavelengths where diffraction dominates, twice the angular resolution.

- **Image quality of better than 0.1 arcsec.** Achievement of outstanding image quality will have the highest scientific priority for the project. The intent is that the Gemini telescopes will achieve image quality equal to the best conditions of the sites. With wavefront-tilt correction, the Gemini telescopes are to deliver image quality at near-IR wavelengths of better than 0.1 arcsec over a 1 arcmin field. Adaptive optics capabilities will extend this near-diffraction-limited angular resolution to shorter wavelengths.

- **Broad wavelength coverage and high throughput.** For full realization of their scientific potential, the Gemini telescopes will need high throughput from ultraviolet wavelengths longer than 0.3µm through the visible and infrared bands to at least 30µm. In order to achieve high performance across this very broad wavelength band, capability for a variety of mirror coatings is required.

- **Low emissivity configuration**. An optimized IR configuration will provide an extremely low emissivity, with a goal of 2%, for making the most sensitive thermal IR measurements. Through key windows around 2.3µm, 3.7µm, and 11µm, a factor of two reduction in telescope emissivity is equivalent to increasing the collecting area by the same factor. The combination of superb imaging and high sensitivity of the Gemini telescopes at IR wavelengths will be unmatched by any other facility.

- **Wide-field configuration.** The Gemini telescopes will include a capability at optical wavelengths for a 45 arcmin field, allowing spectroscopic observations of up to several hundred objects simultaneously.

- **Versatility.** To maximize scientific productivity, the Gemini telescopes will need the capability to respond to changing sky conditions, particularly to take advantage of times with the best seeing or lowest water vapor. The telescopes will need to be able to support more than one mode of observing and to change rapidly between selected instruments.

The combination of the above capabilities will make the Gemini telescopes uniquely powerful instruments compared to existing and currently planned telescopes, both for the ground and space.

B. Additional performance requirements

- **Similarity of telescopes.** The telescopes should be designed to have identical capabilities, consistent with the science requirements. The similarity will: 1) give similar performance in programs spanning both hemispheres; 2) facilitate the observing process for astronomers using both telescopes; and 3) enable the interchange of instruments and software between the telescopes. The similarity also will provide significant savings in cost and give practical advantages in design, manufacture, installation, and operation.

- **Provision for future upgrades or modifications.** The telescopes will be international facilities serving a large community of users. They should be designed with a minimum of limitations on future use, even if they are initially commissioned with a small number of capabilities. They should also be designed so that upgrades and new instruments can be accommodated in the future.

- **Long Lifetime.** The design of the telescopes should consider that their useful lifetime is likely to exceed fifty years.

- **Ease of operation.** Because the telescopes will be located at remote sites and because the operations cost will probably be greater than the capital cost over the lifetime of the telescopes, attention must be given in the design to operations and maintenance with minimum staff cost.

- **Provision for acquisition, guiding, and wavefront sensing.** Acquisition and Guiding (A&G) units will provide the interface between the telescopes and instruments. Issues of what functions are to be performed by the A&G units and what by the instruments need to be addressed from the start. Because of the planned alt-az mounting of the telescopes, there must be a capability to correct for field rotation, which could be incorporated into the A&G units.

Instrument Requirements

The science programs will actually be carried out with the telescopes and their auxiliary instruments working as a system. The instrument requirements are important at this stage for two reasons:

1) The instruments and telescopes together determine the ultimate scientific capabilities of the project.

2) The instruments influence design parameters of the telescopes and vice versa.

The table on the next page summarizes the general types of instruments needed to carry out the science requirements described in § II. The instrument requirements are described in more detail in § IV.

PROGRAM	INSTRUMENT	FOCAL STATION
Circumstellar Disks	• Near & Thermal IR Imager • Medium-to High-Resolution IR Spectrometer	Cassegrain Cassegrain
Star Formation & Stellar Structure	• Near-IR Imager • Medium-to-High-Resolution IR Spectrometer • High-Resolution Optical Spectrograph	Cassegrain Cassegrain Cassegrain/High Stability Lab
Formation of the Elements	• High-Resolution Optical Spectrograph with ultraviolet capability • Wide-field, multi-object Spectrograph	Cassegrain Cassegrain
Formation and Evolution of Galaxies	• Wide-field, multi-object Spectrograph • Optical and IR Imagers • Multi-aperture spectrograph • Low to moderate resolution IR spectrometer	Cassegrain Cassegrain Cassegrain Cassegrain

A main requirement for the telescopes that emerges from the above table is:

Provision of focal stations. The telescopes must provide accessible focal surfaces at which the instruments can be located. The telescopes must provide adequate space and weight carrying capacity for mounting the instruments as well as necessary data links, power, and cryogens. Large instruments as well as experimental instruments will be located at the Cassegrain focus. The telescopes must also provide a high stability focal station in the telescope pier for instruments requiring high thermal stability and constant gravity orientation. Note that a scientific requirement has not been identified for use of the prime focus.

Operational Requirements

The operating conditions and modes will be key parameters in achieving maximum scientific productivity of the Gemini telescopes and therefore become part of the top level project requirements. The Gemini facilities represent the premier ground based astronomical facilities available to the partner communities. As such the goal of Gemini operations is the effective utilization of these facilities to exploit the unique characteristics of the telescopes and sites, and execute the highest priority observations as identified by the partners, consistent with the allocation of time among the partner countries.

- **Operating Conditions.** The telescopes will be designed to meet the performance requirements up to the 70th percentile of the wind distribution in clear weather conditions. The operating limits must be consistent with maintaining the cleanliness of the optics, protecting the telescope mechanisms, and achieving the image quality requirements. Main environmental parameters to be considered for shutdown conditions will be humidity, wind, and dust. In addition, the observing facilities must be designed to survive intact the extremes of environmental conditions at the sites (e.g. storms and earthquakes).

- **Down time**. Time lost due to failures of the telescopes, enclosures, computers, control systems, acquisition and guide units, and facility instruments should be kept to a minimum, no more than 2% of the scheduled observing time, with 1% being a goal.

Observing modes

Efficient use of the Gemini telescopes will require capability for the following observing modes:

- **Astronomer at the telescope,** using a Gemini instrument or his or her own instrument. There should be provision for the support, installation, and operation of outside instruments brought by the observer.

- **Service observing / Remote observing / Queue scheduling**. Some programs will be best carried out with the investigator not at the telescope. Examples include programs requiring excellent seeing, extremely dry conditions, or synoptic observations. The observations would be carried out by local staff. There should be provision for high-bandwidth communications links to a remote observer located at his or her home institution or national observing center.

Observing time will be at a premium on the Gemini telescopes, and every effort must be taken to obtain observations a highly efficient manner that exploits the unique characteristics of the telescopes and sites. It is recognized that some programs will be carried out in classical observing modes. However, in order to exploit the best conditions scientifically, be they of seeing, atmospheric emissivity, or conditions suitable for adaptive optics, it will be necessary to allocate a significant fraction of telescope time as queue scheduled observing during the operations phase. To realize effective and reliable queue scheduling,

(1) The time accounting schemes for queue and classical observing modes will have to be different, with time for queue observing based on hours actually used, and time for classical observing based on the total allocated hours,

(2) Observing time will have to be allocated internationally, involving both telescopes, to allow the operations team maximum flexibility in optimizing the scientific return to the Gemini Partnership.

Versatility

To achieve maximum scientific productivity under changing sky conditions, the Gemini telescopes will require capabilities to change between different instruments during the night. These capabilities can also result in lower operational costs through a reduced demand for installing and removing instruments from the telescope. The required capabilities are:

- **Change between instruments.** The telescope design should permit the simultaneous mounting of at least 2 instruments. It should be possible to have a rapid change (less than a minute) between a narrow-field imager and the instrument in use at the Cassegrain via the insertion or removal of a flat mirror. It is a requirement that it should be possible to change between mounted instruments in less than 20 minutes, with 5 minutes as a goal.

Telescope Configurations and Parameters

Here we begin the development of the telescope configurations and parameters needed to achieve the scientific goals of the project. At this point a variety of practical considerations, such as issues of design and optical fabrication and of detector size and format, to say nothing of cost and risk, enter into the planning. In these paragraphs we outline the critical parameters and issues; the national proposals and technical reports may be consulted for more details. We conclude that two configurations will be needed.

Let us consider the main project features that affect the telescope configurations. The scientific benefits of 8-m diameter primary mirrors were described previously. Remaining parameters of the primary mirrors, such as focal ratio, and mirror quality, are critical to achieving the high image quality of the telescope. The central mirror bore size affects the concentration of light in the image core (through diffraction and the accuracy of wavefront distortion measurements for adaptive optics) and the effective collecting area of the system, all of which point in the direction of a smaller bore. However, the requirement for a wide field of view pushes toward a larger bore.

Achieving image quality of 0.1 arcsec, or better, in the near IR at a Cassegrain focus has many implications for the telescope design. Because re-imaging will be necessary for proper sampling with infrared instruments and for background control, considerations of camera optical design, detector format, and detector size influence the telescope parameters. An additional factor is the use of the secondary mirror for wavefront-tilt correction. To achieve the high-performance, diffraction-limited imaging planned for the infrared, a focal ratio of f/1.8 for the primary and about f/16 for the secondary is indicated. A primary focal ratio faster than f/1.6 does not produce the needed image quality at the extremes of wavefront-tilt correction; a secondary much slower than f/16 makes correction for field curvature in the reimaging optics more difficult and leads to reduced sensitivity. Also, as mentioned above, the central obscuration of the system must be kept small because of diffraction effects and of the needs of adaptive optics. Finally, the field of view will be limited because of atmospheric distortions; considerations of detector formats and articulation requirements lead to an unvignetted diameter of 3.5 arcmin.

The low emissivity configuration will require a secondary mirror slightly undersized for the primary mirror. The secondary must be articulated for wavefront-tilt correction so that it can be chopped between two positions on the sky for cancellation of the sky and telescope background signal in the thermal infrared. These articulation requirements drive the secondary toward a smaller size and slower (larger) focal ratio, opposite to the image quality requirement and at the expense of system sensitivity. However, studies to date indicate that f/16 is an acceptable value. The low emissivity requirement also leads to :

1) A secondary with a central hole;

2) The need for low emissivity coatings on the primary and secondary mirrors;

3) A design of the telescope structure with a minimum area of obstructing structural members and components in the beam; and

4) A means of keeping the mirror surfaces free of dust and other contaminants during operations.

Note that the requirements for low emissivity and high angular resolution can be met by a single configuration of the telescope.

For optical spectroscopic problems involving a high surface density of faint objects or continuous angular coverage along a conventional slit, direct beam feeding of the spectrograph has significant advantages. In that case, a field of view of 6 to 10 arcminutes is required. High image quality is desired in this case, to minimize the background contribution to the light from stellar sources or centrally concentrated galaxies, and to achieve high angular resolution for spatially continuous coverage of extended objects such as galaxies or jets from proto-stellar objects. The requirement is therefore to deliver seeing-limited images over the field. Since wind shake and vibrations of the mount may limit the quality of the images without an articulated optical element, some moderate to small size optic in the train must have tip-tilt capability. If the secondary itself cannot be articulated, an active tertiary is implied; in a conventional configuration that would be a diagonal flat, which would make spectropolarimetry more difficult. The f/16 configuration discussed above for high image quality would be suitable for the beam-fed optical spectrograph, because the small secondary is itself articulated for rapid guiding. The undersized f/16 secondary could be used with a modest vignetting penalty, but substantial UV throughput losses for $\lambda < 380$ nm would be produced by silver coatings. A dedicated optical secondary would be required for highest UV response.

Versatility in addressing the high stability focal station with the narrow-field secondary in place could be achieved by optical fibers with micro lens coupling, or with a more complex system of remotely insertable mirrors and lenses.

The wide-field requirement demands a separate secondary mirror and has significant impact on the telescope design. Two factors motivate the configuration:

1) Multiple object spectroscopy over a large field is best accomplished by coupling the spectrograph to the telescope focus with optical fibers. The best bare fiber performance is achieved by minimizing the losses through mismatch of the light cone while achieving complete ray scrambling for uniform illumination of the output face. The optimum corrected focal ratio for that purpose is f/6.

2) Accurate sky cancellation can be achieved with fibers, so that the telescopes can perform sky-limited spectroscopy of faint stars and galaxies over a wide field of view. The design requirement is then to achieve seeing-limited image quality over the largest possible field, so that sub-arcsecond fibers can be used to minimize the sky background contribution to faint object signals. With conservative corrector design, the achievable field of view is 45 arcminutes. For spectroscopic problems involving a high surface density of faint objects or continuous angular coverage along a conventional slit, direct beam feeding of the spectrograph has significant advantages. In that case, a smaller field of view of 6 to 12 arcminutes is required; a

set of correctors and atmospheric dispersion compensation prisms optimized for narrower wavelength ranges can achieve higher quality imaging and would be used in place of the wide field correction optics.

A main implication of the requirement for broad wavelength coverage and high throughput is that the project will need the capability to put on and maintain a variety of coatings on the telescope optics. No single coating is currently available with high reflectance and low emissivity over the wavelength range 0.30 to 30μm. For operational reasons, the secondary mirrors will have different coatings. One f/16 secondary will be optimized for high throughput in the visible and infrared and for low emissivity in the infrared. At least one secondary mirror will be optimized for high reflectivity in the ultraviolet. The f/6 secondary will have high reflectivity in the ultraviolet and optical.

The requirement for versatility affects the telescope design and operations through the need to change between telescope configurations at night. Practical considerations limit this requirement to the f/16 focal stations. This will require mechanisms to insert and remove auxiliary optics and baffles. In addition, the high-angular resolution (IR optimized) and any dedicated optical f/16 secondaries should have nearly the same location so that they can be mounted on the same top end hardware.

Summary

The science requirements lead to two main configurations of the telescope, each with its own secondary mirror:

1) High-angular resolution Cassegrain, including fibre or direct feed to the High Stability Laboratory

2) Wide field

The high-angular resolution Cassegrain configuration is to be optimized for infrared performance. It will also have outstanding optical performance over at least a 10 arcmin field and at wavelengths down at least as short as 0.4 microns.

The wide-field configuration is to be optimized for optical and ultraviolet wavelengths.

The main properties of the configurations are summarized in the following table.

Configurations
8.0-m, f/1.8 primary

Parameter	High Angular Resolution	High Stability Laboratory	Wide field
Focal ratio	16	Mirror relay f/16 feed and fiber feed from f/16 Cassegrain focus	6
Primary Field of view (arcmin)	3.5 (Infrared) 7 (Optical)	1 (Mirror) 7 (Fiber)	45
Usable field of view (arcmin)	>10	>1 (Mirror) 7 (Fiber)	45
Primary spectral range (μm)	0.30 - 30	0.30 - 2.5 (Mirror) 0.40 - 1.6 (Fiber feed)	0.3 - 1.0
Usable spectral range (μm)	0.30 - 1000	0.3 - 2.5 (Direct) 0.35 - 2.5 (Fiber feed)	0.3 - 2.5
Image quality at center of FOV, without ADC's or correctors (50% e.e., arcsec)	0.1 at 2.2μm Goals: 0.13 at 0.31μm 0.12 at 0.55μm 0.33 at 10.0μm	TBD (Direct) (Fiber feed goals) 0.13 at 0.31μm 0.12 at 0.55μm	0.25 (FWHM) at 0.55μm
Location of focal surface (meters behind primary mirror vertex)	4	In Telescope Pier	~ 3.5

The configurations and related topics such as adaptive optics are described in more detail in subsequent sections. The image quality specification is also described in detail in § V.

IV. INSTRUMENTS

The function of the telescope optics and system is to collect the incoming radiation from astronomical sources while preserving the spectral and spatial information according to the science requirements and to provide it in a form that can be used efficiently by the instruments. The instruments, with their associated optics, deliver the radiation to the detectors from which the final signal is obtained. The instruments for Gemini fall in two broad categories, imagers and spectrographs. Imagers emphasize spatial information over spectral information in astronomical sources; spectrographs have the opposite emphasis. The two-dimensional format of modern detectors often enables instruments to be developed that provide both imaging and spectrographic capabilities simultaneously.

The combination of technology of mirror coatings, detectors, optical materials and atmospheric windows leads to the separation of instruments by wavelength into four broad categories: Ultraviolet (UV), 0.3 to 0.38 microns; Optical, 0.38 to 1 micron; Near Infrared, 1 to 5 microns; and Mid-Infrared, 8 to 30 microns. The boundaries among the categories are approximate, and instruments in practice may operate over more than one wavelength region.

Instrument planning for Gemini to date has taken into consideration the key science programmes, the properties of the telescopes described in the previous section, the current state of instrumentation and detectors, and projections for future developments, especially in the areas of adaptive optics and detectors.

Common requirements for all instruments provided by the Gemini project are;

1) The instruments must fully exploit the 8-m aperture and excellent image quality of the Gemini telescopes.

2) They must be easy to use "facility class" instruments enabling a high degree of productivity from observers.

3) The instruments must be stable throughout at least a one hour integration. Slit losses, flexure and misalignments may contribute to no more than 0.1 pixel shift throughout this integration period for zenith angles up to 60 degrees.

4) Facility instruments should be reliable and easy to maintain since the requirement of the project is to keep the scheduled telescope time lost to both telescope and instrument failure to below 2% of the scheduled time; a goal being 1%.

The following tables provide an illustrative description of individual instruments and their performance requirements. The instruments described emerged from discussions with the astronomical communities in the partner countries and represent the range of capabilities that are currently expected from the Gemini telescopes. The performance requirements are only indicative at this stage and are subject to modification as the instrument definition process continues. The goal of the project should be to provide these instruments for both telescopes as part of the Gemini facilities.

Further definition of the initial instrument complement for the Gemini telescopes, together with revised performance requirements as recommended by the Gemini Science Committee and approved by the Gemini Board, are included in Appendix I of this document.

Gemini Instruments

Instrument	Wavelength (microns)	Spectroscopic Resolution	Pixel Scale Slit Width Array Size	Throughput (includes detector)	Field of View	Other Characteristics
f/16 Optical Imager	0.4-1		• 0.1 arcsec / pixel • 4096 X 4096 with 15 micron pixels	> 50%	7 arcmin	• Incorporates focal reducer • Broad and narrow band filters • 3.5' unvignetted FOV • AO mode 0.024"/pixel and 100 arcsec field
f/16 Infrared Imager	1-5		• 0.03 arcsecond / pixel at 2.2 microns • 1024 X 1024 with 25 micron pixels	> 45% at 2 microns	30 arcsec at 2.2 microns	• Standard broad band filters • Complement of about 20 narrow band (1%) filters • Provision for grisms • Provision for polarimetry capability (1% linear)
f/16 Infrared Spectrometer	1-5	Few hundred to 20,000	• 0.1-0.5 arcsecond slit width • 1024 X 1024 array with 25 micron pixels	> 30%	Up to 2 arcmin slit length	• Provision for grisms • Provision for polarimetry capability (1% linear)
f/16 High Resolution Optical Spectrograph (HROS)	0.3-1.0	Moderate to 125,000	• 0.25-1 arcsecond slit width • 4096 X 4096 array with 15 micron pixels	Req: > 10% at max of grating blaze and detector QE	Req: 0.5 arcmin Goal: 1.0 arcmin	• 2000 spectral resolution elements/order sampled with > 2 pixels/resolution element and 0.1 arcsec pixels in the spatial direction • Complete free spectral range coverage in cross-dispersed mode • Minimum 5" inter-order spacing • Highest spectral or spatial resolution may be achieved with 0.25" slit • Retain capability for dispersion by cross-disperser only
f/6 Optical Imager	0.4-1		• 0.064 arcseconds / pixel • 4096 X 4096 array with 15 micron pixels	> 50%	4.4 arcmin	• Direct imaging • Broad and narrow band filters

Instrument	Wavelength (microns)	Spectroscopic Resolution	Pixel Scale Slit Width Array Size	Throughput (includes detector)	Field of View	Other Characteristics
f/16 Sub Arcsecond Imaging Spectrograph (SIS)	Req: 0.4-1.0 Goal: 1-2 microns	200-5,000 [i.e. Maximum permitted with grisms]	• 0.1 arcseconds / pixel • 0.2-1 arcsecond slit width • 4096x4096 array with 15 microns/pixel • 0.05 arcsec/pixel • 0.1 arcsec slit width	>25% at R $\leq$ 1,000 for 4000-7000 A, without slit losses >1/2 of maximum value at 4000-7000 A, when using low dispersion for the two adjacent ranges of 3600-4000 and 7000-9000 A at comparable resolutions, and for R=5000 in the range 4000-7000A.	Req: 6 arcmin Goal: 10 arcmin	• 0.1"/pixel, assuming 0.21 delivered to focus by tip/tilt • Simultaneous coverage 3600-9000 A at R=2000 • Throughput is highest priority • Tradeoff study to evaluate dual-beam or cross-dispersed configuration to meet simultaneous wavelength goal vs. simpler layout with costs and exposure time efficiency. • Capacity to produce multi-aperture masks for the instrument with a slit location accuracy of at least 0.05" • Possible imaging mode • Capability for second near-IR arm optimized for use with adaptive optics. The spectrographs are being specified for use with adaptive optics and will have slit widths for this mode.
f/6 Wide Field Faint Object Spectrograph (WiFOS)	Req: 0.4-1.0 Goal: 0.4-2	200-5,000	• 0.5-1 arcsecond slit width • 4096 X 4096 array with 15 micron pixels	> 25% for 4000-8000 A Peak throughput 45% for 6000-7000 A	Req: 12 arcmin Goal: 15 arcmin	• Capability for imaging mode
f/16 8-30 Micron Imager	8-30		• 0.1 arcsec/pixel at 8 microns • 0.4 arcsec/pixel at 30 microns • 256 X 256 array with 25 micron pixels	Req: > 20% at 8 microns Goal: >40% at 8 microns	25 " at 8 microns 100" at 30 microns	• Diffraction limited performance • Broad band filters • About 10 narrow band filters (NeII, SIV, SiC, Silicate) • Provision for spectroscopic mode
f/16 8-30 Micron Spectrometer	8-30	Goal: 1,000-60,000 Req: 10,000-60,000	• 0.15 arcsec/pixel @ 10 microns • 0.3 arcsec slit @ 10 microns • 256 X 256 array with 25 micron pixels	Req: > 10% @ 10 microns Goal: > 20% @ 10 microns	Req: 0.5 arcmin	• Provision for polarimetry

Instrument	Wavelength (microns)	Spectroscopic Resolution	Pixel Scale Slit Width Array Size	Throughput (includes detector)	Field of View	Other Characteristics
f/6 Multiple Object Spectrograph (fiber fed MOS)	Req:0.4-1.0 Goal:0.3-1.5	Req: 500-30,000 Goal: up to 120,000 with some throughput loss	• 2,000 resolution elements/exposure with 2 pixels/resolution element for each fiber • 12 pixel interfiber spacing • 3 pixels / fiber spatial profile	> 10% at low spectral resolution at maximum detector QE	Req: 40 arcminutes Goal: 45 arcminutes	• Fiber positioning accuracy no worse than 0.1" for zenith angles < 60º • Minimum of 400 fibers in each mode • Range of fiber diameters • Reset time < 30 minutes to position 400 fibers • Requirement for viewing capability at the focal surface • Spectrograph mounted in gravity-stable configuration • Optimized channels for red and blue wavelengths Revised 10/21/92 inst_tbl.sam

V. IMAGE QUALITY SPECIFICATIONS

Once 8-m mirror blanks are successfully fabricated, achievement of the image quality goal is perhaps the greatest technical challenge facing the project. Therefore, the specification must be set carefully and in detail.

Three factors to consider as background for the specification are:

1) The median seeing at optical wavelengths at the Mauna Kea site is ~0.4 arcsec FWHM.

2) At optical wavelengths where the Gemini telescopes will be seeing limited, the goal is that the telescopes not degrade the best seeing profile by more than 15%.

3) At infrared wavelengths the atmospheric distortions decline, and, at sufficiently long wavelengths, diffraction effects set the ultimate limit on image quality. Recent advances in polishing and testing techniques, combined with the advent of active and adaptive optics techniques, are what make it possible to specify near-diffraction-limited imaging at 2.2μm with the Gemini telescopes. It is also now possible to establish a quantitative relation between the results of different optical testing techniques and the final image delivered by the telescopes.

The top-level image quality specification will be encircled energy as a function of diameter for a point source, because there is a direct relation between the scientific capabilities of the telescopes and the image profile. With modern optical programs, it is straightforward to transform between various properties of the individual optical surfaces and the final image profile of the telescope system.

The image quality specification must take into account the requirements of the different scientific programs. For example, in spectroscopic programs the amount of light entering the slit or optical fiber is the critical parameter; this can be characterized by the image diameter at 85% encircled energy. In the thermal IR, where the dominant background comes from the sky and telescope, a slit width corresponding to 50% encircled energy is often preferred. For high resolution imaging programs, the amount of light concentrated in the core of the image is crucial. For programs where observation or detection of faint sources adjacent to bright ones is the goal, minimizing the light in the wings of the image is essential. Finally, the needs of adaptive optics corrections must be taken into account.

The plan is that the final image quality specification will be in the form of a table of encircled energy that characterizes the intensity and width of the image core and suitably constrains the image wings. The specification will be given for each configuration and at the relevant wavelengths. The specification will be for the final delivered image profile, including diffraction effects, the performance of the telescope structure (tracking and alignment effects) and the enclosure (local seeing effects).

Because the work is not complete as of this writing, we present here some baseline requirements based on considerations of the atmospheric seeing profile and expected performance in the near IR with wavefront tilt correction, and on preliminary design work on the narrow and wide-field optical correctors.

High-angular Resolution Configuration

The intention is to achieve near-diffraction-limited images at infrared wavelengths for a field of view limited by the correlation lengths of atmospheric distortions. At optical wavelengths, the intention is to have the image quality be limited by the external seeing. The requirement for the system performance (including tracking and enclosure effects) with the use of wavefront-tilt correction is:

Encircled energy %	**Diameter arcsec**
50	0.1
85	0.25

Wavelength = 2.2μm

This is for a 1 arcmin field. The dependence on zenith distance is proportional to $(\sec z)^{0.6}$.

Goals for the f/16 focus including diffraction effects, but without correctors are:

Encircled energy	**0.31mm**	**0.55mm**	**10mm**
50% diameter	0."13	0."12	0."33
85% diameter	0."27	0."24	1."00

The 10μm, Optical, and UV specifications for the f/16 focus should be considered desirable goals, recognizing:

(a) That the detailed specification of the UV performance requires a more complete atmospheric model that accounts for UV atmospheric scattering;

(b) The 10μm goal is specified without chopping;

(c) That the infrared image quality requirements are the highest priority requirements. It is not the intent to significantly increase in complexity and cost the Gemini Telescopes by the adoption of these image quality goals for the f/16 focus.

Wide-field Configuration

The national proposals discussed the image performance goals at length, particularly for the wide-field optical case. The outcome, which also included optical design considerations, was that the wide-field optical system should have 0.25 arcsec (FWHM) image quality.

The 0.25 arcsec imaging is to be achieved over a 45 arcmin field within 20° of the zenith. Away from the zenith, the system performance may follow the effects of atmospheric seeing, which are proportional to $(\sec z)^{0.6}$. The image quality should be maintained for exposures up to one hour in duration.

The atmospheric seeing profile corresponding to 0.25 arcsec (FWHM) will be used as a model for the shape of the image profile required to be delivered by the telescope system. The profile is:

Encircled energy %	**Diameter arcsec**
36	0.25
50	0.33
90	0.75
98	1.35

Wavelength = 0.55μm

The seeing profile is calculated from a characterization of the point-spread function provided by R. Racine for Kolmogorov turbulence,

$$\frac{I}{I_o} = \frac{1}{\left[1+\left(\frac{r}{R}\right)^2\right]^{2.7}}$$

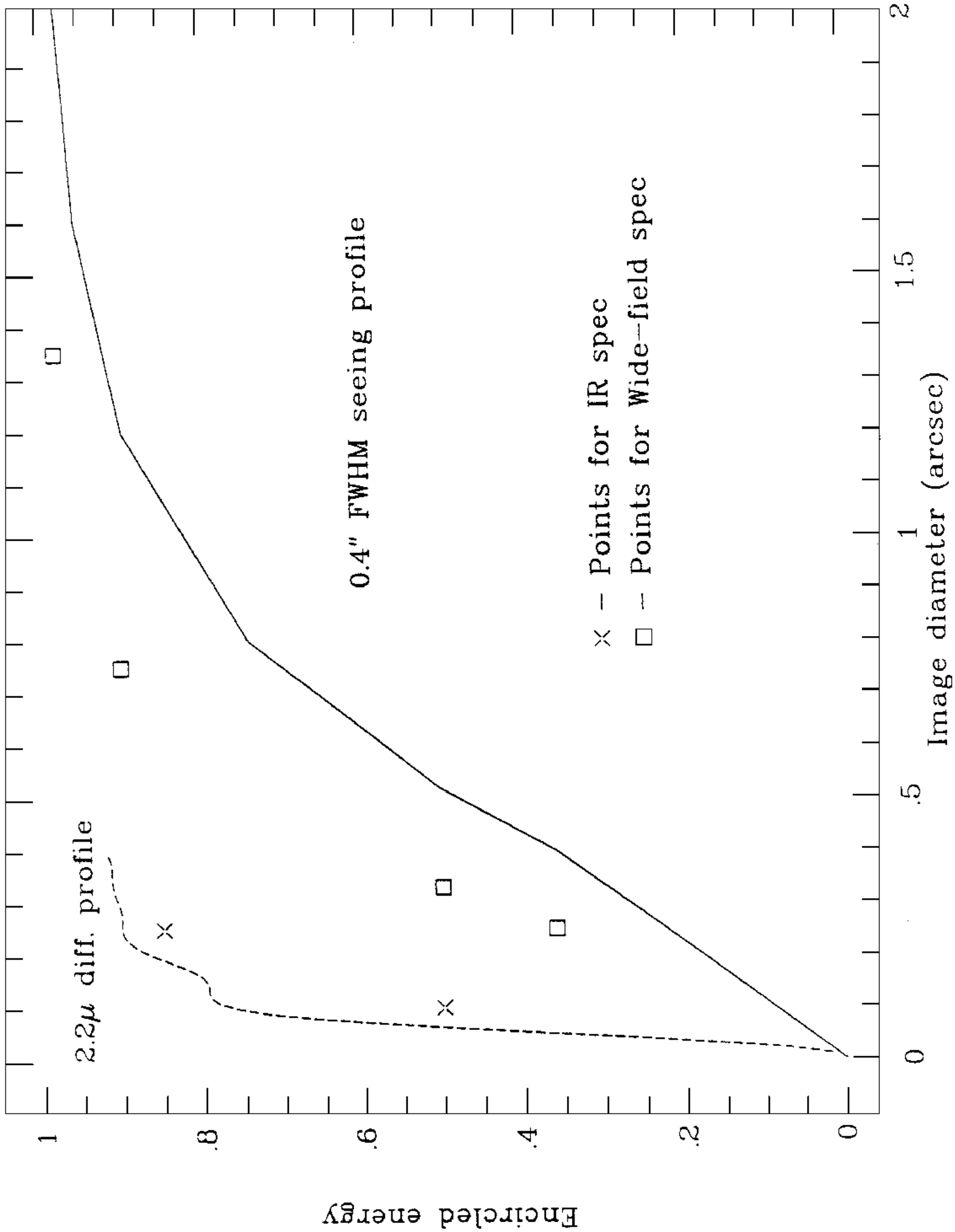
where R is a scaling factor (0.924 FWHM for this profile). This configuration presumes the use of active but not adaptive optics.

For the narrow field configuration described below in §IX, the set of smaller correctors and prisms will be able to produce better image quality, and the goal will be 0.21 arcsec FWHM over its 6 arcmin (10 arcmin goal) field with the same profile shape, zenith dependence, and exposure time requirement.

The ranges for wavelength coverage and the requirements for atmospheric dispersion correctors are discussed in §IX.

Summary

The figure on the following page illustrates the wide-field optical and IR image specification in the context of the median seeing profile on the one hand and the theoretical diffraction profile at 2.2μm for an 8-m telescope with a central obscuration of 0.15 on the other.


0.4" FWHM seeing profile
2.2μ diff. profile
× – Points for IR spec
□ – Points for Wide–field spec
Image diameter (arcsec)
Encircled energy
0
.5
1
1.5
2
0
.2
.4
.6
.8
1

VI. THROUGHPUT REQUIREMENTS

Broadband coverage in wavelength is a major feature of the Gemini telescopes, as described in §II and III. This section contains the requirements and goals for the telescope throughput in the different wavelength ranges.

Optical

At optical wavelengths a main issue on throughput is the achievement of high performance from the ultraviolet to the long wavelength limit of the band for the whole optical system, which will involve reflecting and transmitting elements and is subject to losses at multiple air-glass surfaces. For these purposes, the optical band divides into three wavelength regions. The performance requirements and goals are given in the table below.

Broad-band anti-reflection coating
Loss per surface

	0.33-0.4μm	**0.4-0.7μm**	**0.7-1.1μm**
Requirement	< 5%	< 1%	< 5%
Goal	< 2%	< 0.5%	< 2%

Narrow-band anti-reflection coating

Requirement	1%	1%	1%
Goal	0.2%	0.2%	0.2%

Reflectivity (fresh coatings)

Requirement	0.88	0.88	0.84
Goal	0.92	0.98	0.98

Infrared

For the infrared, the throughput is calculated as the fraction of photons transmitted by the IR configuration compared to that transmitted by an 8.00 m diameter telescope with no obscuration and with perfectly reflecting mirror surfaces.

The throughput of the proposed IR configuration is constrained by the configuration requirements (the secondary mirror is the telescope pupil stop, and a 1.2 m diameter primary mirror central obscuration) together with the 3.5 arcmin diameter unvignetted FOV requirement, and the telescope emissivity requirement, ε, of 4% with a 2% goal.

In this configuration, each point in the unvignetted FOV "sees" a slightly different annular region of the primary mirror with all points "seeing" the same total collecting area. For the on-axis point in the focal plane, the width of the unused skirt at the edge of the primary and central obscuration is about 5.0 cm for the f/1.8 - f/16 system with a focus 4m behind the primary mirror vertex. Thus the effective collecting area is 7.90 m diameter with a 1.30 m central hole.

The combined reflectivity of the primary and secondary mirror surfaces must be more than 1-ε. Indeed, one could estimate the losses other than that due to the pure collecting area effect outlined above, including less than unity reflectivity, scattering, obscuration by secondary supports, etc as being equal to the telescope emissivity. With this assumption, then the throughput of the IR configuration (for wavelengths > 2.2μm) is given by

$$\textit{Throughput} = (1-\varepsilon)\ \frac{7.90^2 - 1.30^2}{8.00^2} = 0.91\ (0.93\ \textit{goal})$$

VII. IR PERFORMANCE REQUIREMENTS

Configuration

1) The IR configuration will be a f/16 Cassegrain focus, nominally located 4m behind the vertex of a f/1.8 primary mirror. The linear central obscuration of the primary mirror, in the IR configuration, will be less than or equal to 1.2m in diameter.

2) The IR configuration will incorporate a secondary mirror with a central hole as a pupil stop, minimizing the non-reflecting surfaces seen by IR instruments either directly or in reflection off the primary and/or secondary mirrors. The secondary mirror will be articulated for chopping and rapid image motion compensation.

3) The IR configuration will contain deployable baffles around the secondary mirror for use at wavelengths shorter than 2μm. The baffles will be remotely deployable during an observing session on a time scale of < 5 minutes.

4) The IR configuration will incorporate

a) "fast guiding" consistent with the imaging performance, including differential refraction. The intent is that this "fast guiding" capability be such that for at least 90% of high galactic latitude lines of sight an adequate guide star will be available within 100" of the center of the science field, and more than 99% of low Galactic latitude lines of sight (LOS), an adequate guide star will be available within the range of the guider.

b) IR acquisition capability adequate to identify the science target and place it on a spectrograph slit with a precision of <= 0.05". The capability may be provided by the instrument and/or facility.

c) The facility will be capable of offsetting over the infrared science field of view, using a guide star, with an error not to exceed 0.05”. For offsets of 5 arcseconds or less, this will take no more than 1 second. For offsets of 60" or less, this will take no more than 5 seconds. Both these offsetting requirements include settling of the telescope and relocking on the guide star.

5) The telescope will be capable of blind offsetting at least 10 arcmin with an accuracy of at least 0.1 arcsec rms under median wind conditions.

Image Quality

1) The IR configuration, including tracking and enclosure effects, will produce images at 2.2µm with 50% of point source energy within 0.1 arcsec diameter and 85% within 0.25 arcsec diameter over a 1.0 arcmin diameter FOV and time intervals of up to 3600 sec with "fast guiding" capability and while pointing near the zenith. The above requirement will be met at the 70% percentile wind speed and image diameters will increase with zenith angle no more than proportional to $[\sec(z)]^{0.6}$.

Telescope emissivity

1) The fully optimized IR configuration will have a telescope emissivity, including scattering and diffraction, of 4% with a goal of 2% immediately after coating or recoating optics, with 0.5% maximum degradation during operations, at any single wavelength beyond 2.2µm.

2) An on-site coating facility capable of the deposition of high quality Silver (Ag), Aluminum (Al) and dielectric surfaces will be provided at both sites.

3) A frequent, regular and efficient primary mirror cleaning program and careful contamination control at the observing facility will be critical to meeting this requirement. (The required cleaning frequency is estimated to be about once/week.)

Secondary Mirror Articulation

1) The IR secondary system will be capable of two axis square wave "chopping" with a focal plane amplitude of up to ±7.5 arcsec image motion at 6 Hz (10 Hz goal) and 80% duty cycle, and up to ± 15 arcsec image motion at 3 Hz (5 Hz goal) with 80% duty cycle. The image quality during the dwell time of the "chopping" cycle will be 50% encircled energy within 0.4 arcsec at 10µm. A chop amplitude of up to +/-7.5 arcsec is a requirement.

2) The secondary system will be capable of two axis tilting for image motion compensation. The intent is to remove the dynamic image motion due to wind buffeting and enclosure vibrations (fast guiding) as well as to reduce the tilt power in the incoming wavefront by at least 90% rendering this component of the "seeing" to negligible levels compared to higher orders. This may require motions in the focal plane of +/-1 arcsec with a 3 dB bandwidth of 8Hz.

3) The IR secondary system will be capable of simultaneous chopping and image motion compensation so that during the chopper dwell time the residual image motion from wind buffeting and dome vibrations as well as the tilt power in the incoming wavefront are consistent with the 10µm image quality requirements.

Field of View (FOV)

1) The secondary mirror will be sized such that the unvignetted FOV of the IR configuration will be 3 arcmin in diameter. This FOV will remain unvignetted at the extremes of the secondary chopping cycle and therefore is 3.5 arcmin in diameter overall.

2) An extended FOV of at least 7 arcmin diameter, with vignetting only by the primary mirror, is required. That is, all points in the 7 arcmin FOV have an unvignetted view of the secondary mirror.

VIII. ADAPTIVE OPTICS

Exploiting the superb seeing conditions on Mauna Kea and Cerro Pachon is the highest priority science requirement for the Gemini Telescopes. At such sites, where the median seeing at 0.55μm is 0.4 arcseconds (<FWHM>), the ratio of telescope diameter to Fried coherence length D/r_0 can be small at IR and near-red wavelengths even for 8-m telescopes. In this context adaptive optics is a key requirement as even a simple implementation can extend the near-diffraction-limited performance of the Gemini Telescopes from the thermal infrared to near-infrared and within a factor of two of diffraction-limit in the visible red.

Terms and Definitions

In this section on adaptive optics the image quality is quantified in terms of two profile (or PSF) independent parameters, the **Strehl width** and **Strehl ratio.** The Strehl width is the diameter of a cylinder, which is the same height as the peak intensity of the delivered image, with a volume equal to that contained in 100% of the delivered point spread function (PSF). The Strehl width has units of arcseconds in the focal plane. The Strehl ratio is the ratio of the central intensity of delivered image to that of the central intensity of a perfect, diffraction-limited image. Note that the discussion uses the Strehl ratio to characterize the initial science requirements.

The atmospheric turbulence degraded wavefront can be described by an expansion in **Zernike polynomials**. Correspondingly, the performance of an adaptive optics system can be described by the number of polynomial terms which are corrected. The Zernike polynomials are described by radial order, or degree, n. For each order n, there are n+1 polynomials, and the number of polynomials up to and including order n is (n+1)(n+2)/2. Image motion compensation (using the secondary mirror for example) is equivalent to a n=1 correction.

In the following table we tabulate the reduction in Strehl width as a function of wavelength and order of adaptive correction for median seeing (0.40 arcseconds FWHM at 0.55μm) and for the 10% best seeing (FWHM = 0.25 arcseconds at 0.55μm).

The reduction in Strehl width for a 8-m telescope as a function of wavelength and order of adaptive correction.				
	median (FWHM = 0.40")		*10% (FWHM = 0.25")*	
$\lambda(\mu m)$	n=1	n=4	n=1	n=4
0.7	1.20	4.5	1.4	6.7
1.2	1.40	6.5	1.7	6.5
1.6	1.60	7.0	2.0	5.0
2.5	2.20	5.5	2.2	3.5
3.5	2.50	3.0	1.8	2.0
5.0	1.70	2.0	1.2	1.3

For an 8-m telescope simple n=1 tip/tilt correction can produce for median seeing near diffraction limited images for $\lambda > 3.5\mu m$. (Strehl widths w_S = 0.11"). However an n=4 adaptive optics system can give diffraction limited performance (w_S = 0.05") in the near infrared and enhance the telescope efficiency by a factor of 4 in the visible. For such low order corrections the field of view corresponding to the isoplanatic patch is reasonable as can be seen in the next Table. Tabulated are a number of characteristics at the optimum corrected wavelength (the one for which most reduction in Strehl width is obtained) as a function of seeing and order of correction.

The expected Strehl width, Strehl ratio and isoplanatic patch as a function of optimum wavelength taken from the above table with order of correction. *Note*: Columns in this table should not be intercompared.				
atmospheric seeing FWHM	*0.40" (median)*		*0.25" (10%)*	
order of adaptive correction	n=1	n=4	n=1	n=4
$\lambda_{optimum}$ (μm)	3.50	1.60	2.50	0.70
expected Strehl width, w_S (“)	0.21	0.07	0.15	0.05
Diff. limited w_S at $\lambda_{optimum}$ (“)	0.11	0.05	0.08	0.02
Strehl ratio	0.30	0.50	0.30	0.20
Isoplanatic ang. Θ_{iso} (arcmin.)	6.20	1.50	6.20	1.50
Θ_{iso}/ 0.5 x w_S (pixels)	3600	2600	4800	3600

$\lambda_{optimum}$ is the wavelength which gives the greatest reduction in Strehl angle for a given order of correction, n. For each of these wavelengths are tabulated the expected Strehl angle, Strehl width, isoplanatic patch and the number of pixels required to cover the diameter of the isoplanatic patch (or angle) Θ_{iso} assuming 2 pixels across the expected Strehl width w_S.

For low order corrections the large improvements in Strehl ratios given above can be achieved over scientifically useful fields (the isoplanatic patch) for visible red to near infrared wavelengths. The isoplanatic patch will fill a 2000 x 2000 - 4000 x 4000 area detector assuming 2 pixels across w_S, the images in all cases having Strehl ratios greater than 0.2. In median conditions for an 8-m mirror with an n=4 system there are approximately 64 sub-pupils 1m across and the isoplanatic patch is 1.5 arcminutes in diameter. With current detectors and wavefront sensors this level of correction could be applied using reference stars within the isoplanatic patch up to a limiting R magnitude R = 16.

Laser Guide Stars

The laser guide stars, or beacons, provide bright artificial reference stars. It is then possible to have correction of higher order, extending the gains in Strehl ratios to shorter wavelengths, even to achieving diffraction limited PSF's in the visible. However, such a system puts stringent demands on reducing the wavefront tilt error which must be accomplished with natural guide stars. The appropriate strategy for laser beacon use is to obtain higher order aberration information from the laser and use a natural guide star for tilt information. A design study for the Keck telescope showed that Strehl ratios of the order of 0.5 could be routinely obtained at 2 μm for 100% of the sky using a single 20W sodium laser. To extend the performance of this technique requires the use of two or more laser beacons which can potentially produce diffraction limited imaging to visible wavelengths for nearly 100% of the available sky.

Currently a simple single laser beacon gives some increase in capability over a simple low order natural guide star system. Significant gains in sky coverage and shorter wavelength improvements can probably be realized with multiple laser beacons, however this is not as yet a mature technology for astronomical telescopes. It is not a requirement that a laser beacon capability be implemented at first light.

Infrared Performance

Current designs of adaptive optics systems beyond simple tip/tilt use multi-element optics, which at thermal infrared wavelengths will increase the system emissivity. However at $\lambda > 3.0\mu m$, simple tip/tilt correction using only the low emissivity IR secondary will produce near-diffraction limited images for the 8-m Gemini Telescopes under median seeing conditions. In the best seeing conditions tip/tilt will give Strehl ratios of the order of 0.3-0.4 at 2.2μm. It is predominantly in the region between 1μm - 2μm where order n=4-5 adaptive optics will give the greatest gains and where a lower system throughput (and consequent increased thermal background) will not detract from the scientific gains from increased imaging capability and decreased spectrograph slit widths.

Initial AO System Requirements and Goals

The implementation of AO capabilities on the Gemini telescopes should be a multi-phase program, with the initial phase providing a Natural Guide star system on the Gemini-North telescope. Later phases of this program include use of Laser Guide stars and implementation of AO capability on Gemini-South. The AO implementation will utilize the f/16 high resolution configuration. In order to facilitate rapid changeover between AO and non-AO use, with minimal impact on the instrumentation, the AO implementation will maintain the location of the science focal plan, apparent location of the telescope pupil, and the f/number of the high resolution configuration.

Other Requirements

1) The tilt performance of the secondary mirror must be adequate to reduce tilt error to a negligible level for tilt-only correction (estimated response bandwidth requirement = 8 Hz), and a goal is to reduce tilt-error to a negligible level for 5th order correction estimated response bandwidth = 25 Hz).

2) The primary and secondary mirrors must have optical quality which allows the tilt-correcting and adaptive optics systems to reach Strehl ratios of 0.5 at 1.6μm and 0.2 at 0.7μm. This particularly requires that the mirrors must be smooth on the spatial scales which cannot be corrected by the primary active optics. A suitable criterion is that the mirror contribution to the wavefront error on all spatial scales must be less than the wavefront error introduced by the atmosphere when the seeing is at the best 10 percentile level. In other words, any 1.0-1.5m diameter area of pupil must be of the optical quality required to produce near diffraction limited performance at 0.7μm for an 8-m aperture, w_{diff} = 0.02 arcsec.

3) An instrument position must be provided below the primary mirror cell and above the instruments for installation of a slide-in or addressable adaptive optics system. A vertical space allowance of 0.4-0.6 meters is recommended.

4) The atmospheric turbulence at Mauna Kea and Cerro Pachon must be characterized in the 0.7 to 2.2μm range to ascertain the necessary bandwidths and angular decorrelation length.

5) Allowance must be made in the Gemini facilities for the future implementation of a laser launch telescope, with approximately 1 meter aperture. The laser will be located elsewhere, and a light path (not a fiber) must be planned to conduct the laser beam to the launch telescope.

IX. WIDE-FIELD CONFIGURATION

To carry out the optical programs described in §II, the Gemini telescopes will need to have a wide field configuration, high throughput at all optical wavelengths accessible from the ground, excellent image quality, and the capability for spectroscopy from low to high resolution. Also needed is rapid access to optical imaging capability, with optical imagers mounted simultaneously with the spectrographs and addressable by insertable or rotatable tertiaries.

General properties of the configuration were given in §III. Here we note that the configuration needs two modes: the wide-field mode, as already described, and a narrow field mode, which will use the same secondary but operate with its own, small-field corrector in place of the wide-field corrector. It is envisioned that this mode will be used for imaging and spectroscopy of objects with higher surface density than would be studied in the wide-field mode. In addition, this mode will produce better optical image quality, and provide direct-beam feeding without fiber coupling, which will enable observations of fainter objects.

Wide field mode

1) Focal ratio: Suggested focal ratio to be f/6.
2) Focal Position: Cassegrain - 3 - 4 m behind vertex of primary mirror.
3) Image Quality Specification: see §V.
4) System throughput: see §VI.
5) Simultaneous wavelength range: Any one octave (factor of two) interval in the range 0.33 - 1.2µm; with ADC prisms removed, comparable performance from 0.9 - 2.2µm.
6) Field of View: 45 arcminutes.
7) The focal surface should have a radius of curvature greater than 10 m; it would be desirable to have the center of curvature coincident with the exit pupil.
8) Polarization: 0.05% goal.
9) Scattered light and sky baffling: TBD

Other comments:

1) Corrector elements to rotate with fiber positioner; ADC independently rotatable.
2) Error signals for guiding and rotation to be generated by scientific instrument; no requirement for guiding field beyond science field.
3) Requirement for rapid addressing of optical imager with 6 arcminute field of view, image quality of 0.25 arcsecond FWHM and profile of §IV; fast guiding (fold mirror) capability and options to include narrow-band filters, such as a Lyot system.

4) No requirement for night-time change-out of wide-field corrector assembly.
5) Mechanical and optical design to minimize primary central bore diameter, consistent with performance requirements. Diameter to be no more than approximately 1.2 m.

Narrow-field mode

1) Focal Ratio: Close to value of uncorrected Cassegrain with wide-field secondary, about f/6.
2) Focal Position: Cassegrain - about 3 -4 m behind vertex of primary mirror need not be exactly par-focal with wide-field instruments.
3) Image Quality Specification: See §V.
4) Simultaneous wavelength range: Any one octave range from 0.30 to 2.2µm, with appropriate set of optics.
5) Field of View: 6 arcminute requirement, $\geq$12 arcminute goal. Wider field with less complete correction of aberrations required for guiding.
6) Throughput: See §VI.
7) Requirement for rapid addressing of optical imager with 6 arcminute field of view; 0.21 arcsecond FWHM image quality; fast guiding and narrow band capabilities as for wide-field.

Other comments:

1) Not acceptable to divert beam to the narrow-field spectrograph with a tertiary.

X. TELESCOPE AND ENCLOSURE PERFORMANCE REQUIREMENTS

To achieve the scientific performance requirements given for the different telescope configurations, the telescope and enclosure will have to meet the following specifications:

Telescope mount

1) Horizon limit for observing: 15°
2) Zenith blind spot: 1° diameter. This value may be relaxed if it compromises the tracking and guiding requirements near the zenith.
3) Absolute pointing accuracy for zenith distances $\leq 60°$
   - Requirement: 3 arcsec rms in service implying 2 arcsec rms from pointing test
   - Goal: 1 arcsec rms in service implying 0.6 arcsec rms from pointing test
4) Tracking requirement:
   - Open loop - Consistent with pointing performance, stability sufficient for acquisition of guide star
   - Closed loop - Requirement: 0.1 arcsec rms in 10 minutes, 0.25 arcsec rms maximum in 1 hour
   - Goal: 0.02 arcsec rms in 10 minutes, 0.05 arcsec rms in 1 hour
   - With image motion compensation correction - Requirement: 0.01 arcsec rms for 3600 seconds
5) Time to move between positions on the sky and be ready for observing:
   - 1 second: Offsets or IR nods up to 5 arcseconds or less on the sky.
   - 5 seconds: Offsets up to 1 arcminute or less on the sky.
   - 30 seconds: Traverse less than 10 degrees and azimuth movements less than 10 degrees.
   - 300 seconds: Between any two allowed positions
6) Offsetting accuracy: (open loop)
   - Requirements: 0.1 arcsec rms over a 10 arcmin field, 0.2 arcsec rms over a 1 degree field
   - Goals: 0.05 arcsec rms over a 10 arcmin field, 0.15 arcsec rms over a 1 degree field
7) Acceptable downtime for maintenance:
   - Primary mirror recoating: Goal - 2 nights
   - Telescope configuration changes - Daytime
8) Acceptable time for instrument changes. No more than 20 minutes if instrument mounted on the Cassegrain focus.
9) Provision for more than one instrument on telescope: At least two instruments mounted simultaneously.

10) Focus stability during night after zero point calibration: Telescope should meet imaging requirements with use of mirror figure and focus sensing device only. Instruments should be mounted with sufficient precision and stiffness that the focus adjustment should not compromise the Gemini imaging requirements.
11) Provision to maintain collimation and tilt of secondary consistent with image requirements.
12) Cleaning of the primary mirror should be a daytime operation and not impact negatively on night-time observing.

Acquisition, guiding, mirror figure sensing

1) Field of view and limiting magnitude for acquisition:
   - Range of motion: >10 arcmin for the narrow field (f/16) Cassegrain
   - configuration
   - 45 arcmin at Cassegrain.
   - Field of view: 1-5 arcmin, limiting magnitude $\geq$ 23.
2) Ability to correct for field rotation at all focal stations.
3) Mirror figure sensor to provide measures of focus, collimation, and mirror figure.
4) Frequency bandwidth for guiding. This should be consistent with removing the dynamic image motion from wind buffeting and enclosure vibrations (fast guiding) to maintain the Gemini image requirements. For the f/16 focus the guide signal bandwidth must be adequate to articulate the IR secondary to reduce the tilt component of the atmospheric power spectral density function in the incoming wavefront by 90% rendering this component of the turbulent wavefront to negligible levels compared to higher order modes for both staring and IR chopping observation modes.
5) Limiting magnitude for guiding. In the f/16 configuration the limiting magnitude should be sufficient to detect and generate signals from a star within 100" of the line of sight for 90% of objects at high galactic latitude and for 99% of objects low galactic latitudes capable of driving the articulated secondary with sufficient precision to meet the Gemini imaging requirements. In the wide-field configuration the guider should be able to detect and correct for wind, telescope and enclosure induced imaging motions over 99% of the available sky to ensure the wide-field imaging requirements are met.
6) IR configuration to allow acquisition viewing in an IR band close to the one used for observations (see §VI).

Enclosure

1) Acceptable limit on image degradation to be consistent with system image specification and the derived error budget for all telescope configurations.

2) Provision for adequate ventilation (to meet above) and shielding of telescope from wind. Also, wind flow properties consistent with above requirement.
3) Clear aperture limits in elevation: Lower limit $\leq$ 15°, Upper limit $\geq$ 92°
4) Tracking requirement: Follow telescope. The background variation in the thermal IR due to repositioning of the enclosure should be undetectable.
5) Slew speed: Follow telescope.
6) Azimuth range: Consistent with efficient use of telescope.
7) Provision of capabilities for instrument handling and telescope servicing.
8) Provision of thermally controlled room or space for instruments.
9) Vibration induced by enclosure motion not to degrade image beyond spec.
10) Provision of wind blind to maintain image spec.

Communications requirements

Communications capability to include video, voice, fax, and data (networks) connectivity.

1) Destinations: Canada, UK, US, Chile
2) Bandwidths: TBD (but at least a T1 link).

Data archiving

The requirements are:

- The encoding of devices and recording of data be sufficient for the future re-creation of the observations from the information recorded with the data.

- Establishment of a permanent record of observations and ancillary data in perpetuity.

- The data as recorded should be suitable for inclusion in an existing data center. Gemini should not be required to establish such a data center.

Support facilities

1) Coating facility: Provide for possibility of aluminum, silver, and dielectric coatings. Location on site.

2) Provision of base, mid-level, and telescope facilities to meet reliability and maintenance needs.

APPENDIX I
INITIAL SCIENTIFIC INSTRUMENT COMPLEMENT

In May 1994, the Gemini Board approved the following initial instrumentation program for the Gemini telescopes.

Mauna Kea	Cerro Pachon
Optical Acquisition Camera	Optical Acquisition Camera
1-5μm Imager	Multi-Object Spectrograph
1-5μm Spectrograph	High Resolution Optical Spectrograph
Multi-Object Spectrograph	Shared Instrumentation with CTIO
8-30μm Imager (May be shared between Gemini North and South)	
CFHT Fiber Feed	

The Gemini Science Committee (GSC) has established the following requirements, options, and goals for each of these instruments.

The 1-5μm imager will be used for commissioning the Mauna Kea telescope, as well as for scientific observations, and will have the following capabilities (GSC Resolution 6.5; Sept 1995):

1-5.5𝕞m wavelength coverage
Array: 1024x1024 InSb array, 27μm pixels
High Throughput
Internal Instrument Background:
- < 1/2 telescope emissivity for wavelength >2.2μm
- < 0.5 e/s/pix at shorter wavelengths

Three Plate Scales:

Pixel Size	Field of View
0.02”	20”
0.05”	50”
0.11”	110”

Filter Requirements: two wheels of 20-30 slots for filters, grisms, and polarizers
Goals:
- Design for 2048 x 2048 arrays
- Grism capability; R~700, 1-2.5μm
- Coronagraphic mode
- Pupil viewing

This instrument will include a near-IR on-instrument wavefront sensor for tip/tilt and fast focus correction (GSC Resolution 8.4; Apr 1996).

The 1-5μm Spectrograph for Mauna Kea will have the following capabilities (GSC Resolution 4.7; Apr 1994):

Wavelength coverage: 0.9-5.5μm
Array: 1024x1024, InSb array, 27μm pixels
High Throughput
Spectral Resolution: R ~ 2,000, R >= 8,000
The lowest dispersion mode must allow each atmospheric window to be covered across the 1024 array, and the intermediate dispersion mode must be provided which allows the observation of key astrophysical lines between the atmospheric OH lines.
Pixel Scale: 0."05 / pixel
Slit Width: 0.”1 to 0.”2
Slit Length: >= 50 arcsec
Polarizing Prism: Yes
The following are considered to be desirable options, which will enhance the multiplex advantage of the spectrograph. With the exception of the first of these, they are not listed in any particular order:

- Integral Field Mode
- Cross Dispersion or Simultaneous Wavelength Coverage, covering J, H, K
- Multi-Slit, with particular emphasis on J, H, K
- Slit Length of 150 arcsec, with a pixel scale of 0.15 arcsec/pixel
- Spectral resolutions of 15,000 - 30,000

This instrument will include a near-IR on-instrument wavefront sensor for tip/tilt and fast focus correction (GSC Resolution 8.4; Apr 1996).

There will be two Multi-Object Spectrographs (MOS): one with red optimized coatings for Gemini-North, the other with blue optimized coatings for Gemini-South. The intent is to have competitive scientific performance at 3727Å at Gemini-South. Their other capabilities will be (GSC Resolution 8.5; May 1996):

Wavelength coverage: 0.4-1.1μm
Arrays: 4096x6144 CCD mosaic
Image scale: 0.08 arcsec/15μm pixel
Minimum slit width: 0.2 arcsec (i.e. 2.5 times spation 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 error no greater than 1 km/s/hr for zenith distances less than 60 degrees at a spectral resolution of 5,000.
Desirable options:

- Wavelength coverage over 0.36 - 1.8μm
- IFU's with finer spatial sampling for wavelengths longer than 0.7μm.

The 8-30μm imager will initially be deployed at Mauna Kea and will be available for use at first light on Cerro Pachon. The highest priority for this instrument is broad band 10 um capability and it must exploit the high performance, high background characteristics for Mid-IR arrays. Its capabilities will be (GSC Resolution 6.5; Apr 1995):

Wavelength Range: 5 to 25 μm
Array: ~256x256 Si:As IBC
High Throughput
Plate Scale: $\leq$ 0.13 arcsec/pixel
Instrument Background: < 1% effective emissivity
Filter Requirements: 20-30 cold filters
Desirable Options:

- Dichroic feed to InSb array for NIR guiding/simultaneous imaging
- Optical design consistent with x2 upgrade in array size

The High Resolution Optical Spectrograph (HROS) will be installed at Cerro Pachon and will include the following capabilities (GSC Resolution 3.8; Oct 1993):

Array: 4096x4096 CCD, 15μm pixels
Throughput is Highest Scientific Priority, particularly in UV

- Requirement: >10% at R=50,000 and 500nm; goal 15%

Resolution: in the range of 30,000 to 80,000, resolution >120,000 is a second priority
Stability:

- Cassegrain - Maximum Motion of 2μm per Hour of Tracking (1/20th of a Resolution Element Per Hour)
- Fiber Fed - Stability of 30 m/s in the High Stability Lab

Slit:

- Width 0.6”@R=50,000, 0.24”@R=120,000
- Length Up to 1’

Sampling: 2.5 Pixels per Resolution Element

The commissioning instrument for the Cerro Pachon telescope will be a 1-5μm imager borrowed from CTIO. This instrument is expected to be the Cryogenic Optical Bench detector (COB), currently in use on the KPNO telescopes. When mounted on the Gemini telescope, the expected capability will be:

Wavelength range: 1-5.5μm
Array:1024x1024 InSb
Pixel size: 0.05"
Internal optical/IR dichroic for acquisition/guiding
Two filter wheels with 40 filter positions
- Broad bandpass imaging
- Narrow bandpass imaging

Long slit grism spectroscopy; resolution ~500 in the J, H, and K bands
Polarimetry

The Optical Acquisition Cameras listed are not scientific instruments, but provide basic acquisition capabilities and are considered to be part of the Acquisition and Guiding unit. The only scientific optical imaging capability available will be that provided in the MOS instruments.

To increase the scientific capability of the Gemini telescopes the following instruments will be available on the Gemini telescopes for shared use.

Royal Observatory Edinburgh's Mid-IR Spectrometer (Michelle)
Based on ~256x256 Si:As IBC Array
Long slit spectroscopy, 8-25μm range
- R~200: 8-13μm window in a single exposure
- R~1000: Optimum detectivity of narrow ionic and molecular emission lines
- R~30,000: Velocity resolved observations of narrow emission lines
- Pixel scale: 0.18"
- Slit width: 0.36"

Diffraction limited imaging
- Pixel scale: 0.10"

Background limited sensitivity under all of the above conditions

NOAO's High Resolution IR Echelle Spectrometer (Phoenix)
1024x512 InSb array
1-5μm
- Resolution: R~100,000 (2 pixel) or 67,000 (3 pixel)
- Pixel scale: 0.09 arcsecond

- Slit width: 0.17 arcsecond (2 pixel) or 0.26 arcsecond (3 pixel)
- Slit length: 14 arcseconds
- Spectral format: Single echelle order displayed, band pass = 1500 km/s

APPENDIX II
ADAPTIVE OPTICS PERFORMANCE REQUIREMENTS

The Mauna Kea telescope will be equipped with a natural guide star adaptive optics (AO) capability as part of the initial facility (GSC Resolution 8.3; May 1996).

A convincing scientific case has been made for a Natural Guide Star Adaptive Optics system with strehl ratios in the range of 0.2-0.6 in the 1.0-2.5μm range. The system performance requirements are:

- **Wavelength Coverage:** 1-2.5μm with manually changeable dichroic allowing observations to 0.85μm
- **Throughput and Emissivity:** The deployment of the Adaptive Optics system will not lower the telescope throughput by >25% over the operating wavelength range.
- The **total emissivity** of the telescope and Adaptive Optics system (without ADC) in K must be < 19%.
- **Strehl Ratio.** A minimum on-axis strehl ratio delivered to the detector of the near-infrared imager of 0.4 in H during median seeing conditions for bright guide stars. The on-axis strehl must be met during any one hour exposure within 45 deg of zenith when atmospheric conditions remain constant.
- **Field of View:** 2 arcmin diameter unvignetted field of view. Conjugation of the Deformable Mirror to a fixed optimal altitude.
- **Sky Coverage:** The intent is that sky coverage be maximized for the specified strehl ratios. A goal is that the natural guide star AO system should be designed such that it can be upgraded to a laser guide star system and a flexible control architecture, with the priority to increase the system's sky coverage at the above performance levels.