GMTNIRS (Giant Magellan Telescope near-infrared spectrograph): optimizing the design for maximum science productivity and minimum risk

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ABSTRACT

GMTNIRS, the Giant Magellan Telescope near-infrared spectrograph, is a first-generation instrument for the GMT that will provide detailed spectroscopic information about young stellar objects, exoplanets, and cool and/or obscured stars. The optical and mechanical design GMTNIRS presented at a conceptual design review in October 2011 covered all accessible parts of the spectrum from 1.12 to 5.3 microns at R=50,000 (1.12-2.5 microns) and R=100,000 (3-5.3 microns). GMTNIRS uses the GMT adaptive-optics system and has a single 85 milliarcsecond slit. The instrument includes five separate spectrographs for the different atmospheric windows. By use of dichroics that divide the incident light between five separate spectrographs, it observes its entire spectral grasp in a single exposure while having only one cryogenic moving part, a rotating pupil stop.

Large, highly accurate silicon immersion gratings are critical to GMTNIRS, since they both permit a design within the allowable instrument volume and enable continuous wavelength coverage on existing detectors. We describe the effort during the preliminary design phase to refine the design of the spectrograph to meet the science goals while minimizing the cost and risk involved in the grating production. We discuss different design options for the individual spectrographs at R=50,000, 67,000, 75,000, and 100,000 and their impact on science return.

Keywords: infrared spectrograph, immersion grating, Giant Magellan Telescope

1. INTRODUCTION

GMTNIRS, the Giant Magellan Telescope Near-Infrared Spectrograph, is one of the first-generation instruments for the GMT[1]. The instrument development is a collaboration between the University of Texas at Austin, the Korea Astronomy and Space Science Institute and Kyung Hee University. GMTNIRS completed a conceptual design in 2011 and is currently beginning its preliminary design phase by making critical design decisions to permit fabrication of the Si immersion gratings, the highest risk and longest lead-time components of the instrument. We have discussed the development of the instrument design in two previous papers.[2,3]

1.1 Instrument and project description

GMTNIRS is a single-object infrared spectrograph with high spectral resolution and a large spectral grasp. It exploits the laser guide star adaptive optics system of the GMT[4] to maximize its sensitivity at 3-5 μm and to keep the instrument size modest. Table 1 lists the functional features of the point design developed during the conceptual design phase. The instrument observes its entire 1-5 μm spectral range simultaneously through a single slit with five separate spectrographs covering the individual atmospheric windows. The broad coverage enables efficient observations, encourages serendipitous detections, simplifies the optomechanical design and data taking and analysis software, and leads to a more stable instrument. During the next development phase, we will fix the science requirements and use them to derive a set of technical specifications. We will produce the Si immersion gratings and do a detailed design and evaluation of the instrument.

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Table 1. Basic characteristics of GMTNIRS.

GMTNIRS	
Spectral grasp (simultaneous)	1.15-5.3 μm
Slit width (arcsec), pixel sampling	0.080, 4.0
Slit length (arcsec)	1.30
Resolving power (1.15-2.5 μm)	$\lambda/\Delta\lambda$ = 50,000
Resolving power (3.0-5.3 μm)	$\lambda/\Delta\lambda$ = 60,000-100,000

1.2 Science goals

GMTNIRS' grasp and sensitivity in a wavelength range only barely explored at high resolution up to now give it a tremendous discovery space across many different science fields. Figure 1 illustrates the comparative sensitivity of GMTNIRS on GMT and the current incarnation of CRIRES on the VLT. The per resolution element sensitivity improvement results from a combination of the larger aperture, detector improvements since the construction of CRIRES, and somewhat better optical efficiency. The biggest improvement is in spectral coverage which, due to the smaller instantaneous grasp and gaps in coverage for CRIRES, is about a factor of 100 (note, however, the near-term plans to improve the coverage of CRIRES by an order of magnitude by adding a cross-disperser)[5].

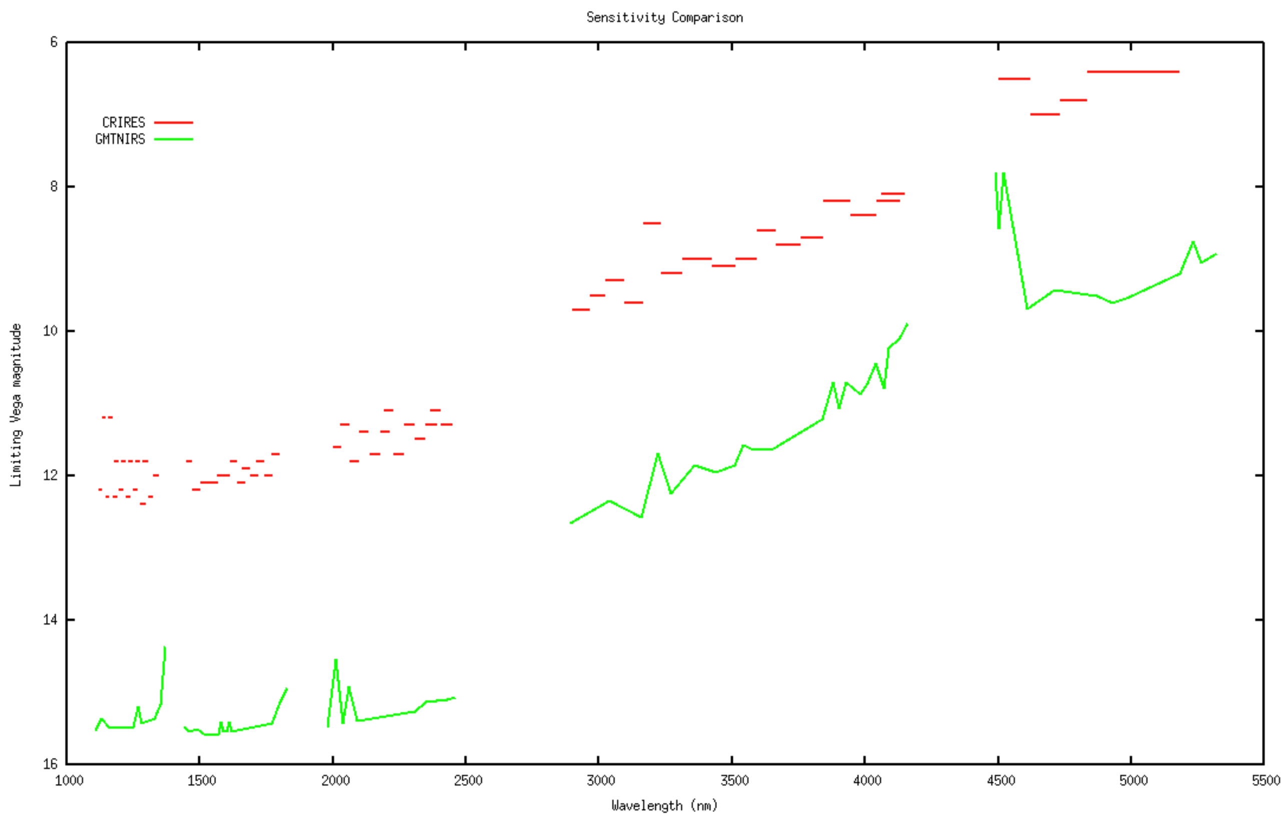

Figure 1. Sensitivity comparison for GMTNIRS at GMT and CRIRES on the VLT for S/N=100 in one hour. The green lines together represent a single exposure with GMTNIRS. The red dashes represent *individual* exposures with the current version of CRIRES (prior to the addition of a cross-disperser)[5] needed to cover the same range.

One of the most exciting fields where GMTNIRS can play a leading role is the direct detection of exoplanet spectra. Pioneers in this field on 8m telescopes have used high-resolution spectroscopy to detect transiting hot Jupiters.[6,7] They have also phase-correlated spectra of planets in non-transiting systems to obtain precise planetary masses without inclination ambiguities.[8,9,10] With GMTNIRS, data of this sort will provide not only the basic planetary parameters but also significant information about the physics and chemistry of the planetary atmospheres in systems not approachable with low-resolution spectroscopy.

GMTNIRS will probe the physics of young stellar objects and their disks across the mass spectrum from their earliest phases through their maturity. The short wavelength channels will let us measure effective temperatures, surface gravities, rotation velocities, and magnetic fields from the photospheres, as well as accretion rates and the flux distribution from the inner disks. The long wavelength channels grant access to the molecular emission line spectrum of the protostellar disks where the velocity-resolved multi-line spectra will provide us with spatially resolved information about excitation and chemistry. GMTNIRS will have sufficient sensitivity to study very young sources down to well below the hydrogen burning limit and to detect lines from the nascent photospheres of highly embedded, higher-mass objects.

Studies of stellar evolution and the star formation history of the Galaxy will also benefit from the advanced capabilities of GMTNIRS. Use of the near-IR allows us to study objects throughout the galaxy by penetrating through the interstellar extinction. For the coolest stars, the much cleaner near-IR spectra facilitate quantitative measures of stellar abundances not possible at visible wavelengths.[11] Molecular lines probe the variation in isotopic abundances for C,N,O and other key species.

GMTNIRS also has a significant role to play in interstellar medium studies; of jets from protostars, shocks from supernova remnants and other sources, dense gas responding to UV illumination from nearby stars, and molecular absorption along high column density lines-of-sight through the Galaxy. The GMT Science Advisory Group will consider these science areas in formulating the science requirements that underlie the technical specifications of the instrument.

2. OPTICS AND OPTICAL DESIGN

2.1 Immersion gratings

Silicon immersion echelle gratings are the key optical element in the GMTNIRS design. Collimated light passes through a flat entrance surface and strikes the blazed grating inside the monolithic Si prism (Figure 2). Since Si has a refractive index of 3.4 in the IR, the wavelength inside the medium is 3.4 times smaller than the vacuum wavelength and the diffraction-limited resolving power is 3.4 times greater than that of a front-surface reflection grating of the same physical size. Using microlithography, we can create much coarser grooves than by mechanical ruling. The coarser grooves make it possible to operate in high order where we can match the length of the free spectral range to the detector size at our desired pixel sampling. After a lengthy development process, we can now produce Si immersion gratings of sufficient size and accuracy to meet the needs of GMTNIRS.[12-15] Model CA1, the immersion grating used in our existing instrument, IGRINS, has a peak to valley wavefront error of 0.16 waves at 633 nm, measured from the front surface.[13] This means that the error in immersion is less than $\lambda/4$ down to below the short wavelength end of the H band. The measured efficiency at the peak of the blaze, including the losses at the front surface, is ~75%.[13]

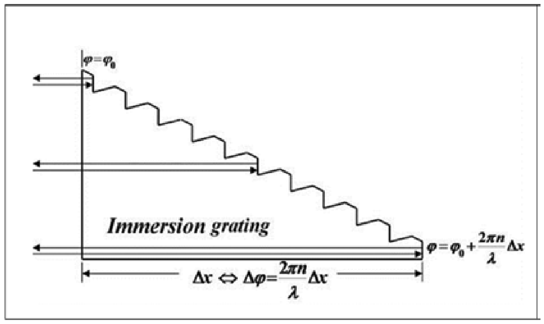

Figure 2. Functional illustration of a silicon immersion grating.[12] Collimated light enters from the left and strikes the grating surface from inside the dielectric material. The dispersed light then exits to the left through the anti-reflection coated entrance/exit surface. The path length difference in waves between the leading (top) and trailing (bottom) edges of the beam determines the diffraction limited resolving power.

2.2 Why adaptive optics?

By placing GMTNIRS behind the GMT facility AO system, we are able to keep the instrument size small, despite the desire for high spectral resolution on a large telescope. Adaptive optics breaks the curve of spectrograph growth with increasing telescope aperture by freeing the instrument designer from the need to maintain a slit size comparable to the seeing disk size while the size of the diffraction image shrinks. This advantage of AO has been present at all telescope apertures beyond 2-3m. With the jump from 8-10m class telescopes to 20-30m telescopes and with the recent improvements in AO Strehl and with the use of adaptive secondaries to minimize the emissivity penalty of adaptive optics systems, AO also offers clear improvements in sensitivity over natural seeing instruments when operating in the background limited regime. In the equation below, we estimate the ratio of the signal to noise for an AO instrument $(S/N)_{AO}$ to that of a natural seeing instrument $(S/N)_{NS}$ when photon noise from the sky and telescope dominate over detector read noise and dark current. In this equation, we take into account the loss due to low Strehl and slit loss for the adaptive optics case, η_{strehl} and the slit loss in the natural seeing case η_{slit}. The emissivity of the telescope and any additional AO optics, ε_{tel} and ε_{AO}, respectively, appear both as a throughput loss in the first term on the right and as a noise source in the second term. The solid angle per resolution element in the natural seeing case is Ω_{slit} and, in the adaptive optics case where it is some factor m (order, a few) larger than the diffraction limited solid angle, is $m\Omega_{diff}$. These terms also factor into the noise from the background. For an 8m telescope with a few extra warm surfaces in its AO system, the sensitivity ratio is of order unity. Going to a 20m class telescope with an adaptive secondary, the sensitivity of the AO system becomes a factor of 20 better than that of the natural seeing instrument, largely due to the increase in the solid angle ratio.

$$\frac{(S/N)_{AO}}{(S/N)_{NS}} = \frac{\eta_{strehl}\,(1-(\varepsilon_{tel}+\varepsilon_{AO}))}{\eta_{slit}\,(1-\varepsilon_{tel})} \left[\frac{\Omega_{slit}}{m\Omega_{diff}}\;\frac{\varepsilon_{tel}}{\varepsilon_{tel}+\varepsilon_{AO}}\right]^{\frac{1}{2}}$$

2.3 Optical design and trades

All of GMTNIRS resides within a cryostat on the rotating instrument platform, apart from a warm calibration system that can produce a beam matched to the telescope f-ratio and inject continuum or line radiation from a diffuse source into the instrument. Inside the cryostat, the instrument optics form an image of the pupil where we place a rotatable physical cold stop to block light from the warm interstices between the GMT primary segments. The pupil stop is the only moving element within the cryostat. Near the pupil stop, a partially reflecting flat removes a small portion of the K-band light for the on-axis wavefront sensor.

After the foreoptics, GMTNIRS reimages the telescope focus to a single fixed slit. The gold-coated Si slit plate reflects the remainder of the light from the focal plane to a K-band camera used for setup and position confirmation. Following slit, a series of dichroics divides the light between the individual spectrograph units for the five atmospheric windows covered by the instrument. The first dichroic at 2.7 μm splits J,H, and K from L and M. On the short-wavelength side, a refractive collimator produces a 25 mm diameter beam that feeds directly to the immersion grating echelles for the individual units (Figure 3), in each case at a small off-Littrow angle. The dispersed light from the echelle then goes directly to a volume phase holographic cross-disperser and into an all-refractive camera. The relatively narrow band covered by each camera simplifies the compensation of chromatic aberration. The basic design of each of these units is the same, with small variations to allow for the difference in wavelength and spectral grasp. We choose the echelle grating constants for each spectrograph unit such that the free spectral range of the lowest order fits comfortably onto the detector for that unit. The cross-disperser grating dispersion then places onto the detector the orders needed to cover a given spectral window. With R=50,000 and 4 pixel sampling across the slit, we are able to provide a slit length of 1.2 arc seconds in all of the spectrograph units.

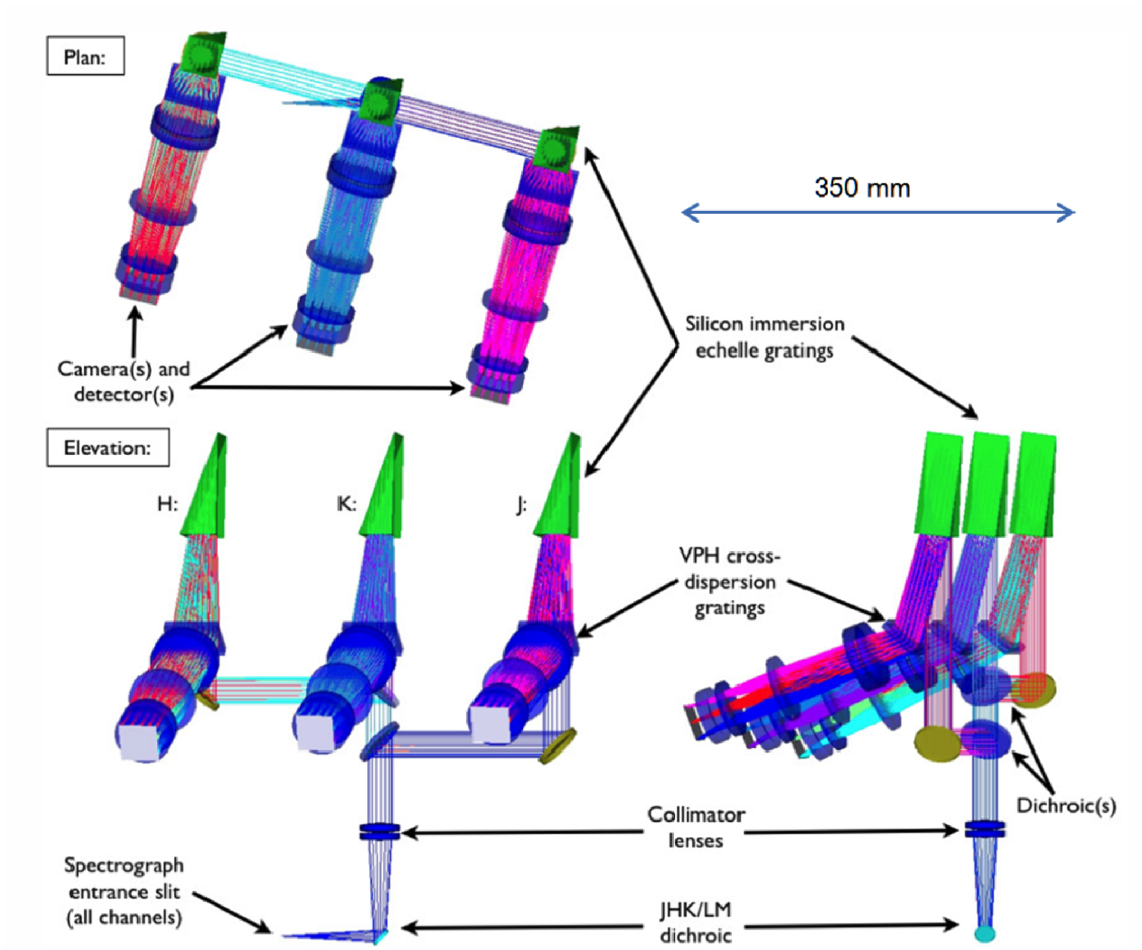

Figure 3. Layout of the JHK spectrograph units. A series of dichroics divides the light between the subunits. Each has its own immersion echelle, VPH cross-disperser, and 2048^2 HgCdTe detector array.

The design of the L and M band spectrograph units is much less of a settled issue. The two most important points in tension with each other are what the minimum requirement on resolving power is and how hard it is to manufacture an immersion grating of a given size. The point design at the time of the conceptual design review in the fall of 2011 called for R= $\lambda/\Delta\lambda$ = 100,000 in an 85 milli arc-second slit and required the use of 200 mm long R3 immersion gratings. As part of the initial phase of our preliminary design study, we are considering the increase in science yield as a function of R going from 50,000 to 100,000 and juxtaposing that with the rising cost and risk of producing gratings going from 100 mm to 200 mm in length. We are looking into whether we can break the correlation between R and cost/risk by going to gratings with a larger value of tanβ or by reducing the slit width. As an example, we assess this last point by looking at loss vs. slit size for the longest wavelength (M) band where the diffraction limited point spread function is largest (Figure 4). At the same time, we are looking at improvements in simplicity, cost, or efficiency over the point design for L and M by varying the optical layout, reducing the slit sampling to permit smaller detector arrays (the L band point design calls for a 4096^2 array), or by dividing the L band with an additional dichroic.

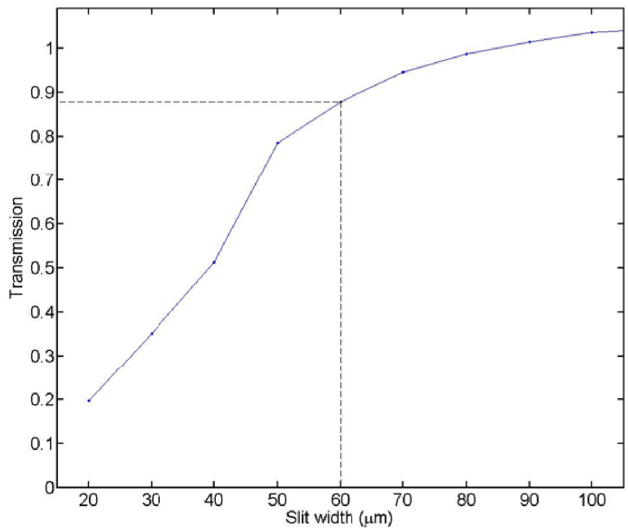

Figure 4. Slit throughput vs. slit width for the M band, normalized to the throughput of the 85 mas slit from the point design. The calculation assumes negligible loss due to tip/tilt guiding errors.

3. OPTOMECHANICAL DESIGN AND SOFTWARE

3.1 IGRINS as forerunner

The plan for GMTNIRS calls for technical elements that had never been field-tested in astronomical instruments including Si immersion gratings and K-band VPH cross-dispersers. The absence of cold mechanisms (apart from the rotating pupil stop) in GMTNIRS brings significant advantages in design, construction, and operation of both the hardware and the software. It also raises the specter of significant difficulties during instrument integration and alignment. In order to develop the hardware and software design and to demonstrate and evaluate some of these new elements, the UT/KASI team constructed a scaled-down version of GMTNIRS for use on 3-8m class telescopes. This instrument, IGRINS, has had its first commissioning runs in March-May 2014 at the UT McDonald Observatory's 2.7m Harlan Smith telescope. IGRINS is a natural-seeing instrument that features a single Si immersion echelle grating and VPH cross dispersers. It covers all of the H and K atmospheric windows in a single exposure at R=40,000. Since there are no cold moving parts and all grating angles remain constant, the operation and data analysis for the instrument are considerably simpler than for most cross-dispersed echelle spectrographs.[16] Two recent SPIE papers describe the design of IGRINS and the results of the initial on-sky testing, all of which has gone extremely well.[17,18] The instrument meets all of its design goals for sensitivity, resolution and stability. The alignment process, our first attempt at the scheme planned for GMTNIRS led to diffraction-limited performance after a limited number (5-7) of adjustment cooldowns. The IGRINS experience assures us that a "build to print" and fixed-format concept can work very well in a cryogenic high-resolution instrument.

3.2 Design and integration strategy

The optomechanical design philosophy for GMTNIRS closely follows our design for IGRINS.[17,18] With GMTNIRS, the only cryogenic moving part is a rotating, transmissive baffle at an image of the pupil. This baffle masks the parts of the pupil not looking at the sky and rotates with respect to the slit as the instrument platform rotates to change the slit orientation. The speed and field of view of the GMTNIRS spectrograph cameras is close enough to the values for IGRINS, that we are confident that our "build to print" strategy will work. With IGRINS, a tolerance analysis of the optical design showed that precision machining could place the parts close enough to their required positions that the pitch, yaw and piston of each spectrograph detector could serve as a compensator. The adjustments inside the instrument will therefore include only shims for tip of the echelle and cross-disperser gratings and pitch of the detectors and a set of calibrated bumpers to provide yaw and piston adjustment for the gratings. Pinned plates below these adjustable sections permit us to remove subassemblies to change out the precision mechanical bumpers.

The spectrograph cameras are the most alignment-sensitive parts. In the IGRINS design, we held off the manufacture of the final axial spacers until we had melt data for the different lens glasses and as-built radii for each element. For the reflective parts with power, we placed tight specs on the internal orientation of the optical axis with respect to the mechanical envelope of each part. We performed interferometric testing of the subassemblies at optical wavelengths at cryogenic temperatures.[19] We will follow a similar path with GMTNIRS.

The IGRINS experience tells us that, even with a complex system like GMTNIRS that has no moveable mechanical adjustments, it is possible to reach a good alignment of all elements in a very limited number of cooldowns (<10) while enjoying the virtues of a system that will not come out of alignment. The focus compensator for the cold-stop system is the telescope, so this system is ready to use once it has been tested interferometrically. By replacing the tilted slit mirror with a target plate, we are able to determine the yaw and piston of the slit viewer and to make it parfocal with the slit. This target plate has a large central hole. We then bring a pinhole at the external focus to the center of this hole, using the slit camera to insure that it is in focus. If we illuminate this hole with a ThAr lamp, we produce a series of monochromatic images in the spectrograph focal planes that allow us to determine the orientation of the cross-disperser and the pitch, yaw, and focus of the spectrograph detectors. When we reinstall the slit, light from an external continuum sources allows us to tip the immersion echelle to center the blaze. We will use a similar strategy for the GMTNIRS alignment.

3.3 Description of design

Figure 5 shows the cryostat mounted on the instrument platform. The total height, including the support legs, is 1.6m while the cryostat itself is 2m in length. The legs support the midsection that, in turn, supports the internal cryogenic elements and contains the vacuum fittings and feedthroughs for the electronics and the cryocoolers. We can gain access

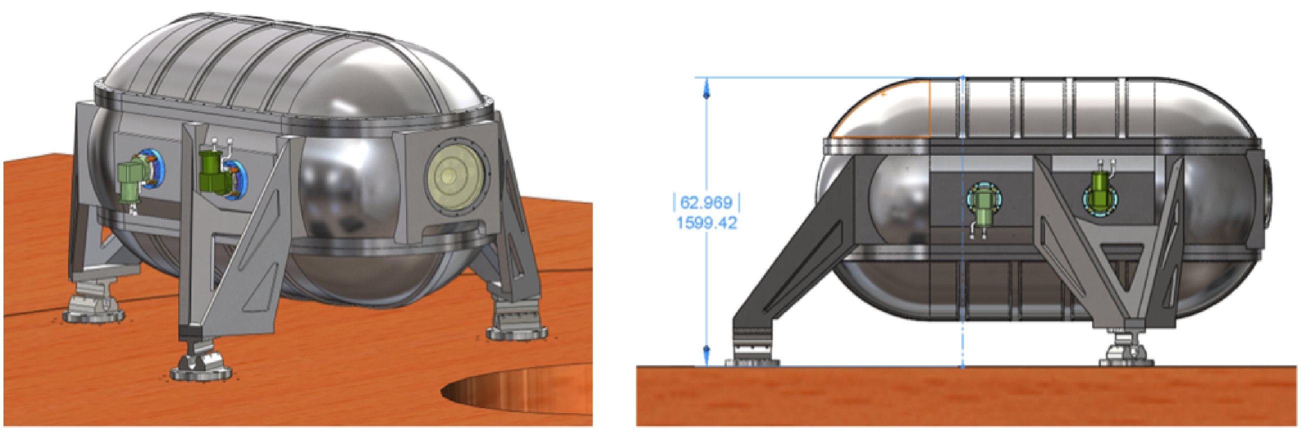

Figure 5. GMTNIRS cryostat mounted on the GMT instrument platform. The entrance window is on the right. The top and bottom covers can be removed for access to both sides of the optical bench. The upper number in the right hand figure is the height in inches while the lower number is the height in millimeters.

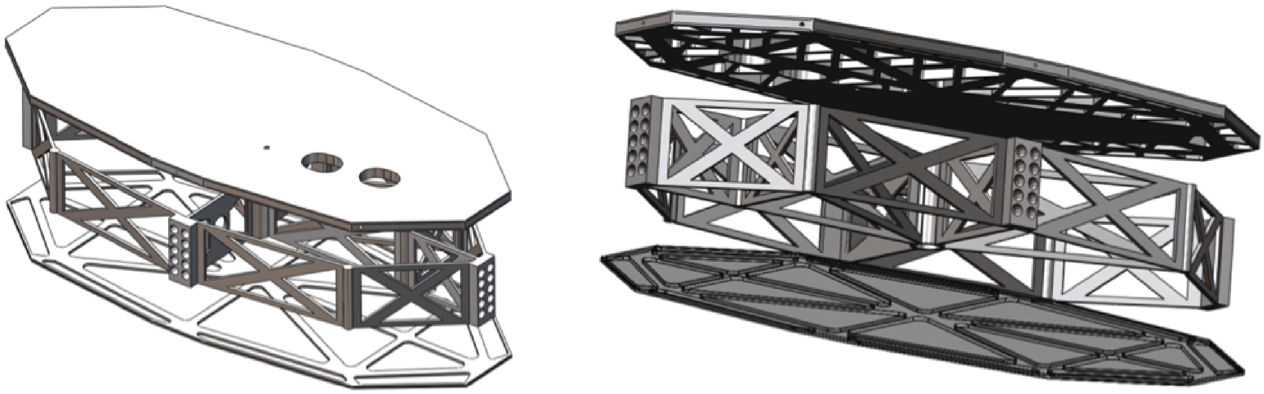

Figure 6. Cryogenic optical bench. The two larger holes in the top surface are part of the pupil reimager light path in the foreoptics. The L band spectrograph mounts to the bottom of the bench. The space frame and bottom cap plate stiffen the bench and serve as mounting points for radiation shielding.

to both the top and bottom of the optical bench by removing the covers while keeping everything else in place. The cryogenic optical bench (Figure 6) connects to the cryostat midsection via a set of G10 standoffs. The top of the bench holds the foreoptics and a mount for the modular J,H, and K spectrographs and for the M band unit. Light for the L band spectrograph feeds through to the bottom of the bench. The space frame and support plate below the bench provide the required stiffness.

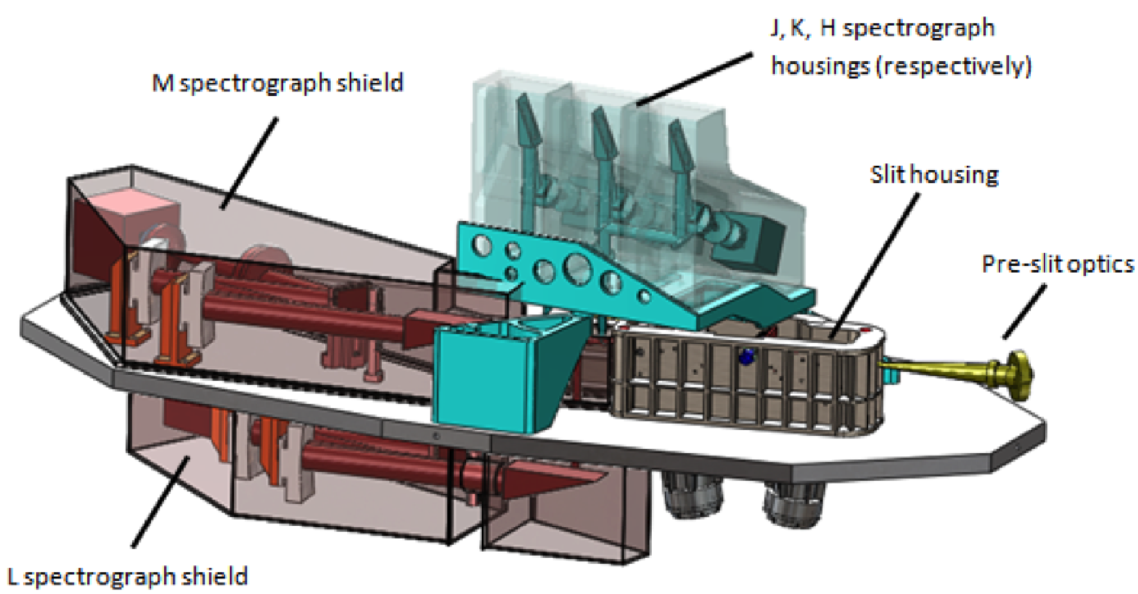

Figure 7. Cutaway layout showing the optical assemblies on the bench. The three short wavelength units mount on a platform above the bench. The slit housing shown here is not part of the current design.

A key element of the cryogenic part of the system not illustrated in Fig. 6 and Fig. 7 is the thermal control system. This consists of a series of copper bars and straps leading from the cold stages to the various subsystems, as well as heaters and temperature sensors. The strap thicknesses are set to remove enough heat to keep each subsystem just below its design temperature and the heaters then supply control to maintain the target temperature. The shields and bench are fairly loosely controlled. The detectors and immersion gratings, which require control at a level below 100mK, are thermally isolated from their surroundings and then each have their own control loops.

3.4 Consequences

The design philosophy for GMTNIRS runs counter to the usual practice in large facility instruments. GMTNIRS has a fixed slit that is common to all wavelength bands and, apart from the rotating pupil stop, no moving parts. We can change the orientation of the slit on the sky by rotating the instrument platform. We can only change the slit width by warming up the instrument and replacing the reflective slit plate. We do not plan to do this after the instrument and the adaptive optics system have been fully commissioned. By covering all accessible IR wavelengths at once, there is no need for changes in grating angles or blocking filters. With the choice of an adaptive optics feed, the tradeoff between throughput and slit width is not necessary.

There are significant advantages to the current design. The enormous spectral grasp at high resolution greatly increases the observing speed for projects that require a panchromatic view of an object's spectrum. The fixed format makes queue observing much easier since there are no configuration changes between observations and since the same calibration will serve for most programs. Most importantly, the fixed format makes it possible to design and build a data reduction pipeline that will produce science-quality results with almost no human intervention. For cross-dispersed echelle spectroscopy, where data reduction is often a significant chore, this feature will reduce barriers to entry and result in a broader user community. The fixed format has the further advantage of providing long-term stability for projects that want to examine source variability or to carry out surveys over an extended period.

4. PLANS

GMTNIRS is currently beginning its preliminary design phase. Because of the critical risk that the immersion gratings represent to the project and because of the long lead time for these components, the production of the immersion grating surfaces will occur during this phase. Over the coming year, we will finalize the science requirements for the instrument and then arrive at a set of performance requirements by trading the science capabilities against the costs and risks, principally those related to the manufacture of the gratings. This exercise will lead to final specifications for the gratings that will allow us to proceed with procurement of material for their production. At the end of this grating development phase, we will begin the detailed optomechanical design. With the thorough work from the conceptual design and the heritage of IGRINS, we expect to be able to complete the preliminary design phase of the project fairly rapidly thereafter.

We thank our many colleagues who contributed to the GMTNIRS conceptual design. The design of GMTNIRS is supported by the Giant Magellan Telescope Organization with additional support from the University of Texas at Austin and the Korea Astronomy and Space Science Institute. Development of the immersion gratings to be used in GMTNIRS has been supported by NASA through grant NNX10AC68G and NSF ATI grant NSF0705058 to the University of Texas at Austin.

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