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1 Technical Section

1.1 Science Goals

1.1.1 Introduction

NIRMOS will be the most powerful tool available to address several of the high priority scientific objectives described in the GMT Science Case and the GMT Science Requirements, and is therefore a strong candidate for a first-light GMT instrument. The Science Requirements document lays out target specifications for a near-infrared, multiple-object spectrograph that are met by the NIRMOS design. We briefly review three GMT scientific objectives below, and give examples of the current state of the art with 8 meter class telescopes.

1.1.2 Detection and Characterization of the First Galaxies

Determining the formation epoch of the earliest galaxies and the time-scale of their formation is one of the key goals of the GMT and other ELT science cases, and learning about this epoch after first light has a visceral appeal among astrophysicists and the general public. Characterizing the population of the earliest galaxies will push ELTs to their limits, and will require pushing these studies to the near infrared. Ly α, the strongest feature used to detect these star forming galaxies and to estimate star formation rates, falls into the spectral range of NIRMOS for $z > 6.5$. With the tremendous collecting area of GMT coupled with the high sensitivity and wide field of NIRMOS, GMT observers will have the opportunity to break open this field of research. Figure 1 shows the current state of the art in this field; tentative detections of Ly α at z=8-10 require long integrations with 8 meter class telescopes.

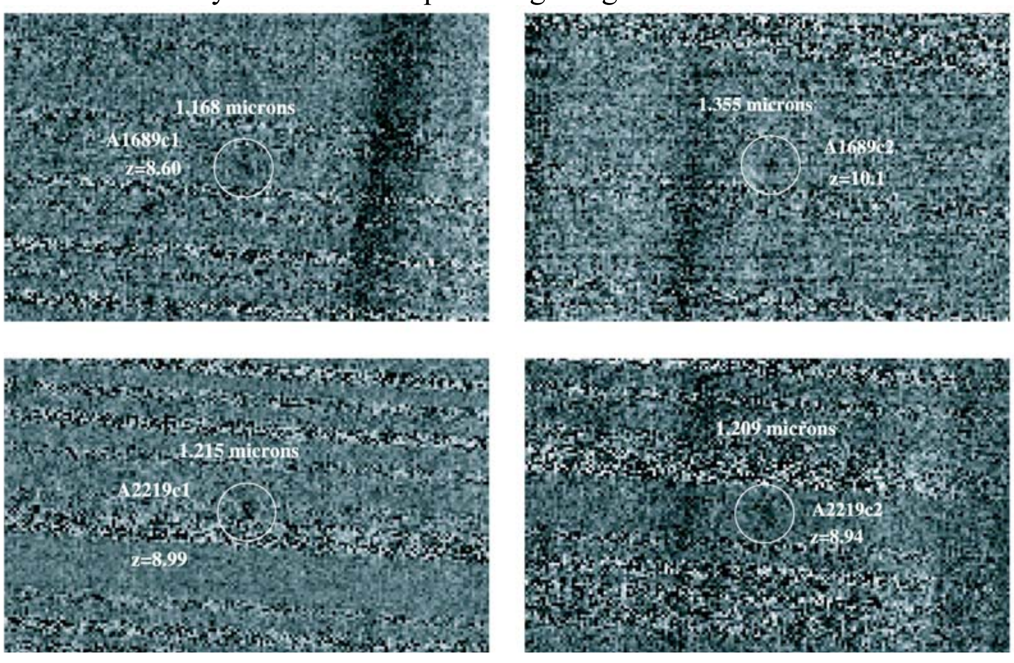

Figure 1. Current state of the art IR spectra of Ly α emission from high-z galaxies (Stark, D. et al. 2007, ApJ, 663, 10). These tentative detections required ~10 hrs of integration on Keck. The authors state: "At the faint limits now being probed, we have found the reliable identification and verification of distant Ly α emitters to be a very challenging endeavor, even with the most powerful facilities available to us."

1.1.3 Assembly and Mass Evolution of Galaxies

Hubble images of galaxies at z~2 show that many have complex morphologies compared with the most luminous present-day galaxies. These morphologies suggest that star formation at this epoch is driven by mergers and major episodes of accretion. In addition to these star forming galaxies, we also observe galaxies with old stellar populations. These old and luminous galaxies at z~2 are quite compact compared with galaxies of comparable stellar mass in the present-day Universe, suggesting that massive galaxies have expanded in size by a factor of five over the past 10 Gyr. A true understanding of the assembly and mass evolution of galaxies requires deep infrared spectroscopy to understand the dynamics of the merging clumps and to measure masses of the galaxy components. Figure 2 is a heroic 29 hr infrared spectrum obtained with GNIRS on Gemini of a luminous, compact galaxy at z~2.2. As expected, this compact galaxy has a very high velocity dispersion. The noisy character of this spectrum and the long integration time leaves no doubt that ELTs will be required to make significant progress in this area. GMT with NIRMOS will have the required sensitivity.

In addition to measuring velocity dispersions, NIRMOS will be an important tool for gathering large numbers of redshifts for low-mass galaxies to characterize the galaxy population at z~2 and for measuring star formation rates directly from Hα.

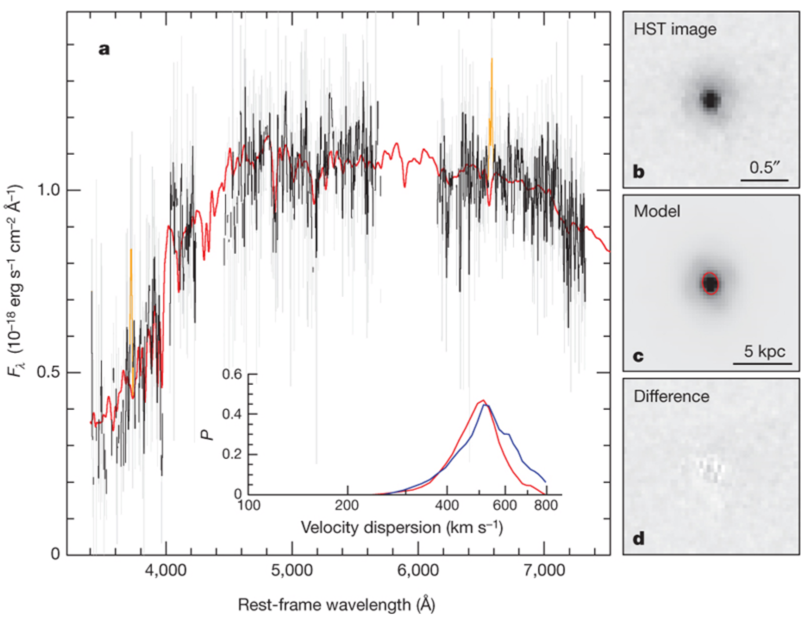

Figure 2. An infrared spectrum of a massive compact galaxy at redshift z=2.186 (corresponding to a look-back time of 10.7 Gyr) shifted to rest wavelengths. The measured velocity dispersion is 510 (+165, -95) km s^{-1}. This very massive and very compact galaxy has a velocity dispersion much higher than present-day galaxies of the same mass. This spectrum required a 29 hr integration with GNIRS on Gemini South! From van Dokkum, Kriek, and Franx 2009, Nature, 460, 717.

1.1.4 Chemical Evolution of Galaxies

The star formation history of galaxies is revealed in their chemical enrichment. Measurements of elemental abundances allow us to study the physical processes that drive stellar evolution and the physics of supernovae. In the infrared, we can observe the same rest frame optical lines from gas in high redshift galaxies that we use to study the chemical abundances in nearby galaxies. The evolution of the mass-metallicity relation is one key tool for these studies.

Figure 3 shows the current state of the art in such studies using NIRSPEC on Keck. The initial mass-metallicity relationship at z~2.2 is similar in shape to the present-day relation, but is shifted a factor of two lower in mean metallicity, albeit with substantial uncertainties.

Erb et al. conclude “Much remains to be done in order to improve on the substantial uncertainties inherent in the present work. Independent measurements of the gas masses of galaxies at high redshift, although very difficult, are essential to determine whether our derived gas fractions and effective yields are valid. Additional metallicity measurements, based on other indicators that use a wider set of emission lines, are needed to confirm the trend with stellar mass revealed by the N2 index, to provide a better understanding of the physical conditions in the H ii regions, and to establish a secure absolute calibration of the metallicity scale. Further investigation of the question of differential metal loss from outflows at high redshift requires observations of fainter galaxies with smaller potential wells, to expand the dynamic range in baryonic mass. We anticipate that all of these measurements will greatly increase our understanding of the interplay between stars and gas, within and outside of galaxies, at high redshift”. GMT with NIRMOS will be a powerful tool for these studies.

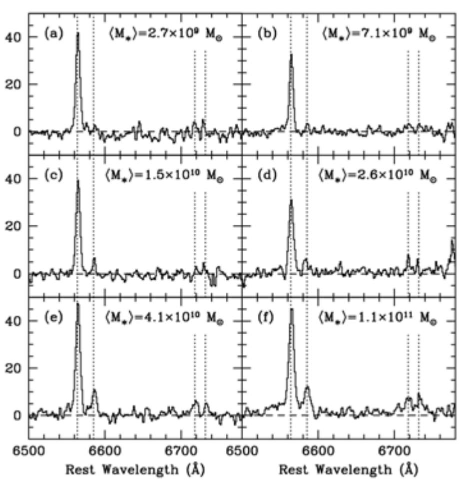

Figure 3. Infrared spectra of star forming galaxies at z~2.3 shifted to the rest frame from Erb et al. 2006, ApJ, 644, 813. These spectra, here binned by stellar mass, contain Hα and [NII] lines that can be used to study the mass-metallicity relation at high redshifts. Erb et al. find a monotonic increase of metallicity with abundance at z~2.3 similar to that observed for low redshift samples, but an overall lower metallicity.

1.2 Instrument Concept

1.2.1 Design Specifications

The GMT Science Requirements list specifications and goals for GMT’s NIR multiple object spectrograph; these are summarized in Table 1. The NIRMOS design meets or exceeds the specifications and comes close to meeting all of the performance goals.

Table 1. Specifications from the GMT Science Requirements compared to the present design

Parameter	Specification	Goal	This Design
Field Area (sq arcmin)	25	>50	34 spectroscopy 46 imaging
Wavelength Coverage (μm)	1.0-2.5	0.9-2.5	0.9-2.5
Spectral Resolution	3000 with 0.5″ wide slit	5000-10000	~3000 with 0.5″ slit (~7500 with 0.2″ slit).
Image Quality		0.15″ 80% EE diameter	0.14″ worst case 80% EE dia.
Throughput	20%	>25% peak	~60% imaging ~50% spectroscopy

1.2.2 Optical Design

The collimator focal length is 2.2 m, producing a collimated beam diameter of 270 mm. The camera has a focal length of 640 mm, with a final focal ratio of f/2.5. Each 15 μm detector pixel subtends 0.05". The detector array is a mosaic of 3x2 Hawaii4-RG HgCdTe devices that are three-edge buttable.

The optical design, shown in Figure 4, uses three optical materials: CaF_2, IR fused quartz, and S-TIM28, an Ohara glass. We contracted with a group at GSFC, who measured the cryogenic refractive indices of S-TIM28.

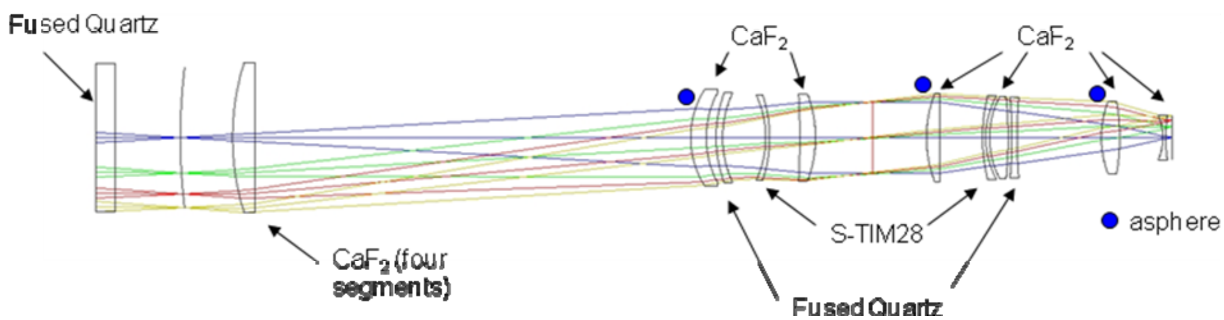

Figure 4. The NIRMOS optical design.

Two large optical elements are required: the entrance window and the field lens. The entrance window is made from IR grade fused quartz, which transmits well to 2.5 μm. The biggest issue with a large fused quartz window is cooling of the window producing a potential for condensation, and we will need to study this issue during the next design phase. The field lens would ideally be made from a single large CaF_2 crystal, but since the closing of the Saint Gobain facility in Ohio, no vendor has large enough equipment to grow the necessary crystal. In order to avoid a costly development effort, we have elected to make a segmented field lens from four smaller CaF_2 pieces. The consequence of using the segmented lens is a small loss of field of view. The alignment and fabrication of the segmented lens are simplified by using a plano-convex field lens.

1.2.2.1 Image Quality

The optical performance of the current design is excellent, even when the demands of GLAO are considered. In imaging mode, the 80% encircled energy diameters, averaged over field angle, are 0.076″, 0.056″, 0.068″, and 0.083″ for the Y, J, H, and K bands, respectively. In spectroscopy mode, the 80% encircled energy (EE) diameters, averaged over field angle and wavelength, are 0.063″, 0.074″, and 0.088″ for the J, H, and K bands, respectively. The worst imaging 80% EE diameter is 0.11" at full field in the K band. The worst spectroscopy 80% EE diameter is 0.132" at full field at 2.45 µm (see Figure 5).

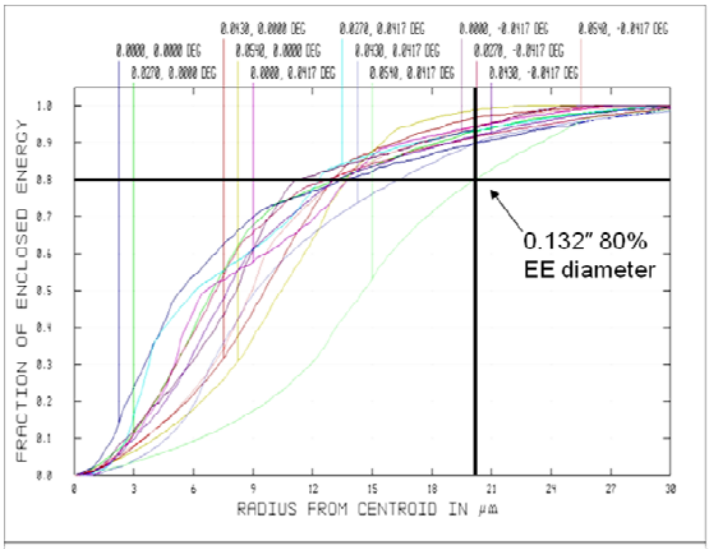

Figure 5. Worst case spectroscopy-mode encircled energy profiles are shown. The worst 80% encircled energy diameter is 0.132" at 2.45 µm at full field.

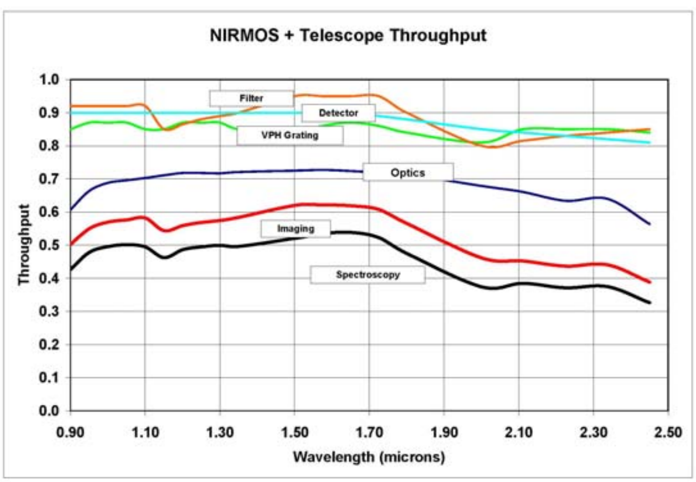

Figure 6. Calculated NIRMOS throughput. The imaging throughput peaks at ~60%, while the spectroscopic throughput peaks above 50%.

1.2.2.1 Throughput

Figure 6 shows the estimated throughput of NIRMOS for imaging and spectroscopy modes. This throughput substantially exceeds the goals in the Science Requirements.

1.2.3 Instrument Layout

We have refined the mechanical layout of NIRMOS (see Figure 7) since the GMT CoDR with a view towards simplifying the required cryogenic mechanisms. We have replaced disperser and filter cassette mechanisms with disperser and filter wheels, retaining slit cassettes if we elect to use exchangeable slit masks in place of a slit robot.

Another mechanical priority has been to reduce the distance between the pupil (cold stop) and the nearest collimator and camera lenses to minimize the size of the largest CaF_2 optics. The breakthrough in reaching this goal came from abandoning the large and thick prisms required to produce a straight beam path in the spectroscopic mode. Eliminating these prisms provides a very large cost savings, and it is not even clear that these prisms could be obtained at any cost. The complication of abandoning the straight beam path is the new requirement for an articulated camera that is pivoted about the center of the disperser. The dispersers will be mounted at a fixed angle in the disperser wheel.

We have elected to retain a gate valve between the slit mask mechanism and the field lens to allow access to this mechanism and the guiders and wave front sensors mounted near the focal surface. This gate valve must be carefully shielded to avoid scattered thermal emission from the warm gate valve.

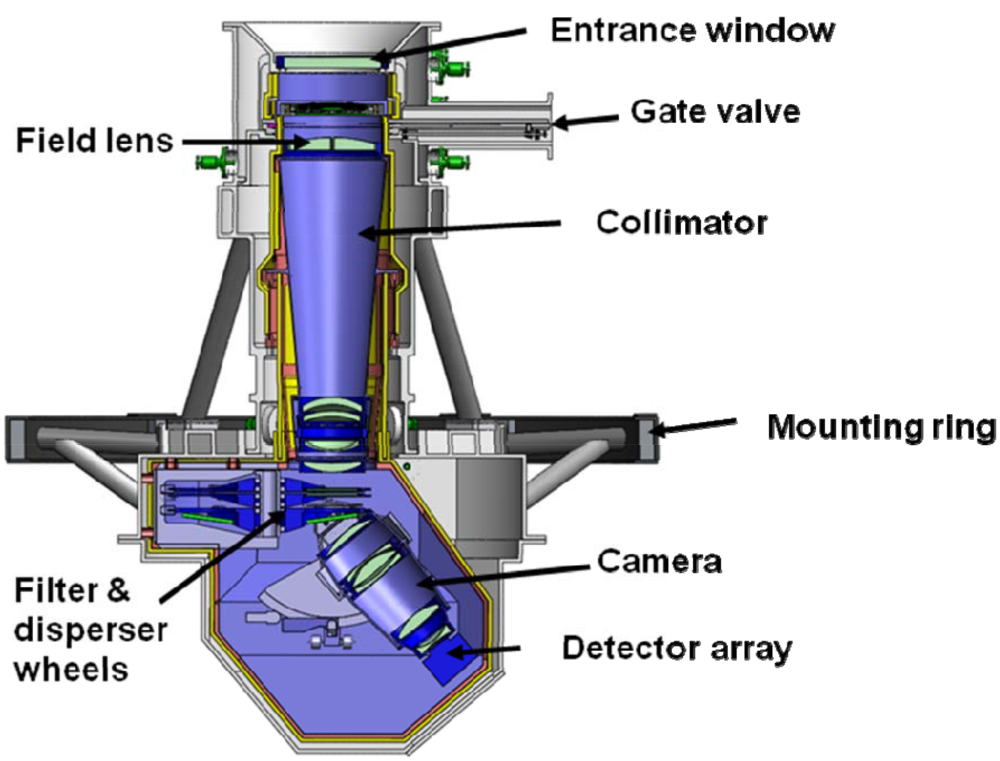

Figure 7. Layout of NIRMOS. The optics are shown in green, cold assemblies in blue, and ambient temperature structure in grey. A rotating pupil stop is located between the filter and disperser wheels.

1.2.4 Slit Masks or Slit Robot

Our baseline plan has been to provide two slit mask exchange mechanisms, each holding 10 slit masks for a full night or more of observing. We propose to mount the exchange mechanism in an accessible location towards the outside edge of the slit mask cassettes as shown in Figure 8. A gate valve is installed above the field lens so that the focal surface can be warmed up independently of the main instrument assembly, and gate valves are also installed between the cassettes and the focal plane assembly to allow removal of the cassettes for service.

The baseline slit mask exchange actuator is a "frog-leg" mechanism as shown in Figure 9. When the slit mask is mounted at the focal surface the frog leg acts as a preload device. This eliminates the need for a separate preload mechanism, and a separate mechanism to engage and disconnect the actuator from the frog leg.

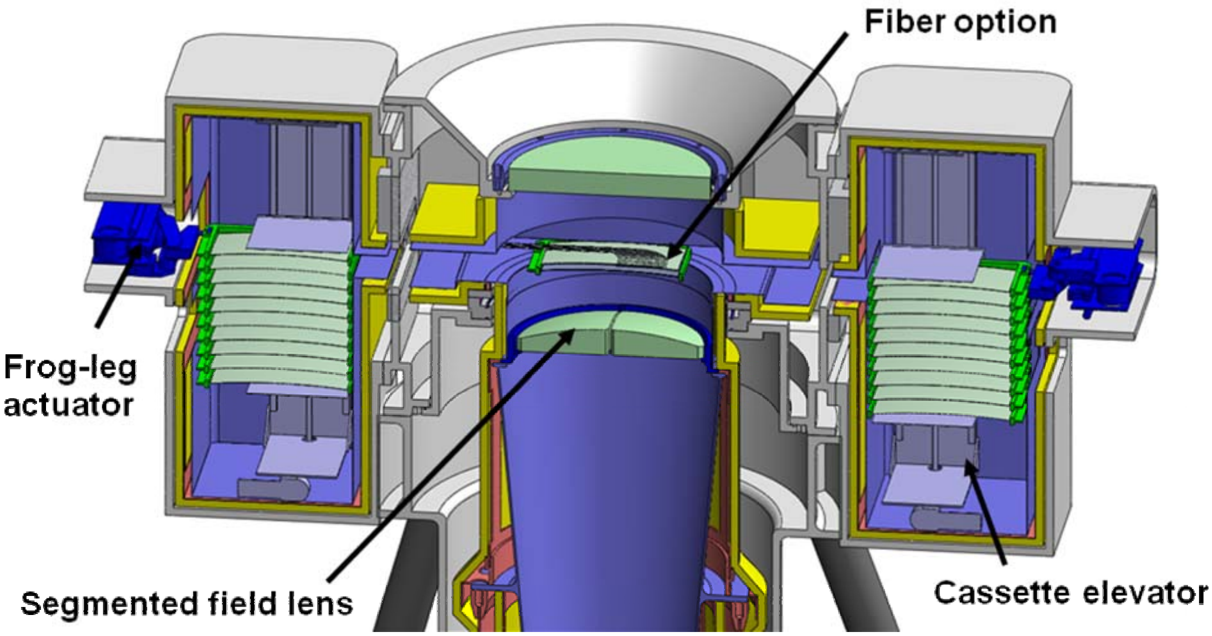

Figure 8. Slit mask cassette assemblies and the focal plane area.

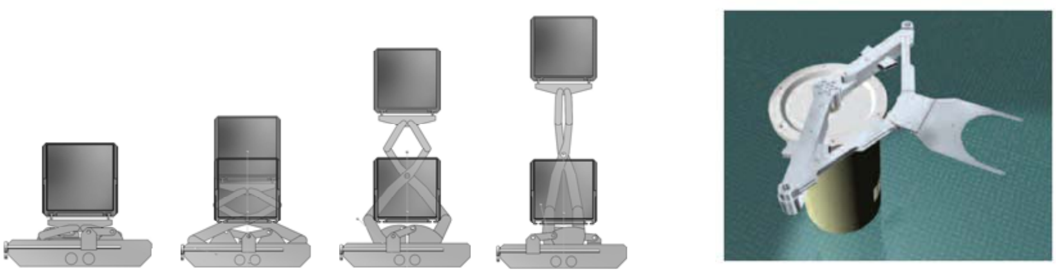

Figure 9. Proposed frog leg slit exchange mechanism. On the right is a commercial Brooks Automation mechanism of this type.

We have also prepared a preliminary conceptual design for a slit mask robot that actuates individual curved slit mask bars as shown in Figure 10. The slit robot, shown in Figure 11, consists of six identical stepper/harmonic-drive/gear assemblies mounted to a stage that moves perpendicular to the slit jaw travel. In each position, the drive assembly will move six of the 36 pairs of bars.

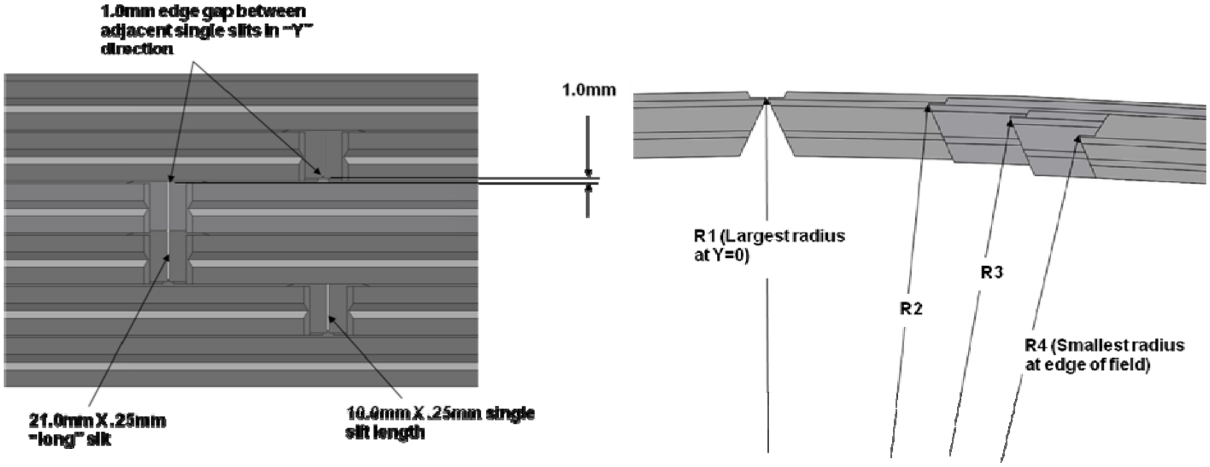

Figure 10. Proposed layout of opposing slit jaws for a slit positioning robot system that could be used in place of slit masks. The slit jaws are stepped to better conform to the curved focal surface. The initial concept calls for 36 slit jaw pairs driven by six actuators that can be moved perpendicular to the slit travel direction to sequentially engage all of the slit jaws.

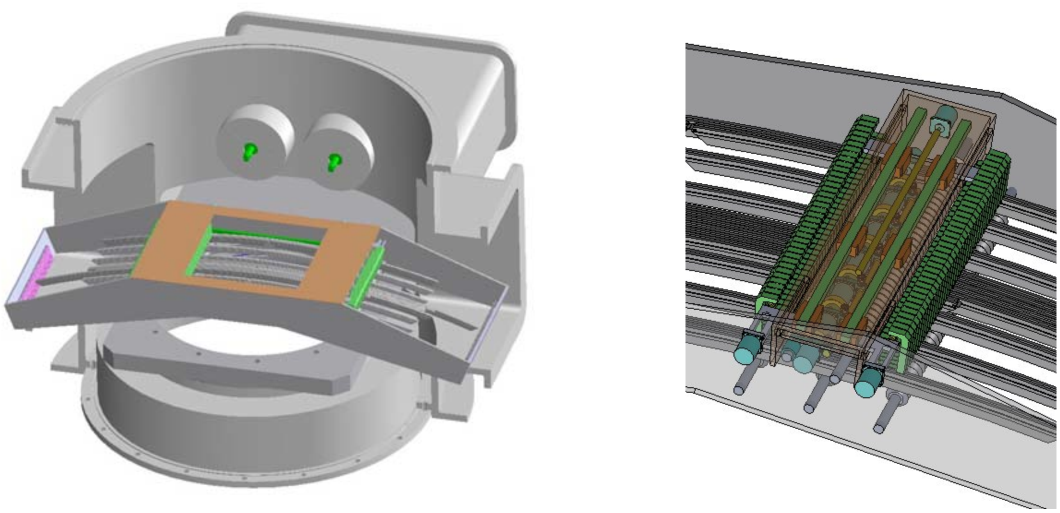

Figure 11. Left, the slit robot assembly in the focal surface. Right, one of two identical drive assemblies for the opposing slit bar pairs. The green L-shaped parts on the outside of the drive assembly are flexured locking assemblies that are released to move the slit bars. Stepper motors release the appropriate locking mechanisms and engage the drive gears to initiate a slit bar motion.

1.2.5 Dispersers and Filters

Figure 12 shows a close-up of the filter and grating wheels along with the rotating camera assembly. Having a mechanism to rotate the camera allows us to dispense with costly (and possibly unobtainable) beam straightening prisms for spectroscopy. The current design accommodates six filters and five gratings.

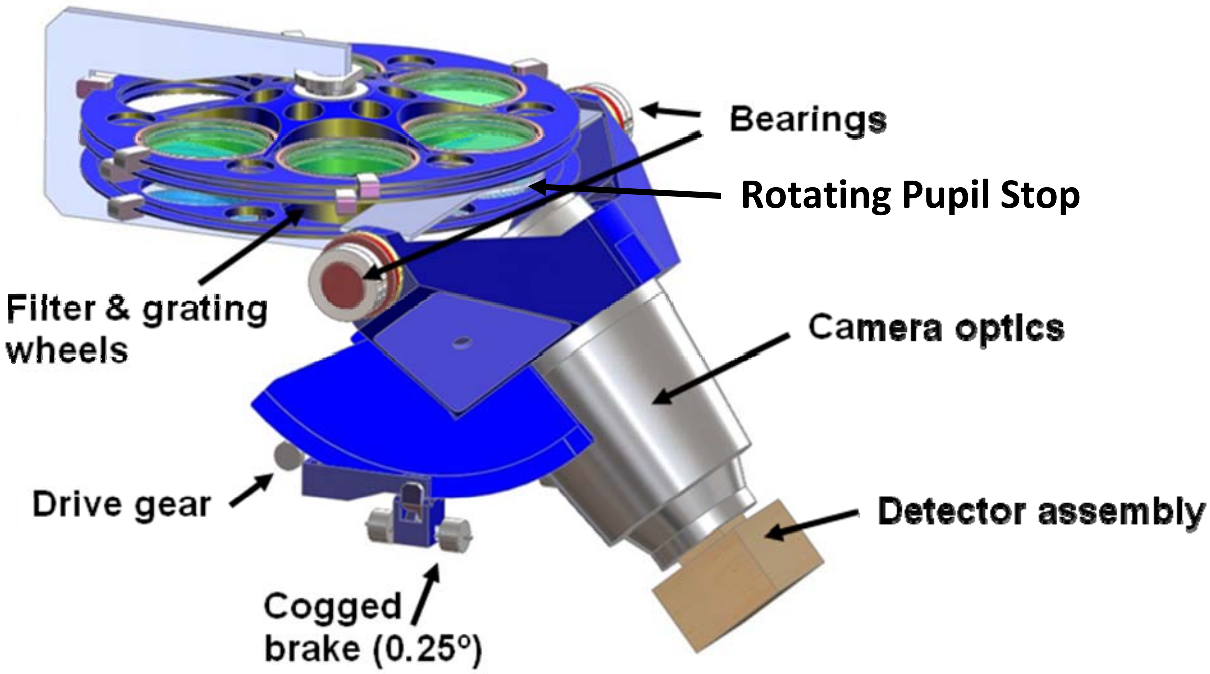

Figure 12. Close-up of the filter and grating wheels, along with the deployable camera assembly. The camera is rotated perpendicular to the wheels in imaging mode, and tilted to the correct angle to intercept the first order dispersed beam in spectroscopy mode. A rotating pupil stop is located between the filter and disperser wheels.

1.2.6 Thermal Design

The NIRMOS cryogenic system requirements include cooling down and maintaining the 1,435 kg cold mass at 70-75 K. The cool down time for the slit mask chambers is one day, while cool down time for the main instrument is four days. During operation, the optics must see only the sky or cold internal surfaces. All optics are mounted in cold bezels and the remainder of the instrument is covered with cold, light tight shielding. A thermally isolated framework mounted from the cold surfaces supports a radiation shield that faces the ambient temperature vacuum housing (see Figure 13).

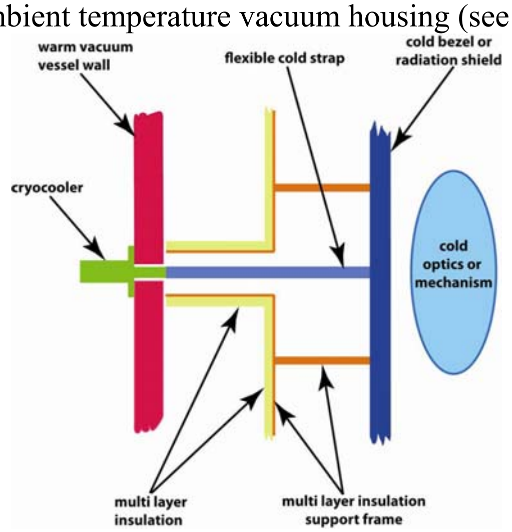

Figure 13. Conceptual diagram of thermal system.

We considered using LN_2 and cryocoolers for cooling NIRMOS. LN_2 cooling allows rapid cool down times with no significant power requirements, but requires complex piping and additional pressure vessels, and ~2,000 kg of LN_2 for each cool down. The large quantity of nitrogen gas evolved during cooling is a safety concern. Cryocoolers allow nimble cooling control and design simplicity, but use significant electric power. We were initially concerned about cryocooler vibration and reliability, but these concerns were addressed through detailed analysis and research. On balance, cryocoolers seem preferable.

The Sunpower CryoTel GT is currently our preferred cryocooler. The CryoTel GT consumes 240 watts of power and provides 46 W of cooling at 293K and 14 watts of cooling at 75K. Liquid cooling jackets are available to minimize local heating. The CryoTel GT has a mean time between failures of 7 to 14 years. NIRMOS's cryocoolers will not run constantly, so our mean time between failures should be longer. In the event of a cryocooler failure, the thermal short loss is 2 watts. The "as designed" cryocooler capacity can be increased so that a cryocooler failure anywhere in the system can be tolerated until the next major maintenance cycle. We estimate that a total of 43 cryocoolers will be required.

1.3 Critical Technologies

1.3.1 Large Calcium Fluoride Lens Blanks

Canon produced a set of twelve large CaF_2 lens blanks for Binospec, SAO's wide-field optical spectrograph. The largest of these Binospec lenses have finished diameters of 372 mm, the same as the expected finished diameters of the largest NIRMOS CaF_2 lenses. The major risk is that Canon and the handful of other companies that produce large CaF_2 crystals could lose interest in growing the largest crystals since the market is not very large. So far, Canon is very interested in future orders.

1.3.2 Large S-TIM28 Blanks with Good IR Transmission

The current optical design calls for two large S-TIM28 lens blanks, or a comparable material. Relatively few optical glasses have the necessary combination of optical properties and good transmission to 2.45 μm. It appears that variations and "improvements" in the glass making process can affect the OH inclusion, and hence the optical transmission. We will explore these issues further during the proposed conceptual design study.

1.3.3 Detector Array

The Teledyne Hawaii4-RG devices are currently under development, but so far none have been delivered. Teledyne has released specification sheets for the array and sidecar ASIC, and is currently accepting orders for the devices. We will follow the development of the H4RG arrays closely.

1.3.4 Large Cryogenic VPH Gratings

Large volume phase holographic (VPH) gratings are the preferred choice for NIRMOS's high dispersion mode (R=3000 to 7500) because they offer considerably higher efficiency than do conventional ruled gratings. We require operation at cryogenic temperatures, but several studies have indicated that VPH gratings survive cryogenic operation with negligible loss of efficiency. Large VPH gratings are currently available from Wasatch Photonics and Kaiser Optical Systems. During the proposed conceptual design study we will explore costs, transmission performance, further cryogenic testing, and delivered wave front quality.

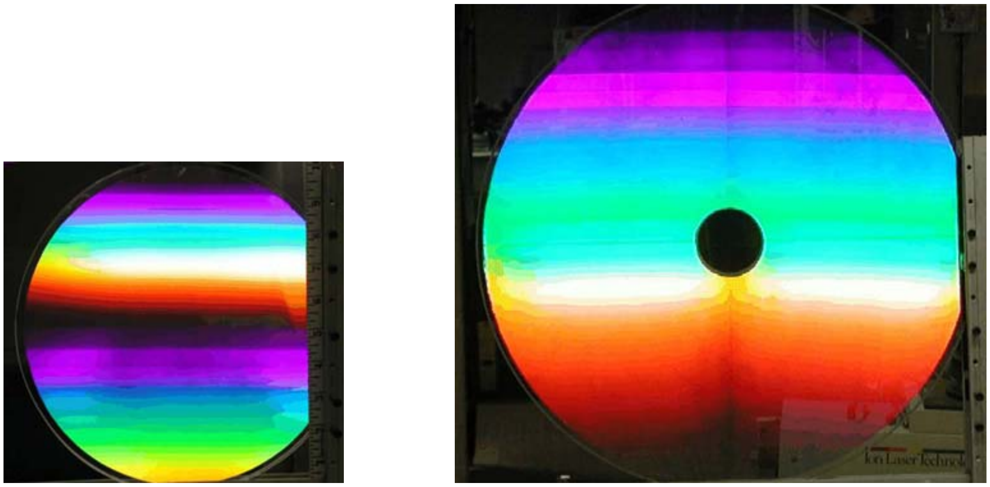

Figure 14. Left, 250 mm diameter IR VPH grating. Right, 400 mm diameter mosaic VPH grating. Both gratings were produced by Wasatch Photonics.

1.3.5 Ground Layer Adaptive Optics

While NIRMOS would still be a powerful instrument without GLAO, the prospect of significantly improved images across a wide field of view is a very exciting scientific opportunity that might well be a unique capability of GMT amongst ELTs. Successful implementation of GLAO will require cooperation between the GMT Project and the NIRMOS team. The GMT project has funded a study of the adaptive secondary and has initiated AO system design studies and AO modeling studies. One of the key issues for the proposed NIRMOS design study is to specify and design the wave front sensors, tip-tilt sensors, and guide probes that must be placed in the focal plane region above the slits.

1.4 Requirements for GMT Facilities

1.4.1 Field of View

The nominal field of view of NIRMOS is expected to be in the range of 6.5' by 6.5' to 7' by 7', depending on the final optical optimization.

1.4.2 Field Derotation

NIRMOS will require field derotation, and it is expected that this will be provided by a high-capacity Gregorian Instrument Rotator (GIR).

1.4.3 Ground Layer Adaptive Optics Requirements

1.4.3.1 Adaptive Secondary

Provision of GLAO at the direct Gregorian focus requires an adaptive secondary mirror since providing cold reimaging optics covering the NIRMOS field is not feasible at reasonable cost.

1.4.3.2 Laser Guide Stars

A constellation of sodium laser guide stars distributed around the outside edge of the NIRMOS field would be required to allow measurement of the wavefront. The GMT CoDR plan called for five sodium laser beacons.

1.4.3.3 Dichroic and GLAO Wave Front Sensors

A dichroic located near the NIRMOS entrance window reflects the sodium laser light to an array of wave front sensors located on the GMT instrument platform. The rear surface of the dichroic has a cylindrical figure to remove the effect of the dichroic substrate on the transmitted IR beam.

1.5 Deployment on GMT

1.5.1 Gregorian Instrument Assembly

1.5.1.1 Instrument Volume and Weight

We estimate a total instrument weight of 11,000 kg, with a diameter of 4.3 m at the interface flange, and an overall length of 4.8 m as shown in Figure 15.

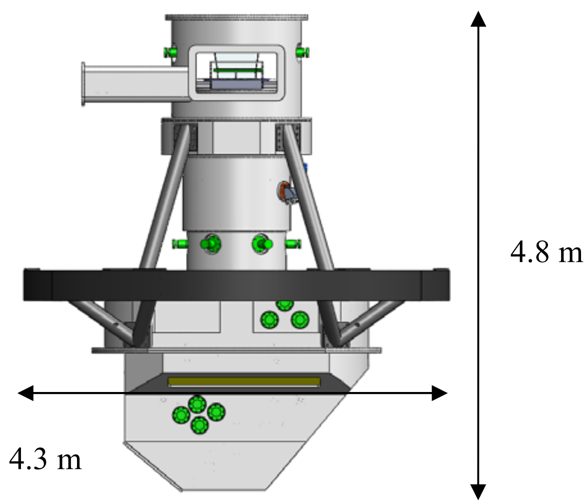

Figure 15. NIRMOS dimensions.

1.5.1.2 Elevation Mechanism and Mounting Requirements

We expect that NIRMOS would share the GIR with one or more instruments. It therefore is necessary to move NIRMOS into operating position at the telescope focus, and to retract NIRMOS from the focus when another instrument is operated. The most straightforward implementation is an elevation mechanism that translates ~1.0 m along GMT's optical axis. During NIRMOS operation, the instrument would be docked and precision latched to the Gregorian Instrument Rotator (GIR). When another instrument is in use, NIRMOS would be translated away from the GIR in a structurally sound, but optically imprecise manner. We expect to develop the elevation mechanism in collaboration with the GMT Project team and other instrument teams that would share the Gregorian instrument module.

Figure 16 shows the current state of the Gregorian instrument module with NIRMOS in the observing position.

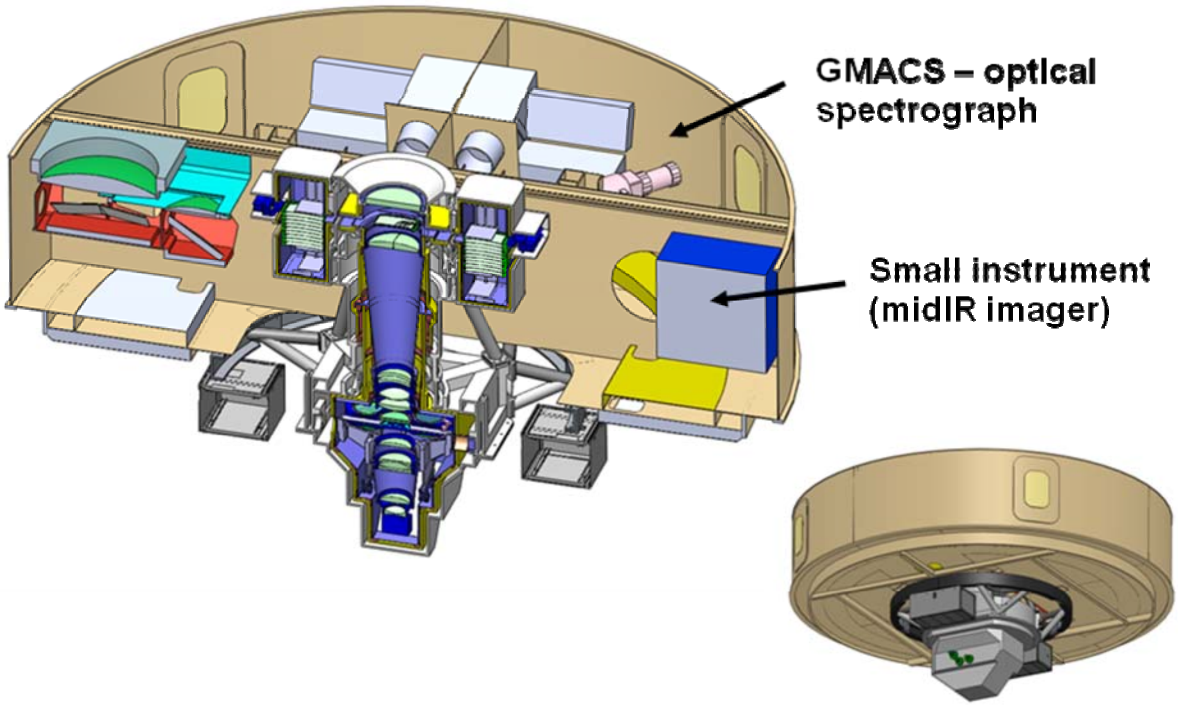

Figure 16. Current view of NIRMOS on the Gregorian instrument module with NIRMOS in the observing mode. In standby mode, NIRMOS is retracted ~1 m along the optical axis of GMT with an elevation mechanism. In the observing mode, NIRMOS locks to the Gregorian instrument module at its 4.3 m diameter interface flange.

1.5.2 Electronics Package

We anticipate that the NIRMOS electronics will be contained in two insulated 19 inch racks, and four electronics boxes. Rack 1 carries the motion control electronics for the 30 (robotic slit mask option) or 16 (dual slit mask cassette option) axes of motion control and drives, the PZT control and drive electronics for flexure control and focus, and the power and communications interfaces. Rack 2 would carry the vacuum pumps, the vacuum gauge readouts, and control electronics. Boxes 1 and 2 carry the drive and control modules for the cryocoolers. Box 3 houses the science array readout electronics and the flexure control system electronics. Box 4 contains the camera electronics for the guide cameras and wave front sensors. Both racks and all four boxes will have their waste heat extracted by liquid cooling loops.

1.5.3 Access Requirements

NIRMOS is not directly accessible from the telescope chamber floor. This is addressed by providing permanent decking and railings around the lower vacuum housing of NIRMOS. The decking may be accessed by lift from the observatory floor or from inside the GIR. Second, access panels must be able to be handled by one or two personnel. This guideline applies to slit mask access panels and slit masks, detector access, camera mechanism access, and filter / disperser wheels access. Third, limited access to large masses (such as electronics boxes greater than 100 pounds) must be accommodated. Large masses will be moved using locally supported hoists with capacities in the 500-2,000 pound range. Throughout the instrument, hoist locations will be provided, both at the hoist points and at the object to be hoisted.

1.6 Performance Estimate

One significant uncertainty in estimating the performance of an infrared spectrograph is the background level between the OH sky lines. Early measurements of the interline background with MMIRS are consistent with the 1993 Maihara et al. measurement (PASP **105**, p 940), so we adopt their value of 590 photons s^{-1} $arcsec^{-2}$ m^{-2} μm^{-1} in the J and H bands. In the K band we add a thermal background for a 281K blackbody with 10% emissivity, giving a total background of 4490 photons s^{-1} $arcsec^{-2}$ m^{-2} μm^{-1}. Considering realistic aperture losses and assuming a 40% throughput (see Figure 6), we calculate the signal to noise in a 0.5" by 0.5" aperture in 0.40" seeing. For an hour-long integration on an object with J, H, or K AB magnitude of 23, we present the estimated signal to noise in Table 2.

Table 2. Signal to noise in an 0.5" by 0.5" aperture in 0.40" seeing for a one hour integration on a object with J, H, or K =23 (AB). Signal to noise with GLAO would be higher.

Band	S/N
J	22
H	19
K	6.7

1.7 Descope Options

1.7.1 Seeing Limited Operation Only

The GMT adaptive optics (AO) conceptual design applies the wave front correction at an adaptive secondary mirror. This approach is well suited to implementing ground layer adaptive optics (GLAO) because it avoids field-limiting reimaging optics, and because the secondary mirror is conjugated to an altitude of ~200 m. If the adaptive secondary were to be deferred for cost reasons, we have the option of eliminating GLAO hardware from NIRMOS. The GLAO-specific telescope hardware includes a wide-field GLAO wave front sensor (WFS) mounted on the GMT instrument platform and a dichroic that reflects optical light to the GLAO WFS and passes IR light to NIRMOS.

1.7.2 Slit Mask vs. Slit Robot

We have explored the tradeoff between using interchangeable slit masks or a slit robot with opposed slit jaws that can be used to form slitlets of variable width but with lengths restricted to an integer multiple of the slit jaw length. The **advantages of using a slit jaw robot** are: (1) elimination of the operational complexities and costs associated with designing, machining, and exchanging slit masks, (2) the ability to rapidly adapt to changing conditions, (3) a more compact and lighter weight design, and (4) fewer cryocoolers are required. The **advantages of using a slit mask** are: (1) complete freedom in the choice of slit length, slit orientation, and use of complex shapes, (2) lower initial cost, and (3) greater design heritage.

1.7.3 Eliminate Low Dispersion Modes

Increasing the spectral coverage to simultaneously observe the J and H bands, or the H and K bands requires additional dispersers. These gratings will most likely be conventional ruled transmission gratings because low dispersion VPH gratings offer low efficiency across a wide field. Conventional gratings will produce more scattered light, and the low dispersion will introduce much higher background from strong OH sky lines, so the scientific impact might be acceptable. The development costs for conventional gratings may be significant since it may be necessary to mosaic four smaller gratings.

1.7.4 Limit Slit Length to 3.4' Temporarily or Permanently

The Teledyne H4RG detectors are currently priced at $750K each, plus the cost of electronics. Reducing the detector complement to three from six would cut in excess of $2.5 million from the budget. Further cost savings could be obtained by reducing the field of view permanently along the slit and perpendicular to the slit, because the largest optics, the GLAO dichroic, the entrance window, and the field lens could be reduced in size. The slit mask mechanisms could also be reduced in size and weight. The scientific impact would be that surveys would take two to four times the telescope time to complete.

2 Management Plan

2.1 Conceptual Design Study Plan

2.1.1 Work Breakdown Structure and Study Plan

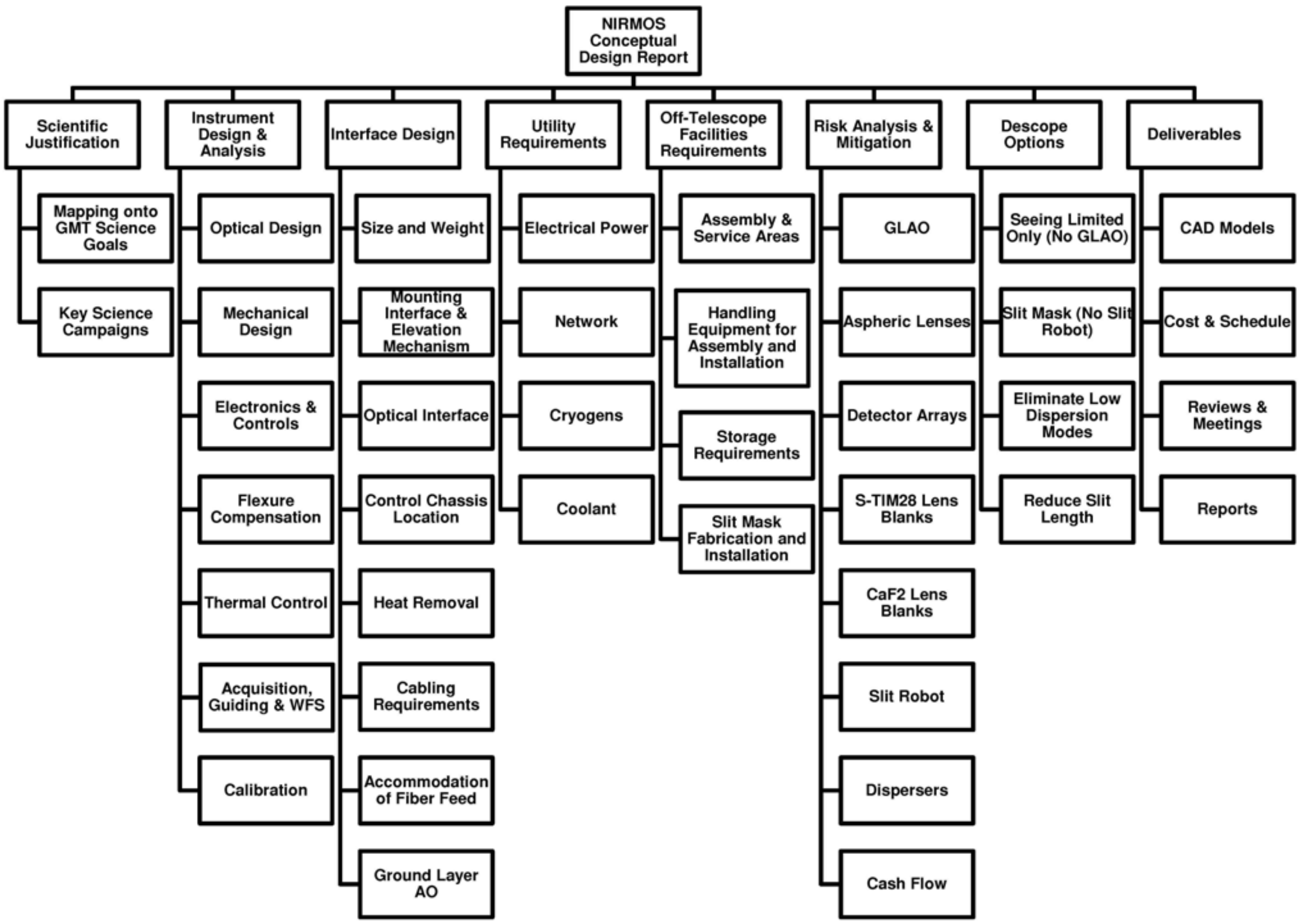

Figure 17. Conceptual Design Study Work Breakdown Structure.

2.1.1.1 Scientific Justification

During the Conceptual Design Study (CDS), the NIRMOS Science Advisory Committee will work on expanding and detailing the scientific case for NIRMOS briefly outlined in Section 1.1. We believe that NIRMOS will be able to address important issues in stellar astrophysics, and will describe that science case. Much of this work will be carried out in e-mails and teleconferences, but we plan on holding a NIRMOS Science Workshop during the CDS, well before the final review.

2.1.1.2 Instrument Design and Analysis

2.1.1.2.1 Optical Design

During the CDS, we will continue to refine the NIRMOS optical design. We will consult with Harland Epps on refining the design following our final studies on optical material availability. Refinement of the optical design may require adjustments to the pupil position and other element spacings. We will perform a scattered light analysis to better understand requirements for internal baffles.

2.1.1.2.2 Mechanical Design

We have a conceptual layout for the key mechanisms and overall packaging of NIRMOS. During the CDS we will study the drive, brake and feedback mechanisms for the slit masks, grating, filter wheels, pupil mask, and the tilting camera assembly. We will investigate several critical vacuum and cryogenic technologies, including rotary and linear encoders, actuators, limit switches, lubricants, motors, gearboxes, and feedback devices. We will design the gate valves used to separate the slit mask assembly and the collimator optics as well as those used to separate the slit mask cassettes from the focal plane area. Articulating cold baffles will probably be needed to control stray light from the warm gate valves. We will continue to investigate the feasibility of a configurable slit mask assembly.

We will develop concepts for mounting the IR science arrays, including a flexure control stage and appropriate thermal control.

In order to design lens mounts and other cryogenic components, we will construct a material properties database to describe material behavior between ambient and cryogenic temperatures. We will establish allowable cool down rates for all sensitive elements to control stress. We will develop component finite element (FE) models to analyze lens support concepts to predict preload and stress variation as a function of gravity, temperature, lens size, and curvature. We will analyze mechanisms for thermal, stiffness, and stability concerns. We will construct a system FE model to predict image motion, image quality, and thermal performance.

2.1.1.2.3 Electrical Design

We will develop a top level description of the electrical system, characterizing the cryocoolers, motors, and drives. We will generate specifications and packaging designs for each rack subsystem including the motion control, vacuum and temperature control, flexure control, cryocooler support, science arrays, and the guider/wave front sensor electronics. We will develop a concept for the flexure compensation system and calibration system.

2.1.1.2.4 Thermal and Vacuum System Design

We will continue to develop the instrument thermal design, identifying the total radiation and conduction heat loads, while optimizing radiation shielding and minimizing conduction paths. We will use the system FE model to determine NIRMOS's time dependent behavior. We will establish the required number of cryocoolers to allow a 24 hrs (or shorter) cool down of the slit masks and a four day (or shorter) cool down for the remainder of the instrument as well as the number required for steady state operation. We develop a conceptual design of the vacuum system including pumps, pressure monitoring equipment, and control systems.

2.1.1.2.5 Wavefront Sensors and Guiders

We will develop conceptual designs for wave front sensors and guiders adaptable to either a configurable slit mechanism or slit mask changer and integrated with the telescope controls and GLAO system.   The NIRMOS team has consulted with Michael Hart for the GLAO requirements and he describes the requirements as follows. "In theory one only needs a single fast tip-tilt sensor, but several would be better because (1) each can patrol a smaller field making the mechanics easier and stiffer and (2) the PSF uniformity will likely be better if the average of a number of tilt signals spread across the field is used. The high-order wave front sensor should sample the pupil at the same 0.5 m scale as the diffraction-limited AO. The sensor is used to remove non-common path aberration between the laser guide star wave front sensor and the NIRMOS focal plane. The highest spatial frequencies in the static aberration refract energy furthest out into the PSF wings where it does the most damage. Although one might think that since the degree of atmospheric correction is not high, one can get away with a relatively low-order static correction, there is real advantage to pushing harder. There's very little cost in doing so. We certainly find this approach to be of benefit at the MMT, where the fast GLAO correction is done with 44 modes, but the static correction uses at least 54, with plans to go to higher modes since static corrections limit our EE at present. Since the wave front sensor is slow, and we're not working at the diffraction limit, there's no point in trying to take advantage of the coherence of starlight. Therefore, a Shack-Hartmann wave front sensor is fine; there's no need to do anything fancier."

2.1.2 GLAO and Seeing Limited Image Quality

The NIRMOS team will work will the AO modeling team and the GMT site survey team to try to better understand the expected image quality in the near IR with and without GLAO. Right now there is substantial uncertainty about the expected seeing in the NIR because all of the site testing data has been taken in the visible. The median free atmosphere seeing at Las Campanas is ~0.45" at 5000 Å. We can crudely estimate the seeing in the NIR after full ground layer correction by scaling the free atmosphere seeing as $\lambda^{-0.2}$, yielding a median seeing at 1.6 µm of 0.36" with full GLAO correction.   Joanna Thomas-Osip, the GMT site testing scientist, has advised that this simple calculation is probably pessimistic because the turbulence has a finite outer scale. During the CDS, we will attempt to place better limits on this calculation.

2.1.3 Interface Design, Utility Requirements, Off-Telescope Facilities

Many aspects of the interface design for NIRMOS will flow directly from the conceptual mechanical and thermal designs. We will work with other instrument groups and GMT project staff to further define the layout of a Gregorian instrument module that will accommodate multiple instruments. If a fiber feed working in the NIR is selected for a CDS, we will work with the selected group to accommodate a fiber feed in NIRMOS. We have had several detailed exchanges of information with the MANIFEST team.   The interface with the GLAO system needs to be worked out in close consultation with the GMT project staff and AO consultants working with the project.

The utility requirements and the requirements for off-telescope facilities will flow from the mechanical and electrical conceptual designs, and will be reviewed with GMT project staff during the CDS.

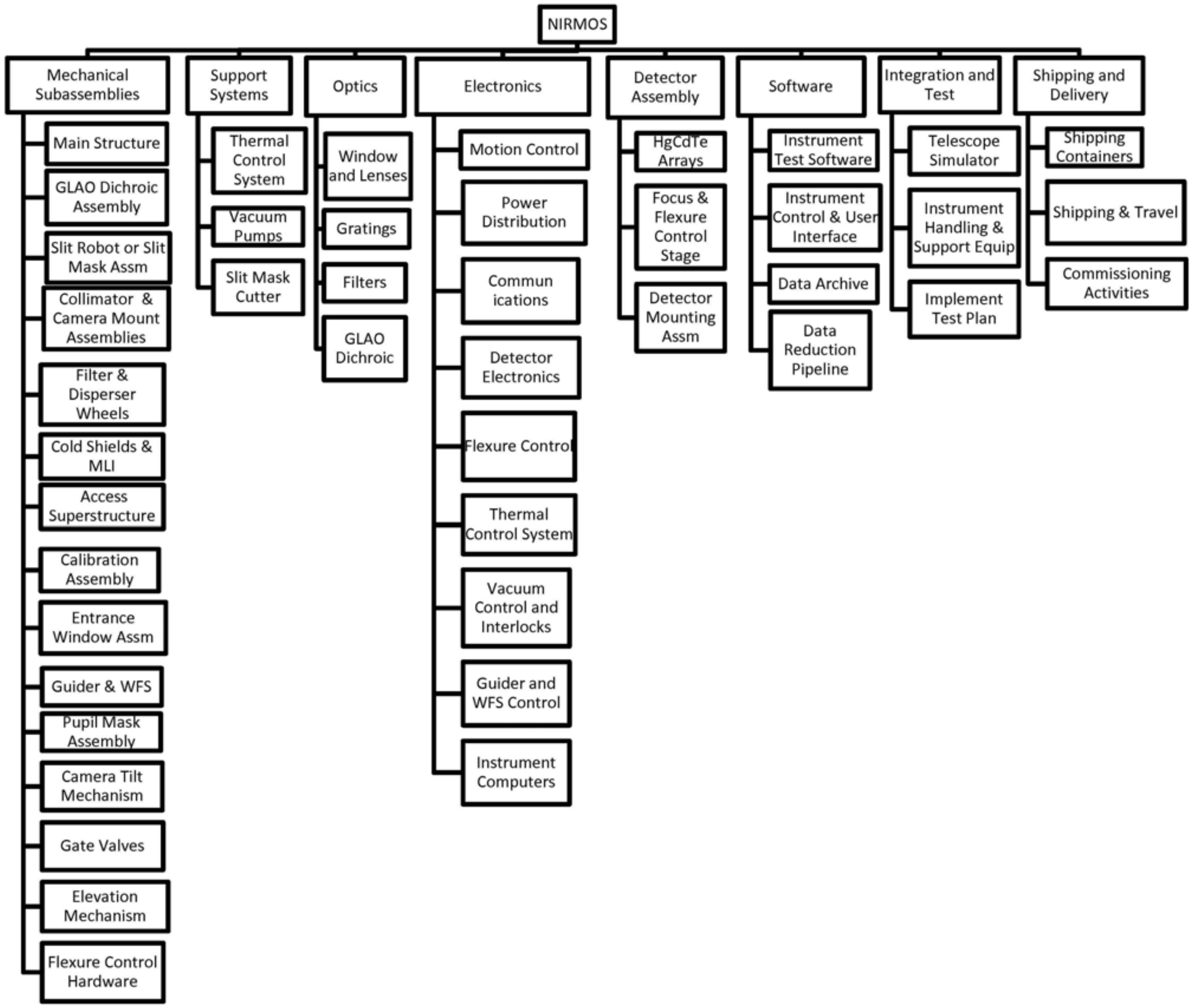

Figure 18. An initial version of the WBS for NIRMOS that will be used for the CDS cost study. This WBS doesn't yet include all of the related scientific and management activities.

2.1.4 Risk Analysis and Mitigation

We present a preliminary risk analysis in Section 2.4 below. The process of risk analysis and mitigation is a key element of the CDS, and will inform all design studies. We intend to follow up each of the elements identified in Section 2.4 through discussion with prospective vendors, the NIRMOS Science Advisory Committee, GMT project representatives, and GMT AO consultants. At the end of the CDS, we hope to have substantially retired many of these risks.

2.1.5 Descope Options

We describe descope options in Section 1.7 above. As part of the CDS, we will quantify the cost and scientific impact of these options to allow the project to make informed decisions about their implementation. Depending on the results of this study, we may propose changes to the baseline project scope.

2.1.6 Cost Study

The Request for Proposals calls for development of a budget accurate to 30%. This is a challenging goal, but we are eager to develop techniques for more accurate cost estimation. We have developed a preliminary WBS for the complete instrument shown in Figure 18 (not to be confused with the WBS for the CDS shown in Figure 17). During the CDS, we will continue to flesh out the instrument WBS. The instrument WBS will be used to develop a detailed bottom-up cost estimate using historical data, catalog prices, vendor quotes, and engineering estimates. This cost estimate will be examined for fidelity using top-down cost analysis and cost analogies with previous instruments produced at the CfA. Appropriate contingencies will be calculated for each cost element based on risk analysis.

2.1.7 Deliverables

The PI and PM will submit quarterly progress reports as requested in the Request for Proposals. The NIRMOS project will hold internal quarterly project reviews, and this process will inform the quarterly progress reports and the quarterly progress reviews for the GMT project described in Section 2.1.8.

At the end of the CDS, CAD assembly models of NIRMOS and associated control equipment will flow naturally from the work described in Section 2.1.1.2. We are designing NIRMOS with SolidWorks for compatibility with GMT project standards. We will provide detailed budget and schedule information from the cost study described in Section 2.1.4.

2.1.8 Meetings and Reviews

The Request for Proposals calls for a videocon kick-off meeting, and quarterly videocon progress reviews. At the end of the CDS, a day-long conceptual design review is to be held in Pasadena. Throughout the CDS, the NIRMOS team will also stay in close contact with other instrument teams building instruments that could share the same Gregorian Instrument Module or that might augment the capabilities of NIRMOS. We recommend to the project at least one meeting approximately half way through the conceptual design period that brings together all of the instrument teams. The resulting exchange is likely to be quite fruitful.

2.2 Management Tools

2.2.1 Communication Tools

NIRMOS communication will be via email, meetings, and postings on the project Wiki pages. The project Wiki pages are security access controlled to individuals within the organization and on an as-needed basis for others. During the conceptual design phase, the project plans to develop web materials accessible to the GMT community and the public.

2.2.2 Project Tracking Software

The project schedule is developed using MS Project software to lay out the tasks described in WBS Work Packages and their interrelationships. The schedule is monitored throughout the study phase, with progress against the baseline plan reported to the team at the periodic meetings and to the GMT Project at reviews.

Engineering labor expenses are tracked at the project level on a weekly basis by the Central Engineering Department and reported to the project monthly in “Cost-to-Complete” reports that identify labor hours and dollars spent by month along with projected future hours and dollars for the fiscal year. These reports are reviewed by the Project Manager (PM) and Project Engineer (PE) on a regular basis. The PE will identify and track resource hours spent against WBS elements on a monthly basis. Shorter term variations are identified during weekly or bi-weekly meetings from which the PE and PM determine the required adjustments to labor resource allocations.

Management maintains budget planning and tracking spreadsheets using MS Excel. The baseline plan, presented in this proposal, is continuously monitored throughout the project. Actual expenditures are logged and compared against plan and an estimate-to-complete is updated periodically; materials services as they occur, engineering labor on a monthly basis. Evaluation of project health is by Earned Value Management method (see Section 2.2.3).

Project Status Reports will be managed by the PM, collecting input through the PE to provide the PI with reports on a monthly basis. The status reports will be against WBS elements, with assessments of progress to date and estimates-at-completion by the PE. The PM will roll up all WBS element inputs into the PSR.

2.2.3 Earned Value Analysis

Throughout all project phases, including the proposed CDS, we will use an earned value management approach to provide the PI with early indication of project health. The baseline project plan presented in this proposal is based on the Work Breakdown Structure (WBS) approach toward project planning. The baseline project plan identifies the projects planned value from the outset of the project. As the project proceeds, we measure progress against WBS elements and establish the value of the work performed to date, or earned value. The earned value is compared to the level of funding spent, or actual cost.

2.3 Key Personnel

2.3.1 PI

Daniel Fabricant will serve as PI. Dr. Fabricant has over 30 years of experience designing instruments for astrophysics. He has led the CfA’s optical and infrared ground-based instrumentation program for the past 15 years. He served as CfA project scientist for the MMT Conversion to a 6.5 m telescope, leading the design, construction, and commissioning of the MMT’s wide-field optics.

2.3.2 Program Manager

Timothy Norton will serve as program manager. He has served as MMIRS program manager, and program manager for the Magellan f/5 instrumentation program. He has considerable engineering experience, and worked previously as a mechanical engineer. Mr. Norton is an employee of Harvard College Observatory (HCO) and his services will be purchased from HCO.

2.3.3 Project Engineer

Robert Fata will serve as project engineer. He has been leading the NIRMOS engineering effort for the past year, and is responsible for the rapid development of the NIRMOS concept in that time. Robert Fata also currently serves as the Binospec project engineer. Binospec is a wide-field optical multi-object spectrograph to be delivered to the MMT in 2012. Previously, Mr. Fata served as project engineer for Hectospec and the MMT's Wide-Field Corrector.

2.3.4 Deputy PI

Brian McLeod will serve as deputy PI. He is PI for the recently completed MMT-Magellan Infrared Spectrograph (MMIRS), a multi-slit instrument with many parallels to NIRMOS. Prior to that, Dr. McLeod served as PI of Megacam, a wide-field optical imager for the MMT and Magellan.

2.3.5 Project Scientist

Warren Brown will serve as project scientist. He played a major role in characterizing the MMIRS Hawaii-2 array, and served as PI of SWIRC, a wide-field JH imager for the MMT using a Hawaii-2 array. Dr. Brown will concentrate on thermal design, IR array issues, and scattered light analysis.

2.3.6 Science Advisory Committee

A NIRMOS Science Advisory Committee has been formed to advise the NIRMOS team about scientific priorities and potential scientific programs. The NIRMOS SAC includes: Edo Berger (CfA), Xiaohui Fan (UA), Karl Glazebrook (Swinburne University of Technology), Gary Hill (UT Austin), Myunshin Im (Seoul U), Daniel Kelson (OCIW), Scott Kenyon (CfA), Peter McGregor (ANU), and Casey Papovich (Texas A&M). Charles Lada (CfA) will join the SAC to advise on the application of NIRMOS to problems in stellar astrophysics.

2.4 Preliminary Risk Analysis

We elect to discuss technical, schedule, and cost risks together, since they are all intertwined at the conceptual design level. Given enough money and time, we could deal with any potential risk. The key for us is to do so in a timely way at an affordable cost.

2.4.1 Ground Layer Adaptive Optics

GLAO offers the potential of significantly sharper images across a wide field of view. The GLAO system uses challenging technology, including an adaptive secondary mirror, a laser system to project a constellation of laser guide stars, a large dichroic mirror and sophisticated wave front sensors. The technical challenge is to keep this complex system working reliably at the required level of performance. Most of these technical challenges will have to be met for the diffraction-limited AO system. The risk mitigation strategy is for the project as a whole to develop an AO modeling capability and to further develop the AO system design. NIRMOS will still be a powerful instrument in the seeing limit and will be capable of addressing its scientific objectives without GLAO. The consequence of compromised GLAO performance is diminished sensitivity.

2.4.2 Aspheric Lenses

NIRMOS will use three aspheric lenses, one in the collimator and two in the camera. The biggest risks with aspheric lenses are testing errors and rough surfaces. We plan to directly diamond turn aspheric surfaces onto calcium fluoride lenses, and it should be possible to achieve sufficiently smooth, low-scatter surfaces without post-polish. However, experience has taught us not to underestimate the effort required to achieve good aspheric lenses.

2.4.3 Detector Performance

We are planning to use six H4RG HgCdTe arrays with sidecar ASIC boards. The array design should be mature when we would need to order the arrays, and the key performance requirements (quantum efficiency, read noise, dark current, cosmetics, etc.) are expected to be at least as good as the H2RGs. However, no H4RG arrays have been delivered yet, so surprises are possible. Everyone we have spoken to about the sidecar ASICs urges us not to underestimate the level of effort required to get the ASICs operating properly.

2.4.4 S-TIM28 Lenses

We have corresponded extensively with Ohara Glass about appropriate “flint” glasses to use with calcium fluoride after we received the disappointing news that it would be impossible to manufacture large S-FTM16 blanks. Their suggestion out of a list of candidates that have appropriate dispersion curves and good IR transmission is S-TIM28. However, no very large S-TIM28 lenses have been produced so far as far as we know. Schott has some candidate glasses to consider, but we have not explored those as of yet. Another issue is that process changes may adversely affect the IR transmission of candidate glasses by introducing OH contamination. Harland Epps has found that recent test samples of MOSFIRE glass show lower transmission than catalog values. This issue can probably be addressed but the expense is unknown.

2.4.5 Slit Robots

We currently operate complex robots in Hectospec, and do not underestimate the cost and difficulty of designing and building a reliable cryogenic multi-slit mechanism. However, as discussed above, there are many advantages to producing such a mechanism. Over the past year, we have developed an initial conceptual design that looks promising. The fallback of using slit masks should be more straightforward, but will add operational costs.

2.4.6 VPH Gratings

It looks as though there are no showstoppers associated with producing and operating 300 mm diameter VPH gratings, but these are not catalog items. Attaining very high efficiency and high transmitted wave front accuracy will take a serious effort, and probably a development effort.

2.4.7 Large Calcium Fluoride Blanks

While we have reduced the maximum required CaF_2 lens blank diameter to 390 mm, there are only a handful of suppliers for these lens blanks. The volume of these large lens blanks sold is small, and the lead time may be quite long for these blanks. There is also a risk that suppliers will stop making these large lens blanks.

2.4.8 Cash Flow Limitations

Typically, cash flow limitations are a major risk factor for schedule. Limited funding can also drive up costs because it is difficult for an instrument team to multiplex between projects with high efficiency, and other projects are not always available to absorb the marching army costs.

2.5 Schedule

2.5.1 Milestones

The conceptual design study is to be completed in 14 months. Our plan is to complete the bulk of the design and make conceptual engineering and scientific design decisions within the first 12 months, leaving the final two months for final updates, documentation, and preparing for the design review.

The CDS tasks are divided into monthly increments with quarterly milestones tied to quarterly reviews. During the first quarter we will develop designs for the drive mechanisms and design mechanical, thermal, and structural attachments to the support structure. We will analyze the thermal environment of the mechanical and optical components and adjust the design to minimize thermal gradients. We will establish a cryogenic mechanical hardware and material property database. We will define the system electrical architecture and select support electronics for the mechanical, thermal, and vacuum systems.

During the second quarter we will organize a NIRMOS science workshop. We will carry out a preliminary review of the NIRMOS optical design with Harland Epps. We will consult with other instrument teams to investigate the definition of a common Gregorian instrument module, define optical interfaces, and update the risk analysis. We will complete a conceptual design of the main vacuum housing and substantially complete the support structural design and analysis. We will carry out the design of the radiation shields and baffles as well as the gate valve assemblies and their baffles. We will carry out a conceptual design of the elevation mechanism.

During the third quarter, we will complete the guider, wave front sensor, flexure control, and calibration system conceptual designs. We will complete the thermal finite element modeling and describe NIRMOS's thermal, structural, and optical performance. We will predict NIRMOS's heat dissipation and describe strategies for heat capture and removal. We will define our facility requirements for operation, maintenance, and storage. We will summarize our approaches for risk mitigation.

During the fourth quarter we will complete the science justification for NIRMOS, summarize de-scope options and design the interface to the GLAO system. We will complete the electrical design showing a layout of each electrical box and interconnect cabling. We will update the mechanical and opto-structural designs to reflect the final optical design and any de-scope decisions. We will develop a plan to implement a fiber feed. During this quarter, the cost study will be substantially completed.

2.5.2 Gantt Chart