GMTNIRS (Giant Magellan Telescope near-infrared spectrograph): design concept

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ABSTRACT

We are designing a sensitive high resolution (R=60,000-100,000) spectrograph for the Giant Magellan Telescope (GMTNIRS, the GMT Near-Infrared Spectrograph). Using large-format IR arrays and silicon immersion gratings, this instrument will cover all of the J (longer than 1.1 μm), H, and K atmospheric windows or all of the L and M windows in a single exposure. GMTNIRS makes use of the GMT adaptive optics system for all bands. The small slits will offer the possibility of spatially resolved spectroscopy as well as superior sensitivity and wavelength coverage. The GMTNIRS team is composed of scientists and engineers at the University of Texas, the Korea Astronomy and Space Science Institute, and Kyung Hee University. In this paper, we describe the optical and mechanical design of the instrument. The principal innovative feature of the design is the use of silicon immersion gratings which are now being produced by our team with sufficient quality to permit designs with high resolving power and broad instantaneous wavelength coverage across the near-IR.

Keywords: GMT, near-infrared, spectrograph, high resolution, silicon, immersion grating, AO

1. INTRODUCTION

The next generation of high resolution ($R=\lambda/\Delta\lambda > 30,000$) near-IR spectrographs must overcome three disadvantages that limited the pioneering instruments in this field: (1) High detector read noise meant that the instruments could not benefit from the lower backgrounds present at high dispersions. (2) The combination of small detector formats and limitations on the coarseness of ruled echelle gratings meant that it was difficult to observe large continuous swaths of wavelength space. (3) Gratings and collimated beam sizes in these cryogenic instruments had to be very large to permit instruments to have sufficiently large slit width- resolving power products. The detector noise and array size problems have largely disappeared, but we still cannot produce coarse enough front surface gratings and designs using such gratings remain uncomfortably large. It is against this background that the University of Texas (UT) group has developed silicon immersion gratings that promise broad, continuous wavelength coverage at high spectral resolution in instruments with volumes an order of magnitude smaller than those of spectrometers using front-surface echelle gratings.

In 2006, we conducted a very preliminary conceptual design study for a 1-5 μm R=30,000-100,000 spectrograph for the GMT[1], calling for a natural seeing module at 1.1-2.5 μm and an adaptive optics module for the L and M bands. Since that study, the UT group has improved the techniques for manufacturing immersion gratings and has produced silicon grisms for use in SOFIA/FORCAST[2] and JWST/NIRCam[3, 4], and UT and the Korea Astronomy and Space Science Institute (KASI) have joined together to build a near-IR spectrograph, IGRINS[5]. We present here our current plans for the design of a compact near-IR spectrometer for the Giant Magellan Telescope that offers high throughput, high spectral resolution, and a very significant increase in spectral grasp.

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2. INSTRUMENT CONCEPT

2.1 Science Goals

GMTNIRS will permit GMT to make significant and unique contributions to studies of many aspects of the formation, evolution and nature of stars and planetary systems, and the abundances and aspects of stellar evolution in our own and nearby galaxies.

A recent review of embedded protostars[6] suggested as key goals substantially enlarging the studied samples and probing a variety of different environments. Such works can put the physical picture of how pre-main sequence evolution unfolds on a much more solid basis by providing concrete tests of protostellar evolution models. Extinctions toward young stellar objects in their early evolutionary phases, however, can be quite high. If one is to study YSOs using a consistent methodology across the entire pre-main sequence life of such objects, observations must be carried out in the near-IR where the stellar photospheres contribute a significant fraction of the total light and where the extinction is significantly less than at optical wavelengths. High spectral resolution is extremely valuable for a number of reasons. Equivalent widths are not particularly useful quantities in studies of YSO photospheres since accretion shocks and circumstellar disks and envelopes can contribute an unknown and often time-variable portion of the near-IR continuum. Line shapes provide a means of deriving stellar parameters that is robust against the presence of this IR excess[7]. For some parameters such as rotation rates, radial velocity (RV), RV variation, and magnetic field strengths, resolved line profiles are an absolute necessity. With the broad spectral grasp of GMTNIRS in the near-IR, we will be able to determine fundamental stellar properties (T_{eff}, log*g*, [Fe/H], *vsini*, magnetic field B_*) of embedded objects, as well as the accretion rate of material onto the protostars and the shape of the non-photospheric excess spectrum from a single observation.

GMTNIRS will also be a powerful tool for studies of the chemistry and structure of protoplanetary disks. With a resolving power of 10^5 and its broad spectral coverage, GMTNIRS will be able to provide velocity-resolved profiles of many molecular emission lines at once. Using spectroastrometric techniques on the brighter lines[8], it will be possible to probe the distribution of the emission on scales of the order of an AU. The access to lines arising in higher energy levels and to thermal lines of critical molecules such as water and methane will make GMTNIRS a powerful complement to ALMA in studies of protostellar disks.

We can gain a more complete and richer picture of planet formation if we extend this work to much lower mass host stars. GMTNIRS will be the first instrument capable of using reflex motions to discover many Jupiter and Saturn-mass objects orbiting brown dwarfs and testing whether brown dwarfs, like main-sequence stars of masses down to 0.1 M_{sun}, can host their own planetary systems[9].

The sensitivity of GMTNIRS for studies of late-type stars and its ability to make use of its broad spectral grasp to measure abundances of different isotopic variants of OH and CO will permit the spectrograph to make significant contributions to important questions in stellar evolution and nucleosynthesis. In the area of stellar evolution, puzzles likely to remain unsolved in the coming decade concern the evolution of red giants and AGB stars: What is the structure of their photospheres? What nucleosynthesis is achieved and mixed to the surface? What are the mass loss rates? These questions demand observations of and comparisons between collections of stars of different masses, luminosities and metallicities. At present, high resolution IR spectroscopy is limited to luminous giants in the Magellanic Clouds and the Galactic bulge. GMTNIRS will allow more thorough coverage of the AGB and RGB branches, as well as fainter massive stars to the cool end of the Hertzsprung gap. In the case of large-scale nucleosynthesis, observations of stars in the same stellar systems (Magellanic Clouds, dwarf galaxies, and globular clusters) and different components of the Galactic disk, bulge, and halo will reveal the chemical history of the system and thus provide clues to the formation and evolution of these galaxies and clusters.

2.2 Overall Concept

GMTNIRS will consist of two modules. In the short wavelength (JHK) module, the resolving power will be ~60,000 and the instrument observes the entire usable region from 1.1-2.5 μm in a single exposure. In the long wavelength (LM) module, R=100,000 and the instrument observes the accessible parts of the 2.9-5.3 μm region in a single exposure. Both modules will operate behind the GMT facility adaptive optics system.

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In the J, H, and K atmospheric windows, stellar photospheres are the principal targets and R=60,000 should be sufficient to resolve photospheric lines in almost all cases. With an adaptive optics feed, there is little reason to provide wider slits for work requiring less resolving power. Binning can provide the optimal improvement in S/N in the source noise or background limits. In the detector noise limit, gaining sensitivity from lower R would require the complication of a second camera. Much of the GMTNIRS science case for the L and M band involves observations of molecular lines. These lines are narrow and the scientific gain in measuring their detailed shapes can be substantial. R=100,000 represents a practical limit for immersion gratings when using a 2.5 λ/D slit at 5 μm (20 cm immersion gratings). At the proposed sampling of 4 pixels across the slit, higher resolving power is in principal possible and we will study the trades involved in using a narrower slit.

We split GMTNIRS into two modules for the following technical arguments. The Teledyne HgCdTe detectors are available with 1.75, 2.5, and 5.3 μm cutoffs. Use of shorter wavelength detectors in the JHK module eases the filtering and baffling problems and could allow us to operate this section at higher temperatures if desired. The grating situation, where the L and M module needs much larger gratings than the JHK module, also argues for separate spectrographs. Finally, the factor of >4 in wavelength across our whole range makes it hard to use a single slit width in a diffraction-limited system.

Since GMTNIRS has only two modes, JHK spectroscopy or LM spectroscopy with no further choices, it will be easy to plan and carry out observations. The instrument can take flat fields and spectral calibration exposures internally, so it can be prepared to operate whenever it is needed. A single movable mirror will change the instrument between JHK and LM operation. The fixed operating modes and the resultant stability of the instrument will make it easy to reduce the data in a pipeline. One design goal for the software is to provide science quality data to users at the end of each night.

2.3 Choice of Adaptive Optics Feed

In the 2006 version of design concept[1], we had baselined an instrument with a JHK module using natural seeing and an LM module fed by the AO system. We are currently considering only a configuration employing the AO front-end at all wavelengths. For a 25-m primary, the all-AO configuration seems a clear choice. The issue of large instrument size for natural seeing instruments on large telescopes is well known. The resolving power slit-width product, Rθ, is given by:

$$R\theta = R_{diff}\theta_{diff} = 2n(W/D)\tan\beta \quad (1)$$

where n is the refractive index of the medium (3.42 for a silicon immersion grating), W the width of the spectrograph collimated beam, D the telescope diameter, and β the incidence angle on the grating. For fixed instrument parameters, the resolving power of a spectrograph will be lower than the diffraction limited resolving power R_{diff} by a factor θ_{diff}/θ. An AO instrument will typically have a slit width $\theta = k\theta_{diff}$ where k~2 and is independent of the telescope size. A natural seeing instrument will want $\theta \sim \theta_{seeing}$ leading θ_{diff}/θ to scale as 1/D and therefore requiring larger values of $W\tan\beta$ to maintain a maximum R. With natural seeing, we required a 30cm immersion grating in order to get even an 0.3" slit at R=50,000. Unfortunately, 20cm is currently the largest size grating one can make reliably since it is the size of the largest high resistivity float zone Si boules. With natural seeing, therefore, throughput losses are a certainty and we will not gain signal as D^2. A second argument for AO comes from a consideration of the background. Adaptive optics systems will always cost some background because of added warm emissivity but this cost is offset by a gain over natural seeing instruments as $\Omega_{seeing}/\Omega_{diff}$ grows. By D=24m, S/N considerations strongly favor an AO instrument.

3. OPTICAL AND MECHANICAL DESIGN

The GMTNIRS spectrograph consists of four optomechanical subunits: a calibration box, a foreoptics section, a short wavelength (JHK) spectrograph module containing three individual spectrographs for the J, H, and K bands, and a long wavelength (LM) spectrograph module containing two individual L and M band spectrographs. Apart from the calibration box, all optical elements and detectors reside within the cryostat. Within the cryostat, only the foreoptics unit will contain moving parts. Stepper motors mounted on the bottom of the dewar will drive the actuators for these parts. The five cross-dispersed spectrographs will all operate as fixed units.

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The f/8 beam relayed by the AO system first encounters the GMTNIRS calibration box. This box can insert absorption gas cells or partial reflectors (e.g. directed toward a laser comb source) into the beam for simultaneous wavelength calibration. Flip mirrors within this box can direct the view of the spectrographs toward discharge lamps and continuum calibration sources. When the flip mirror is out of the way, the light from the telescope enters the GMTNIRS cryostat.
The foreoptics section includes the slit viewing cameras for each module. The light reaches the slit for the LM module along the straight-through path and the JHK slit after reflection by a flip mirror and a second fold. After the slit with its reflective slit jaw canted to feed a guide camera, a three-element reimager relays the telescope focus to the entrance of the single-band spectrograph units. Each of the single-band units contains a cross-dispersed spectrograph based on a white pupil design.

3.1 JHK module

The short wavelength module (Figure 1) is a four-layer stack of optical benches. The lowest level contains the slit viewing optics and detector. A fold followed by a second fold/dichroic brings the beam into each of the J, H, and K units which are mechanically identical, though the specifications of the optical elements will differ slightly: A fold sends the beam to an off-axis parabolic collimator which images a pupil onto the entrance face of the R3 silicon immersion grating. The dispersed beam returns to the parabola and after passing through a dispersed focus is recollimated by a second off-axis (elliptical) mirror that transfers the system (white) pupil onto the VPHG used as a cross-disperser. Immediately following the VPHG, the beam is fed into the spectrograph camera and imaged onto the 2048^2 short wavelength HgCdTe detector. The AO feed and the immersion grating design result in very modest sizes for the single-band spectrographs. In the current working design, each single-band unit has dimensions 80 by 500 by 560 mm. The angular extent of the H2RG corresponds to 9.8x9.8 deg^2, requiring a camera with a 14.0 degree diameter field of view. The camera f/ratio is generously slow compared to other spectrographs with fast (~f/1.3) cameras, which makes it easier to balance monochromatic field aberrations as well as chromatic aberrations with 5 spherical lenses.

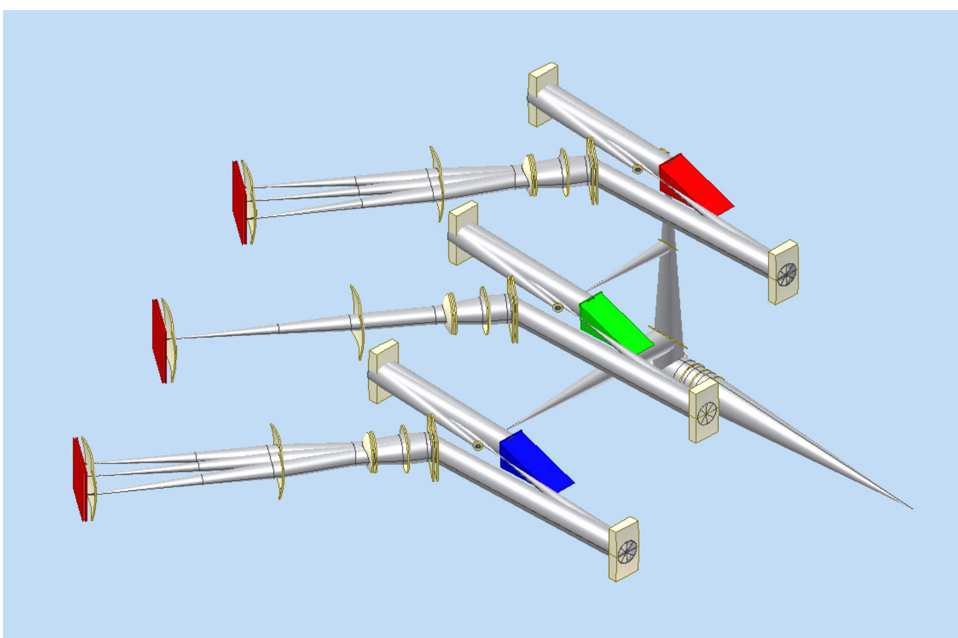

Figure 1. 3-D layout of the JHK spectrograph module. The single-band spectrograph units are fed by fold mirror/dichroics and have identical layouts, apart from the horizontal offset that compensates the vertical path difference. The dispersion of the grating is along the x-axis (vertical in the projected image). The VPHG before the first camera lens separates the overlapping orders of the immersion echelle grating in the direction that lies in the YZ plane and is perpendicular to the optical axis of the camera.

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3.2 LM module

The layout of the L and M band spectrograph units (Figure 2) is similar to that of the J,H, and K band units. Because of the higher resolving power required (R=100,000) and as a result of the large fractional width of the bands, the L and M windows do not fit on a single 2048^2 array but fit rather comfortably onto a 4096^2 array (Figure 3). The higher resolving power and the longer wavelength push up the size of the grating and at R3 result in a beam diameter of 52mm. The collimator forming the first pupil, M1 (paraboloid), and the collimator forming the white pupil, M2 (ellipsoid), are both off-axis sections. The main dispersion element is a silicon immersion (R3) echelle grating. We use surface relief gratings in reflection to separate overlapped orders. The cross-disperser operates in first order but in an off-Littrow arrangement. The beam after the cross-disperser is fed into the f/6.1 spectrograph camera.

The angular extent of the LM module's focal plane corresponds to 11x11 deg^2. This leads to a camera with a 15.6^o circular field of view. The camera field size is moderate for the given f/ratio and the camera design can balance monochromatic field aberrations and chromatic aberrations with 4 spherical lenses with the largest having a ~110mm diameter. With excellent internal transmission in the L and M bands and a proper selection of broadband anti-reflection coatings, the camera design will have high throughput. In the current conceptual design the camera-only image quality is diffraction limited. However, since there are aberrations arising in the spectrograph optics before the camera, further design optimization is needed to improve the overall image quality.

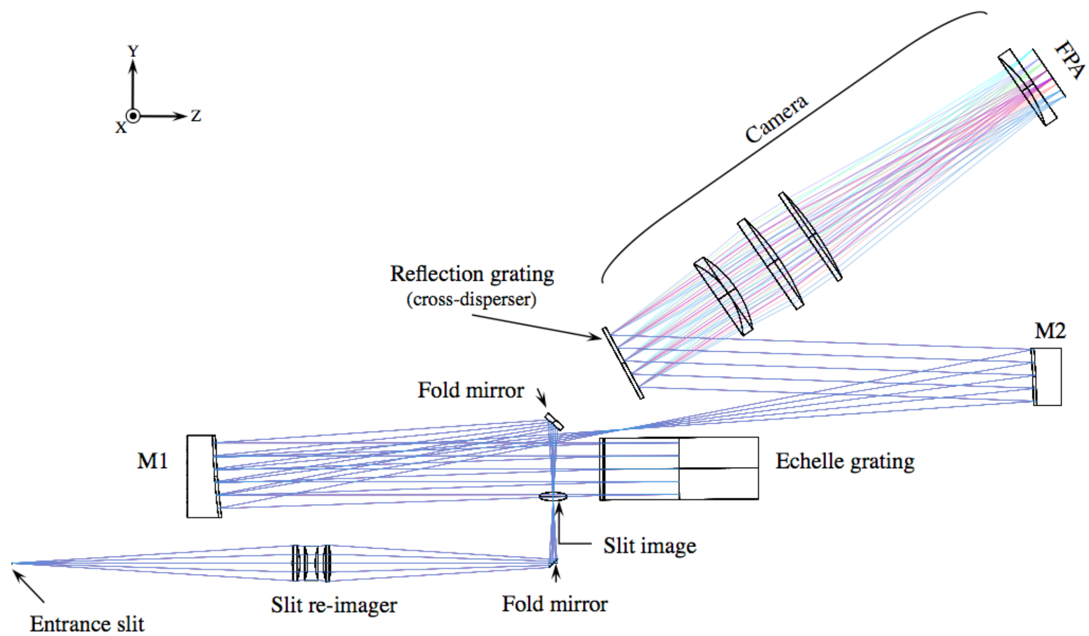

Figure 2. Layout of the L band unit. The image of the slit relayed to the unit by the foreoptics module sits at the entrance. M1 collimates the light, placing a pupil on the entrance of the silicon immersion echelle grating. M1 and M2 together form a white pupil on the reflection grating that serves as a cross-disperser. After this first-order grating, the light enters the spectrograph camera and the image of the echellogram is formed on a 4096^2 HgCdTe array. The echelle dispersion is along the X axis (in and out of the page).

3.3 Cryogenic Design

The main optical bench of GMTNIRS will be held at 50 K, where emission from components in the optical train will contribute negligible amounts of background in all bands. The heat paths of the detectors will be arranged to maintain a detector temperature of 37 K, where the dark currents are <0.01 e/s/pixel and where the detectors have been thoroughly characterized for JWST. The optical properties of the silicon immersion grating also impose a thermal stability requirement. The dominant effect is the change in refractive index with temperature. At 50 K, the thermo-optic

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coefficient of silicon dn/dT is about 2.5×10^{-5} deg^{-1} at 1.5-5 μm. As a consequence, maintaining a wavelength stability of $1/10^6$ requires that we actively stabilize the grating temperature to 0.15 K. A pair of cryocoolers mounted on the underside of the cryostat will maintain the temperature of the optical bench.

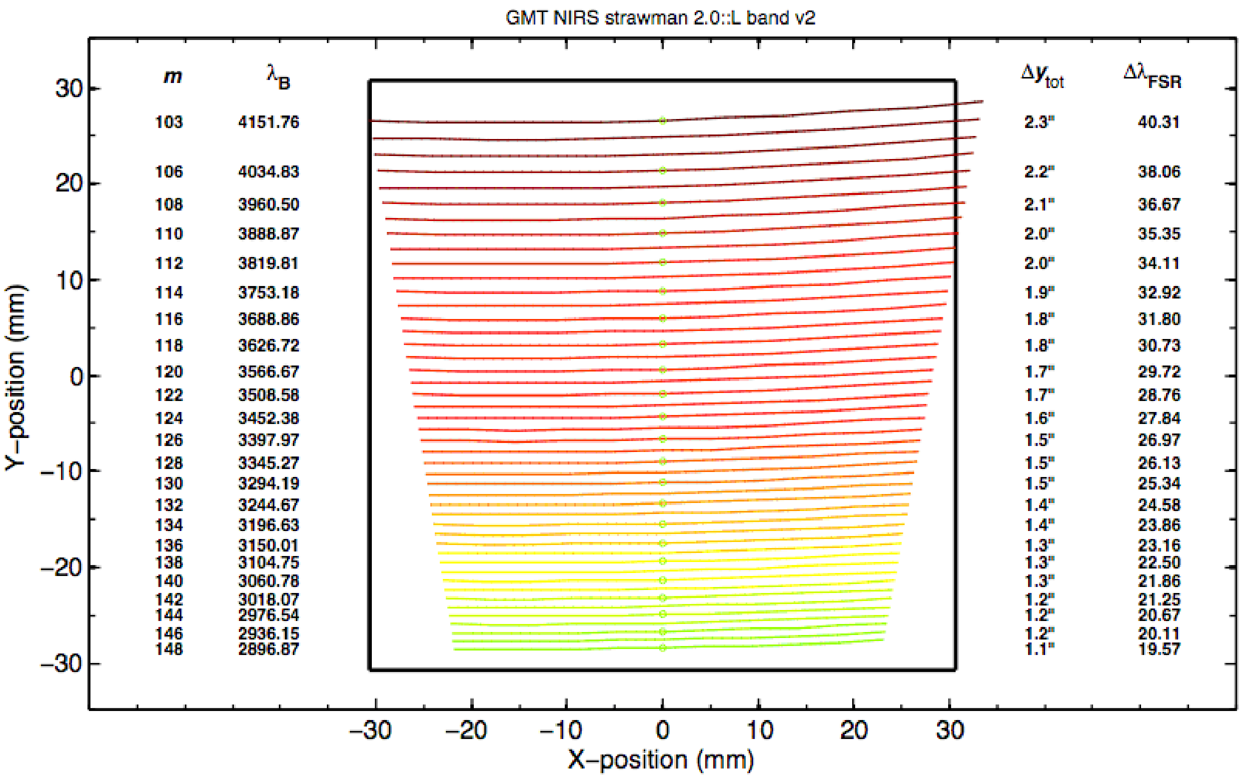

Figure 3. Echellogram for the L band spectrograph unit of GMTNIRS. The info columns list the order number, blaze wavelength (nm), order separation (arcsec), and free spectral range (nm), respectively.

4. ELECTRONICS AND SOFTWARE DESIGN

4.1 Electronics and Detectors

For the JHK module, the baseline detector is the 2048x2048 pixel HAWAII-2RG (H2RG) HgCdTe array from Teledyne Imaging Sensors. This detector, which has 18 μm pixels and a 2.5 μm cut-off wavelength, has the same device architecture as the detectors delivered to JWST and to many ground-based telescopes. For the LM module, the baseline detector is the 4096x4096, 15 μm pixel, HAWAII-4RG (H4RG). A Teledyne SIDECAR ASIC controller will control and read out each of the HxRG detectors in GMTNIRS. The GMTNIRS control system will be entirely IP based; every device that touches hardware has an IP address. All communication links will pass through a standard Ethernet LAN, so highly standard software protocols, standard hardware devices and cabling can be used to facilitate communications. This scheme lends itself naturally to a distributed control system which can evolve as needed.

4.2 Software

The software for GMTNIRS will derive significant heritage from the programs now under development for IGRINS. Figure 4 shows the layout of the GMTNIRS data and control system. The lowest level includes a control computer for

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the tip-tilt sensor and the truth wavefront sensors (if required by GMT) and two array control computers, one for the JHK module and the other for the LM module. Bandwidth requirements may lead the AO sensor control computer to include a DSP front-end. The array control computers, which will control the command and data flow from the seven IR arrays (the two slit viewing cameras and the five spectrograph arrays), will have a high degree of software heritage from the IGRINS array computer which also controls and handles data from a set of SIDECAR ASICS. These lowest-level computers will run Linux and the control code will be implemented primarily in Python.

The higher level GMTNIRS software packages will run on the instrument control computer and the data computer, which will also be implemented in Python running on a Linux OS. The observer will interact with the GMTNIRS hardware through the instrument control computer. In addition to controlling the array computers, it operates the calibration lamps and the moving parts and monitors the temperature, vacuum levels, and the power system. The telescope interface program on the control computer interacts with the telescope control system and the AO system. The commands are in text format and communicated via TCP/IP. The image data from the slit viewing cameras are directly transferred to the Quick Look View program. The spectroscopic raw data in FITS format are automatically saved on the data archive hard disk mounted on the data computer and displayed on the Quick Look View on the instrument control computer. The data reduction pipeline software on the data computer processes the raw data and shows the extracted spectra on the display of the data computer.

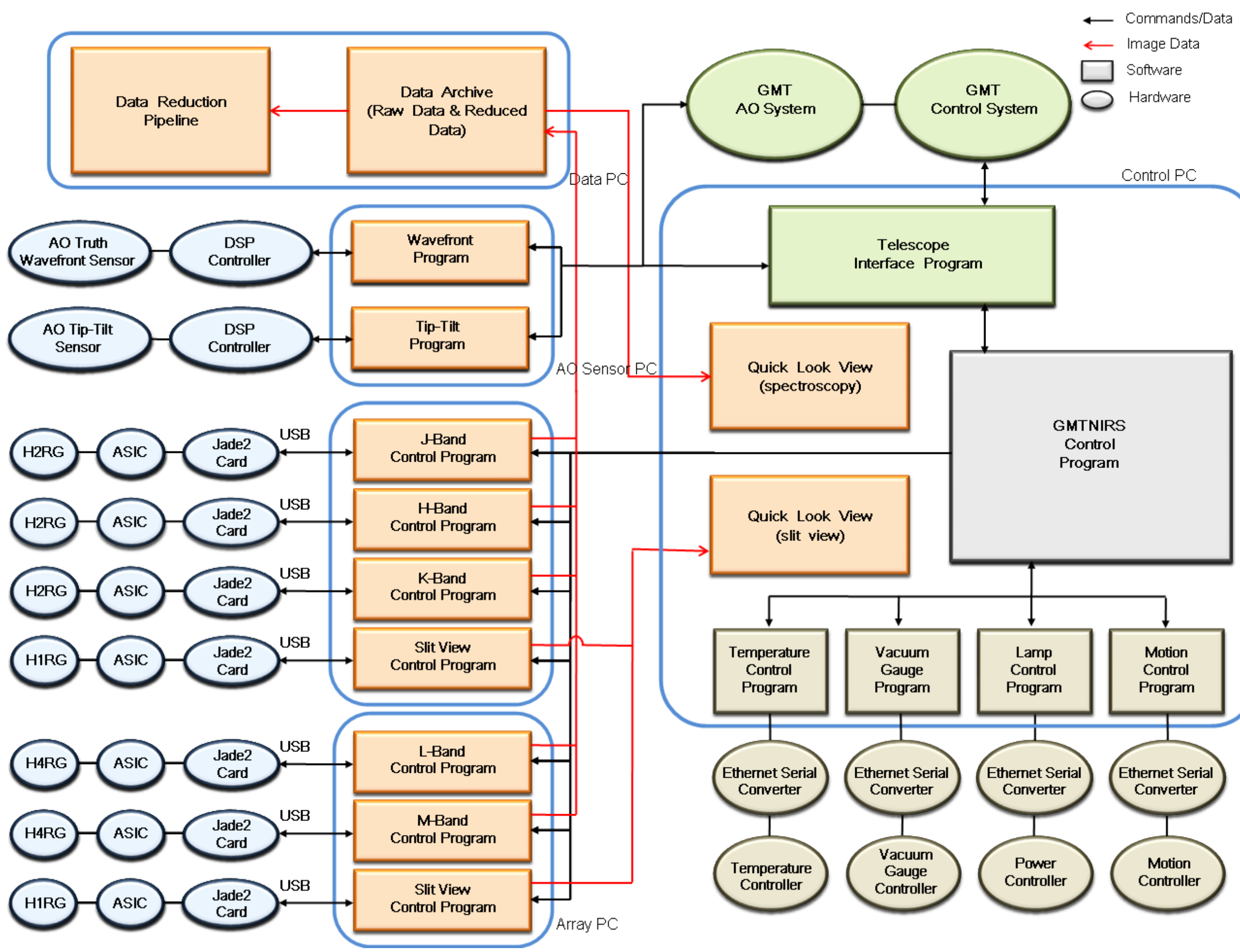

Figure 4. Electronics and Software layout

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5. SILICON IMMERSION GRATINGS

The GMTNIRS design rests on the availability of accurate, efficient silicon immersion gratings. Immersion gratings are prism-shaped reflection gratings in which the incidence light is diffracted on the grating surface inside a medium like silicon[10, 11]. The high refractive index of silicon makes the effective wavelength inside the grating shorter by a factor of 3.4 so that we can keep the same resolving power at a given slit size with a much smaller collimated beam size if we use an immersion grating rather than a front-surface grating. Also, very coarse gratings can be fabricated by silicon lithographic methods which shorten the spectral orders and makes possible continuous spectral coverage at high resolution on today's IR arrays.

The gratings for the JHK module of GMTNIRS are smaller than those currently being constructed for IGRINS, but the accuracy requirements are stringent. For optimal J-band efficiency, the rms groove positioning errors must be less than $\sim\lambda/40$ at 633nm. Periodic errors are particularly pernicious and the science requirements mean that a periodic error larger than about 4nm is not acceptable. All of the GMTNIRS gratings will be used close to the diffraction limit. As a result, the accuracy requirements apply on all scales up to the full size of the grating (20 cm at L and M).

The regularly spaced grooves in an immersion grating are the combined result of the writing step and of a process of crystal orientation, preparation, and chemical etching. These last steps must be controlled not only to position the grooves correct but also to insure that the groove surfaces are smooth and flat on nanometer scales. We are manufacturing 10 cm R3 immersion gratings for IGRINS through conventional contact lithography. A grating surface (code name CA-1) has been completed and its performance measured before cut into a prism shape[11]. Spectral ghosts are measured to be lower than 2×10^{-3} of the diffraction peak, which are produced by ~5 nm periodic errors in the groove position. Spectral grass due to scattered light from the groove surfaces are barely detected at a level of 10^{-5} of the main peak.

6. CONCLUSION

GMTNIRS will be an unprecedented spectrograph for infrared studies of star and planet formation and chemical evolution of stars and galaxies. Larger, lower noise arrays, adaptive optics, and immersion gratings together allow GMTNIRS to achieve sensitivities higher than those of today's instruments by significantly more than the square of the telescope diameters. The tremendous improvement in instantaneous spectral coverage (better than a factor 30 over existing R=60,000-100,000 spectrometers) will make this instrument even more unique and powerful. As GMTNIRS has been selected for a conceptual design study as one of the GMT instrument candidates, the instrument design will be solidified and much more detailed in the near future.

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