# Preliminary design of IGRINS
# (Immersion GRating INfrared Spectrograph)

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## ABSTRACT

The Korea Astronomy and Space Science Institute (KASI) and the Department of Astronomy at the University of Texas at Austin (UT) are developing a near infrared wide-band high resolution spectrograph, IGRINS. IGRINS can observe all of the H- and K-band atmospheric windows with a resolving power of 40,000 in a single exposure. The spectrograph uses a white pupil cross-dispersed layout and includes a dichroic to divide the light between separate H and K cameras, each provided with a 2kx2k HgCdTe detector. A silicon immersion grating serves as the primary disperser and a pair of volume phased holographic gratings serve as cross dispersers, allowing the high resolution echelle spectrograph to be very compact. IGRINS is designed to be compatible with telescopes ranging in diameter from 2.7m (the Harlan J. Smith telescope; HJST) to 4 - 8 m telescopes. Commissioning and initial operation will be on the 2.7m telescope at McDonald Observatory from 2013.

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

## 1. INSTRUMENT OVERVIEW

IGRINS will be one of a new generation of sensitive high resolution spectrographs with broad instantaneous wavelength coverage. Particularly for science cases requiring broad coverage, it will open up a new way of doing high resolution IR spectroscopy. As a result, there is a significant amount of exploratory science to be done on modest-sized telescopes.

IGRINS will cover all of the H (1.6 μm wavelength) and K (2.2 μm wavelength) atmospheric windows in a single exposure at a resolving power, R = 40,000 (Table 1). The instrument performance goals call for a system that will be the best in the world in this wavelength in terms of slit width-resolving power product, instantaneous wavelength coverage, and system throughput. A significant design goal is to produce an instrument with a simple opto-mechanical layout and very few moving parts to allow relatively straightforward use by a broad community of users.

IGRINS uses three key components to improve the performance and to overcome the current limitations on high resolution near-IR spectrographs : (1) Silicon immersion grating, (2) HAWAII-2RG with SIDECAR ASIC, (3) a Volume Phase Holographic (VPH) grating.

- **Silicon Immersion Grating** : The high performance immersion grating is compact and robust. The wavelength of light incident on the grating shrinks by a factor equal to the refractive index, n (3.4 for Si), when the grating is immersed in a dielectric. This means that an immersion instrument can have the same resolving power with a factor of 3.4 times smaller collimated beam diameter than an instrument with the same geometry and a

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conventional diffraction grating in vacuum. UT has been working on silicon immersion gratings for more than a decade and has recently developed high quality immersion gratings recently (Marsh et al. 2007, Wang et al. 2010).

- **HAWAII-2RG with SIDECAR ASIC** : The detector of IGRINS is the HAWAII-2RG 2.5 micron cutoff 2048 x2048 HgCdTe array. This detector has very low read noise (< 5 e-). We plan to use a SIDECAR ASIC readout controller electronics that can be as compact as possible with current technology.
- **Volume Phase Holographic (VPH) grating** : Two VPH gratings will be used as the cross-dispersers in the H and K bands of IGRINS. The transmission geometry of VPH gratings enables a compact design since imaging optics may be placed very close to the grating, which reduces the cost. Therefore a system designed around a VPH grating is likely to be smaller, less expensive, and higher-performance than one designed around a conventional reflection grating. VPH gratings are already in operation or planned to be used in a number of visible wavelength spectrographs on telescopes such as VLT, AAT, Gemini, and Subaru. Recently, VPH gratings have also been employed in the near-infrared wavelengths. However, there is no existing instrument using K band VPH gratings yet. The H and K band VPH gratings are undergoing cryogenic testing at UT by the IGRINS team.

Table 1. Design parameters.

| Item | | H-band | K-band |
|---|---|---|---|
| Wavelength [μm], Band center (range) | | 1.65 (1.49 - 1.8) | 2.16 (1.96 - 2.46) |
| Resolving Power, R | | 40,000 | |
| Slit [arcsec] (4m telescope) | | 0.68 (width), 10(length) | |
| Beam size [mm] | | 25 | |
| Main dispersion grating (Immersion grating) | Glass material | Silicon | |
| | Grating angle [deg] | 71.56 (R3) | |
| | Line density [l/mm] | 36.5 | |
| | Orders (min-max) | 98 - 122 | 72 - 92 |
| Cross dispersion grating (VPHG, first order) | Glass material | Fused silica | |
| | Grating angle [deg] | 32.4 | 26.1 |
| | Line density [l/mm] | 650 | 400 |
| | Order separation [arcsec] (min-max) | 11.8 - 18.3 | 12.1 - 20.2 |
| Detector | | HAWAII-2RG | |

## 2. SCIENTIFIC OBJECTIVES

IGRINS can contribute to our understanding of a broad range of astrophysical problems. We summarize here some of the areas of interest to the IGRINS community,

One of the major thrusts of the IGRINS science program is the study of young stellar objects and protoplanetary systems. The H and K bands are an ideal place to learn the physical characteristics of young stellar objects. T Tauri stars are intrinsically red and frequently heavily reddened. Veiling radiation from accretion shocks and hot dust is at a minimum in the near-IR. Using photospheric lines, we can determine $T_{eff}$, log g, magnetic field strength, *v* sin *i*, abundances, and other stellar characteristics. The broad wavelength coverage at high spectral resolution also allows us to use the variation of veiling with wavelength as a way to determine the SED of the inner part of the YSO disk.

Jets emerging from YSOs play an important role in exciting the neutral ISM and in injecting turbulence into the gas. Many important lines from the shocks produced by these jets are visible in the H and K bands, including the 1.64 μm [FeII] lines and the 2.12 μm $H_2$ 1-0 S(1) line (Pyo et al. 2002). IGRINS will allow us to examine the spatial variations of shock conditions using many diagnostic lines simultaneously.

Large-scale spots in YSO photospheres introduce significant noise into RV measurements. The magnitude of the spot-induced modulation is lower in the IR where the spot-to-quiet photosphere contrast is significantly less than in the visible. This opens up the possibility of examining even very young stars for reflex motions caused by massive planets. Detection of such planets can be extremely useful as it places constraints on the planet formation timescale and thereby on the formation mechanism.

IGRINS will also be a powerful tool for studying the interaction between molecular clouds and the stars within and around them. The H and K bands contain a wealth of $H_2$ lines, not only those excited by collisions in shocks but also lines excited by UV fluorescence on the surfaces of molecular clouds. With the ability to observe many of these transitions at once, IGRINS offers significant advantages for studying the physics of Galactic and extragalactic photo-dissociation regions and large-scale shocks in supernova remnants and galactic nuclei.

The ability to look through extincting dust clouds in the Galactic Plane and access to different CNO isotope abundances through studies of molecular isotopomers makes a near-infrared spectrograph with a large spectral grasp very attractive for studies of stars and of the evolution of abundances. Most low mass ratio binaries, for example, are single-line systems at optical wavelengths because the cooler star is so much fainter than the hotter one. This contrast is much lower in the IR (Prato et al. 2008). With IGRINS, it will therefore be possible to convert many single-line systems into double-line systems and to therefore learn much more about the physical properties of stars in systems where we can derive information about stellar mass. This kind of work can be particularly important for pre-main sequence objects where the relationship of stellar mass to other stellar properties is so much less well established. The IR can also be helpful in the characterization of the orbital motions of optically obscured X-ray binaries (Filliaitre and Chaty 2004). The broad simultaneous wavelength coverage makes IGRINS the ideal instrument for studying variations in CNO and other metals across the galaxy. The IR is rich in diagnostic lines and the ability to see through the dust in the galactic plane is a significant advantage here as well. In addition, there are a number of significant problems in the physics of late-type stars and stellar envelopes that are best approached with sensitive, broad-band IR spectroscopy.

The spectral range between 1.0 and 2.5 μm is useful to investigate molecules, atoms, and ions in the atmospheres of planets and Titan. Using the information embedded in the spectral line profiles of, for example, the transitions of $H_3^+$ in the K band, we will be able to investigate the vertical distributions of haze and clouds in the atmospheres of the giant planets and of Titan. We expect that high-resolution spectroscopy using IGRINS will be very useful for other studies of comets and planetary atmospheres.

# 3. SPECTROGRAPH OPTICAL DESIGN

## 3.1 Overview

An overview of the IGRINS optical design is shown in Figure 1. The system consists of H and K band spectrographs, input optics, a slit-viewing camera, and a calibration system. Apart from the calibration system, all of these units are maintained in a temperature-stable cryogenic environment. The input beam from a telescope is fed to the spectrograph after propagating through the focal converter. The converter changes the focal ratio of the telescope beam to the spectrograph focal ratio (f/10) and reimages the external telescope focus onto a reflective slit jaw. A cold stop is located in the input optics to block the thermal noise. The input optics can be replaced when moving to a telescope with a different Cassegrain f/ ratio. IGRINS is equipped with an infrared slit viewing camera that images the focal plane through a broad-band K filter. The calibration box can provide light from various sources at the position of the telescope focus. The box changes between different modes (normal observation, calibration, dark frame) by use of a sliding mirror. The calibration box will provide a continuum source with an integrating sphere and a line source to the spectrograph. The user can select the desired lamp by moving a folding mirror. An iris in the calibration optics can vary the focal ratio from f/8 to f/15.

The spectrograph uses a white pupil cross-dispersed layout and includes a dichroic in order to split the instrument into the H and K bands. A silicon immersion grating is used for primary dispersion and a pair of VPH gratings are used for cross-dispersion. The H and K band cameras are designed to be as nearly identical as possible.

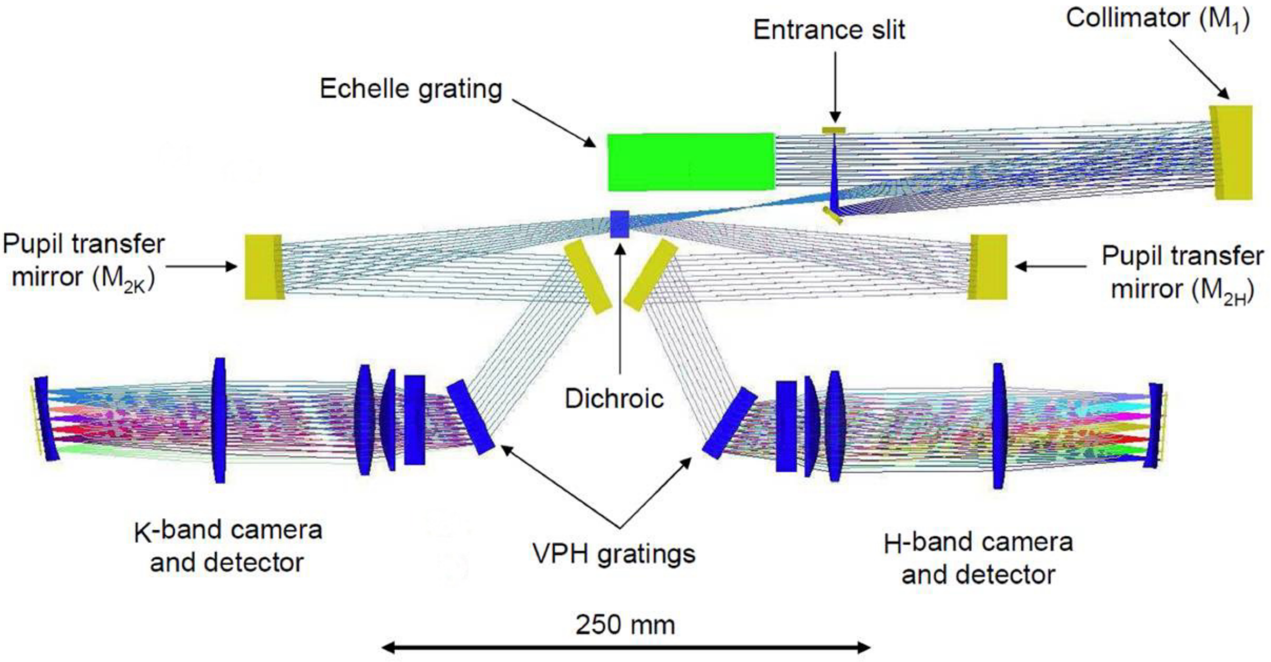

Figure 1. An overview of the IGRINS optical design. The single-band spectrograph units are fed by fold mirror/dichroics and have identical layouts, apart from the horizontal offset that compensates the vertical path difference. The dispersion of the grating is along the x-axis (vertical in the projected image). The VPH grating 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.

IGRINS is designed to be compatible with telescopes ranging in diameter (*D*) from 2.7 m (the HJST at McDonald Observatory) to 8 m. In the description of the design we present here, we give telescope-dependent parameters for a generic 4m telescope. Plate scales, and equivalent resolving power/slit width combinations, can be scaled for other telescopes. The collimated beam size is assumed to be 25 mm. Both of the H and K bands use the same silicon immersion echelle grating. The entrance and exit face of the immersion echelle prism is 30.5x35 mm. This size allows for a comfortable clearance of the incident and dispersed beams through these faces. The H band VPH grating cross-disperser requires a line density of 650 lines/mm, with an angle of incidence of 32.43 degrees. The K band cross-disperser is a 400 line/mm VPH grating used at an angle of incidence of 26.1 degrees. The detector is a Teledyne HAWAII-2RG array, which has 2048x2048 pixels, each 18 μm in size. The optical design results in 3.66 pixel sampling of a resolving power of R = 40,000 with a 126.6 mm focal length camera.

The H and K band spectra formats are shown in Figure 2 and Figure 3. The rectangle represents a 2k by 2k detector area. Two dash dotted lines indicate the free spectral range at each order (The free spectral range in Å is shown in the far right column denoted as $\Delta\lambda_{FSR}$). The separation (in arcsec) between adjacent orders is indicated in the column denoted by $\Delta y_{tot}$ . The format on the detector will allow one additional order above and below the nominal atmospheric band wavelengths to be captured. In the H band the wavelength coverage is complete from 1.47 to 1.83 μm in 25 orders. The width of the detector allows almost 1.5 free spectral ranges (FSR) to be covered in each order. The K band coverage is from 1.93 to ~2.5 μm in 22 orders. Some of the shorter wavelength orders have an overlap; however the detector width is sufficient to allow exactly one free spectral range of coverage at the longest wavelength.

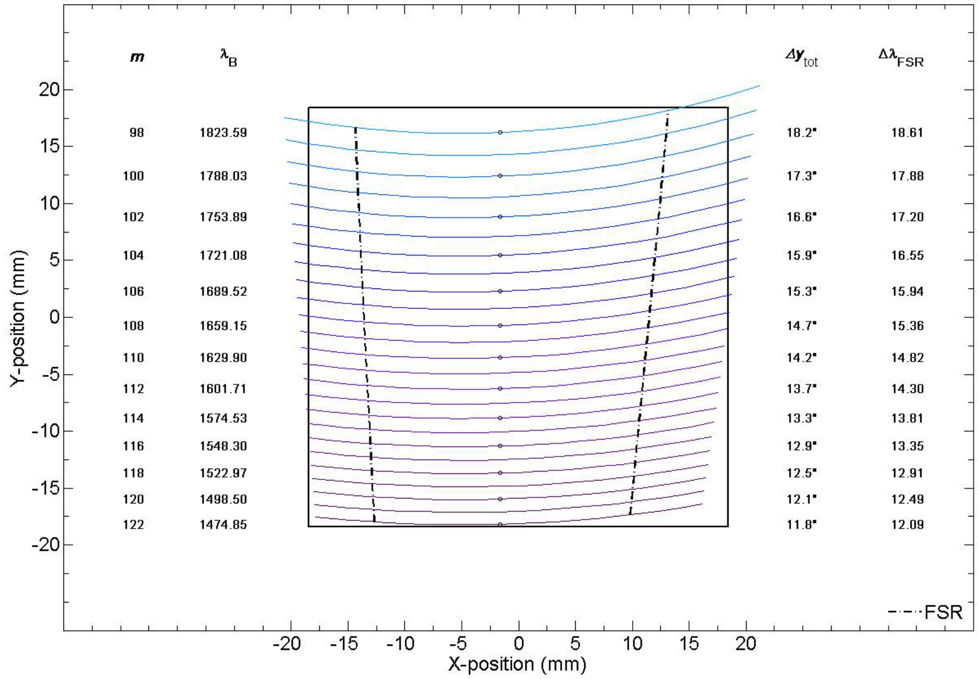

Figure 2. H band spectral format. Orders are traced across 1.5 free spectra ranges (FSR) and the extent of one FSR is shown by the dashed lines. The order numbers (m) and wavelengths ($\lambda_B$) correspond to the center of each order as marked. The inter-order separations ($\Delta y_{tot}$) and the wavelength extent of a single FSR ($\Delta\lambda_{FSR}$) are also shown for selected orders.

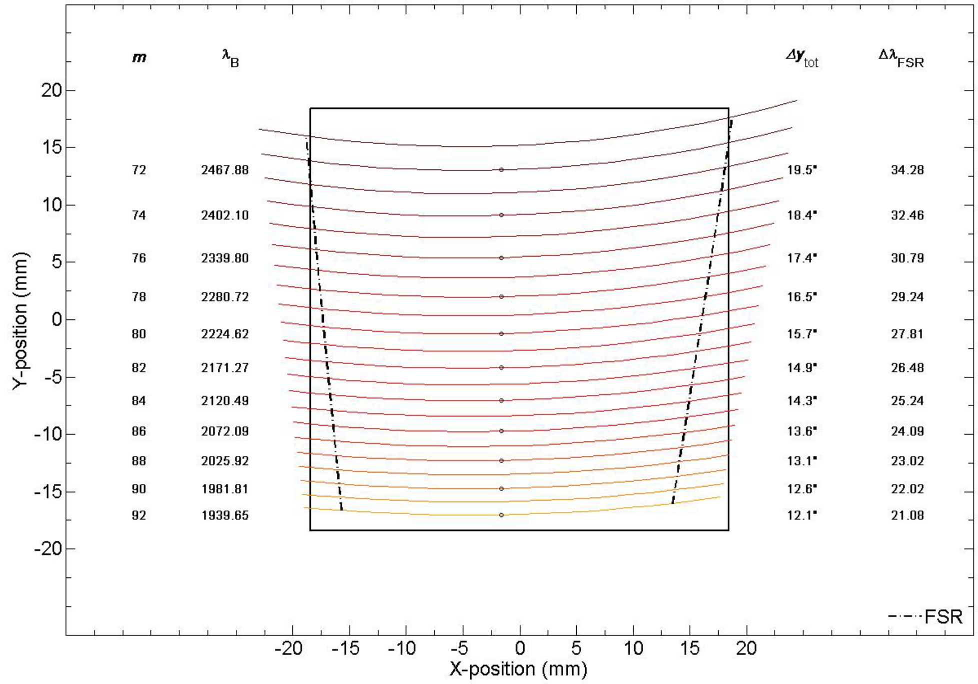

Figure 3. K band spectral format. Orders are traced across 1.25 FSRs and the extent of one FSR is shown by the dashed lines. For further details see Figure 2.

## 3.2 Performance

Spot diagrams for the H and K bands are shown in Figure 4 and Figure 5 respectively. The analysis includes all optics except for the pre-slit relay which should have a negligible impact on the performance. The image quality is sufficient to maintain an 80% encircled energy EE(80) of less than 25 µm at all wavelengths. The majority of wavelengths will have EE(80) of less than a single (18µm) pixel. This requirement is sufficient to obtain high quality spectra at R = 40,000 with 3.66 pixel sampling per resolution element.

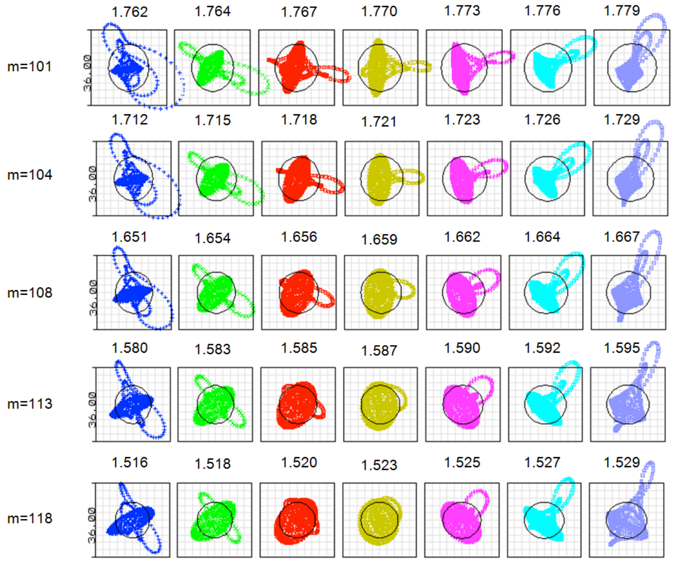

Figure 4. H band geometric spot diagram across spectra. The box size is 36x36 µm. The circle corresponds to Airy disk first diffraction minimum.

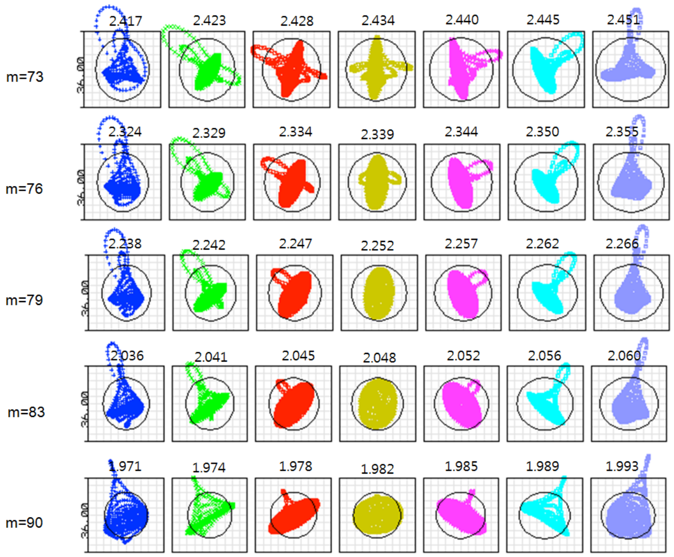

Figure 5. K band geometric spot diagram across spectra.

### 3.3 Tolerance Analysis

The IGRINS spectrograph consists of two subsystems: collimator and camera. We will fabricate, assemble, and test these two subsystems independently before integrating them and conducting final optical performance tests. The science requirements on the acceptable size of the full-width at half-maximum (FWHM) of a point-spread function (PSF) across the IGRINS echellograms drive the tolerance criteria for the optical subsystems which, in turn, flow down to the individual components. This FWHM limit is such that the PSF of a point source across 90% of the area of the H and K echellograms shall be smaller than 1.53 pixels (i.e. 27.4 μm) at 90% confidence level. Therefore, all optical tolerances must be optimally balanced such that no combination of the tolerance parameters leads to FWHM (including diffraction effects) larger than this limit. Table 2 and Table 3 show tolerance budget for H and K band camera system.

Table 2. H and K band camera manufacturing tolerance budget (Design compensator : FPA tip/tilt/focus)

| Lens index | Surface wedge [arcmin] | Surface decenrtration [μm] | Radii [%] | Center thickness [μm] | Surface figure (rms) [λ=632.8nm] | Index ($\times 10^{-3}$) | Dispersion [%] |
|---|---|---|---|---|---|---|---|
| CAM 1 | ±0.6 | ±25 | 0.06 | ±50 | λ/8 | ±0.1 | ±0.5 |
| CAM 2 | ±0.6 | ±25 | 0.06 | ±50 | λ/8 | ±0.1 | ±0.5 |
| CAM 3 | ±0.6 | ±25 | 0.06 | ±50 | λ/8 | ±0.1 | ±0.1 |
| CMA 4 | ±1.0 | ±50 | 0.1 | ±50 | λ/6 | ±0.1 | ±0.1 |
| FF | ±1.0 | ±50 | 0.1 | ±50 | λ/6(1λ pp back) | ±0.1 | ±0.5 |

Table 3. H and K band camera alignment tolerance budget (Alignment compensator: FPA tip/tilt/focus)

| Lens index | Decenter [μm] | Tip/tilt [arcmin] | Sepration [μm] | Rho [acrmin] |
|---|---|---|---|---|
| CAM 1 - 2 | ±100 | ±3 | ±50 | --- |
| CAM 2 - 3 | ±100 | ±3 | ±50 | --- |
| CAM 3 - 4 | ±100 | ±3 | ±50 | --- |
| CAM 4 - FF | ±100 | ±3 | ±50 | ±1.5 (FF rho angle) |
| FF - FP | ±100 | ±3 | ±50 | --- |

## 4. MECHANICAL DESIGN

Figure 6 shows the 3D model of IGRINS opto-mechanics. The size of the cryostat outer vessel is 900 x 580 x 380 mm and the total mass of IGRINS is about 210 kg. Most of the working structures are connected through the bottom plate, allowing maintenance and accessibility into the optical bench easier. Electronics boxes are attached on the top plate. There is no significant volume constraints for IGRINS because the 2.7 m telescope has available working space of about r=1.8 m hemisphere.

IGRINS will be attached at the telescope's Cassegrain focus of the telescope, and so deflection of the optical bench by gravity must be small enough to maintain the required optical performance. To make the optical bench stiff enough against gravitational deformation, the bottom side of the optical bench has honeycomb-style cutting. The optical bench is thermally isolated by G10 supports, and 4 points support is adopted. The slit is used for the thermal contraction center of the optical bench.

The operating temperature of IGRINS is 77 K for the detector and 130 K for optics. The temperature will be controlled with the stability of ±0.06 K for the immersion grating and ±0.1 K for detectors. The temperature will be monitored at least 7 places (cold head, optical bench, radiation shield, cold stop, three cameras). The expected cooldown time is shorter than 40 hours.

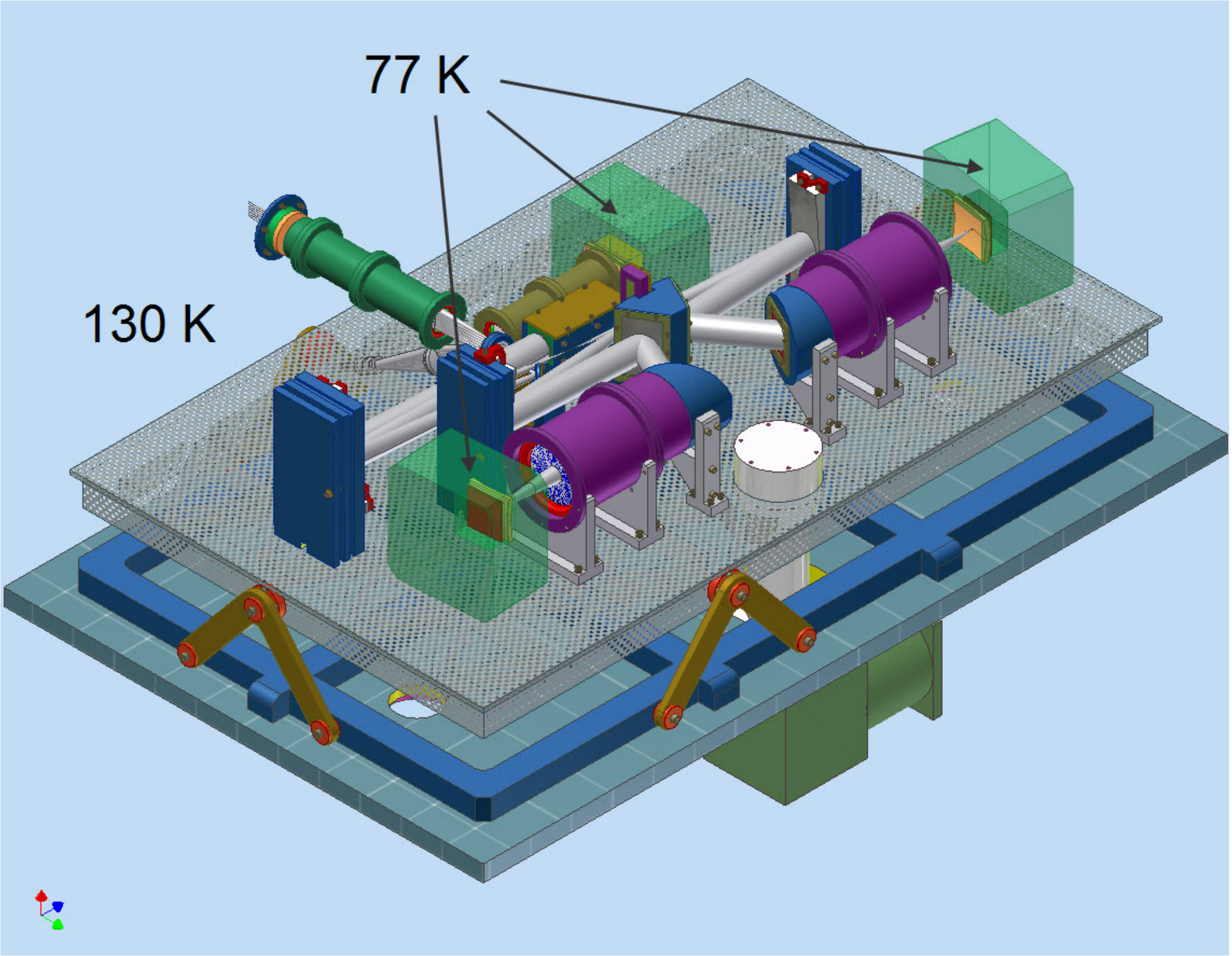

Figure 6. 3D model of IGRINS. Electronics boxes, calibration box, and vacuum jacket except for bottom plate are not shown.

## 5. ELECTRONICS AND SOFTWARE

The IR sensor used in IGRINS is 2.5 µm HAWAII-2RG (H2RG) HgCdTe detector array. H2RG is 2kx2k array with 18 µm pixel pitch. The HgCdTe detector achieves very low dark current (<0.01 e-/pixel/sec) and high quantum efficiency (80-90%) over a wide bandpass (Garnett et al. 2006). The H2RG in IGRINS will be controlled with the SIDECAR ASIC (Loose et al. 2002). The interface between the ASIC and the data acquisition computer is provided by a JADE-2 card that delivers the data to a USB-2 port in a PC running under Windows XP. Two science-grade H2RG sensors are used for H and K band spectrograph, and an engineering -grade H2RG is used for the slit viewing camera.

Figure 7 shows the overall system architecture. IGRINS control system is entirely IP based. Every device included has an IP address and all communications links use Ethernet. Communication between the IGRINS control program and hardware control programs are done by simple ascii text using TCP/IP protocol. The command set for each server is defined in a Software design document.

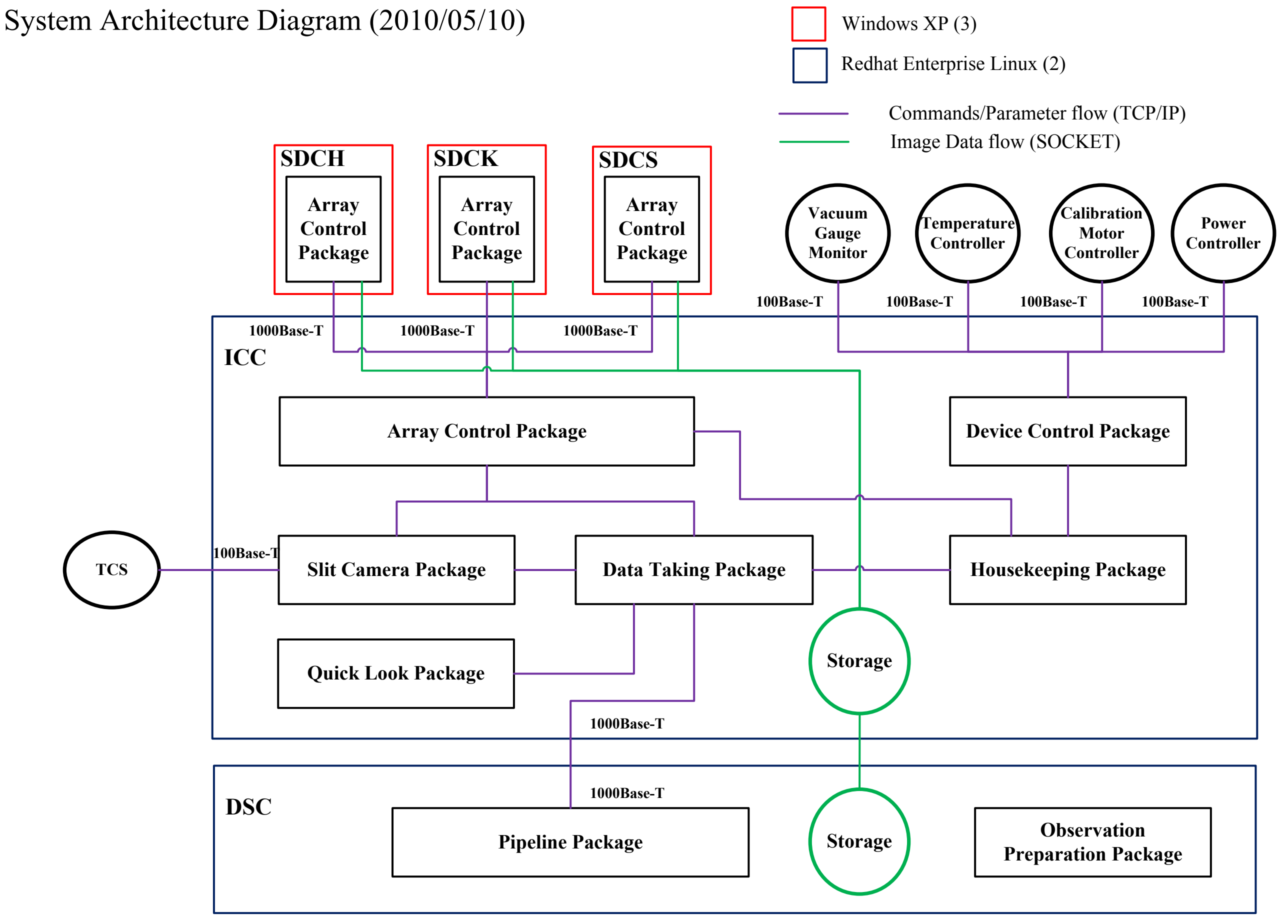

Figure 7. IGRINS system architecture diagram. DSC=Data Server computer, ICC=Instrument Control Computer, SDCH=Science Detector control Computer for H band spectroscopy, SDCK=Science Detector control Computer for K band spectroscopy, SDCS=Science Detector control Computer for Slit viewing camera, TCS=Telescope Control System of the McDonald 2.7m telescope. Three computers (SDCH, SDCK, SDCS) are installed in the electronics box on Dewar and two computers (ICC, DSC) are located in the control room.

The whole IGRINS software consists of the following packages:

- Device Control Package: Low-level control of IGRINS devices, vacuum gauge, temperature controller, calibration motor controller and power controller
- Housekeeping Package: Monitoring, logging, and alarming the status of the instrument and detector
- Array Control Package (SDCs side, Window XP): Low-level control of Teledyne ASIC, string parser and socket for data transfer.
- Array Control Package (ICC side, Redhat Enterprise Linux ): Communicate with array control package in SDCs side, and exchange commands
- Slit Camera Package: Auto guiding, TCS control
- Data Taking Package: Taking science data, FITS file generation, and observing mode selection
- Quick Look Package: Science data viewer and quick analysis
- Pipeline Package: Processing science quality spectroscopic data

- Observation Preparation Package: Utility program for preparation of observation

## 6. CONCLUSION

At this points, IGRINS is in the design phase. The preliminary design was reviewed last year, and the critical design review of the camera system for the spectrograph will be held at the end of this year.

IGRINS shares many technical and design features with GMTNIRS (Jaffe et al. 2006, Lee et al. 2010). IGINRS will act as a field-tested pathfinder for GMTNIRS by reducing the cost, schedule, and risk for GMTNIRS. In particular, most of the IGRINS software can be used directly for GMTNIRS.

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