Near-Infrared Camera and Fabry-Perot Spectrometer - NIC-FPS

M.B. Vincent[1], J.A. Morse[1], S. Beland[1], F. Hearty[1], J. Bally[1], E. Ellingson[1], E. Wilkinson[1], P. Hartigan[2], J. Holtzman[3], J. Barentine[4]

[1]University of Colorado, Center for Astrophysics and Space Astronomy, Box 389, Boulder, CO 80309
[2]Rice University, Physics and Astronomy Dept., 6100 S. Main, Houston, TX, 77005
[3]New Mexico State University, Astronomy Dept., Box 30001, Dept. 4500, Las Cruces, NM, 88003
[4]Apache Point Observatory, 2001 Apache Point Road, Sunspot, NM, 88349

ABSTRACT

The Near-Infrared Camera and Fabry-Perot Spectrometer (NIC-FPS) will provide near-IR imaging over the wavelength range ~0.9-2.45 microns and medium resolution (R~10,000) full-field Fabry-Perot spectroscopy in the 1.5-2.4 micron range. Science observation will commense by mid 2004 on the Astrophysical Research Consortium 3.5-m telescope at the Apache Point Observatory in Sunspot, NM.

NIC-FPS will allow a wide variety of extragalactic, galactic, and solar system observational programs to be conducted. NIC-FPS will support two observational modes, near-IR imaging or Fabry-Perot spectroscopy. For spectroscopy of line-emitting objects, the cryogenic Fabry-Perot etalon is inserted into the optical path to generate 3D spectral datacubes at ~30 km/s spectral resolution. For narrow to broad-band imaging, the etalon is removed from the optical path. Both modes will utilize a Rockwell Hawaii 1RG 1024 x 1024 HgCdTe detector which features low dark current, low noise and broad spectral response required for astronomical observations. The optics and detector will provide a full 4.6' × 4.6' field of view at 0.27" $pixel^{-1}$. NIC-FPS will be mounted to the ARC telescope's Nasmyth port.

NIC-FPS will significantly increase ARC's near-IR imaging and spectroscopy capabilities. We present NIC-FPS's optical design and instrument specifications.

Keywords: Fabry-Perot spectrometer, cryogenic etalon, infrared imager, ARC 3.5 Meter

1. INTRODUCTION

The Near-Infrared Camera and Fabry-Perot Spectrometer (NIC-FPS) will provide the Astrophysical Research Consortium (ARC) a significant improvement in NIR imaging. In addition to the imager, NIC-FPS includes a high spectral resolution Fabry-Perot etalon cooled to cryogenic temperature. The etalon will permit detailed studies of the dynamics within nebulae around pre-main sequence stars, star forming regions, and as well as galactic dynamics. NIC-FPS is being designed and fabricated at the University of Colorado Center for Astrophysics and Space Astronomy in Boulder. Science operations are expected to commence in mid 2004.

The ARC telescope is an alt-azimuth mounted 3.5 m located at Sunspot, NM. NIC-FPS will be mounted on the Nasmyth port #2 (east side when pointing south). To correct for field rotation, the port can rotate up to 270° in either direction. This port is shared by several instruments. An observing specialist can swap instruments in under 10 minutes using a quick connect kinematic clamp system.

Measurements of image quality at ARC constitutes an ongoing program to assess the 3.5 m system performance with the ultimate goal of seeing-limited images. Data are routinely collected from individual instruments and the autoguider camera on the Nasmyth ports; analysis of the data set shows that the image quality of the 3.5 m has improved in steps since the start of operations in 1994. The through-the-telescope image quality in approaching the likely seeing limit for the site location. An example of this is shown in Figure 1, a plot of the stellar FWHM as a function of time as measured by the Nasmyth 2 port guider in 1999-2000. Almost 15,000 individual FWHM measurements, mostly R band, are included in this plot. The gap in late 1999 represents a routine shutdown period during which an improved secondary mirror was installed. This improvement shifted the mean image FWHM from 1.4" to 1.2". Furthermore, the fraction of subarcsecond nights was substantially increased from slight over 1% in 1997-99 to 17% in 2000-01.

Efforts continue to improve the image quality using analysis of these data to indicate progress. It is thought that he site seeing limit is in the few tenths of an arcsecond range, and that "typical" seeing is subarcseconds. This places the ARC site in the class of sites of similar telescopes such as WIYN. Current work includes assessing the contributions of optical miscollimation, tracking jitter, and dome circulation to the stellar PSF in hopes that these effects can be sufficiently isolated and/or eliminated. This work will bring the through-the-telescope seeing closer to the site limited seeing of 0.4" to 0.6". The ultimate goal of these telescope improvements is to allow instrument to realize their full resolution potential and expand their utility to the ARC user community.

The measurements described above are of the visible seeing. ARC also has an active NIR community that uses GRIM (GRism spectrometer and IMager). Although GRIM is used about 25% of the time, 40% of the scientific papers written by ARC members have used GRIM data. Near-infrared seeing measurements are collected from GRIM data. This instrument, with its 256 × 256 pixel detector and 0.5" pixel size in its most commonly used f/5 mode, routinely undersamples the NIR seeing below 0.75". The existing data indicate that the NIR seeing is typically 0.1-0.15" better than the visible seeing. NIC-FPS's finer pixels and rapid readout will greatly aid in the monitoring the future improvements in seeing at ARC.

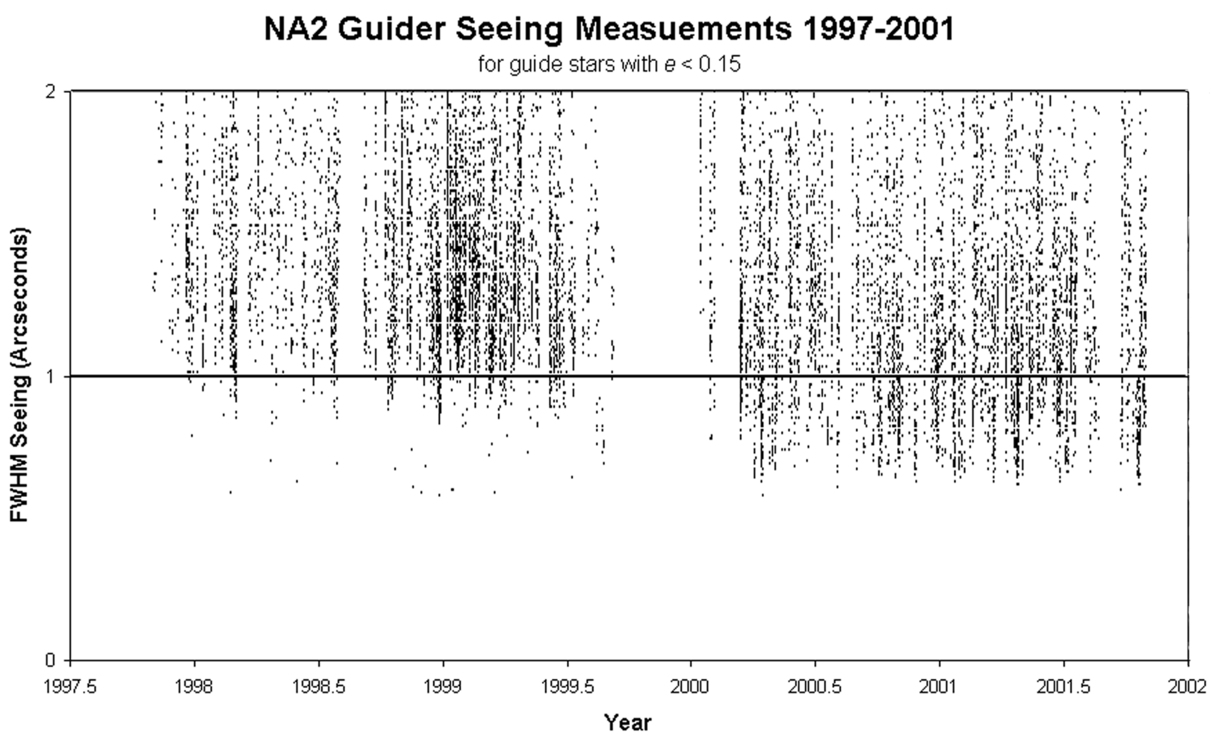

Figure 1. Seeing Measurements using the Nasmyth port guide camera data. The majority of the data was taken in the R band.

2. OPTICS

The ARC telescope is a 3.5 m, f/10.35 modified Richey-Chretien. At 2 µm, the NIC-FPS optics are designed to provide ~2 pixel sampling under good seeing conditions of 0.5" FWHM, and >3 pixel sampling at median seeing conditions of 1". These requirements lead us to select a f/3.99 camera with a 0.27" $pixel^{-1}$ scale. The effective focal length is 13590 mm. NIC-FPS will be one of the first ground-based instruments to employ the Rockwell Hawaii 1RG 1024 × 1024 HgCdTe detector (1016 × 1016 are active), with 18 µm pixels. The field of view is 4.58' edge-to-edge, and 6.42' corner-to-corner. The geometric distortion is minimized and well characterized at 0.75% at the edges, and 1.6% at the corners. To simplify manufacturing, all surfaces on both the collimator and camera lenses are spherical. Manufacturing and alignment tolerances range from easy to moderate. See Figure 2 for the optical layout.

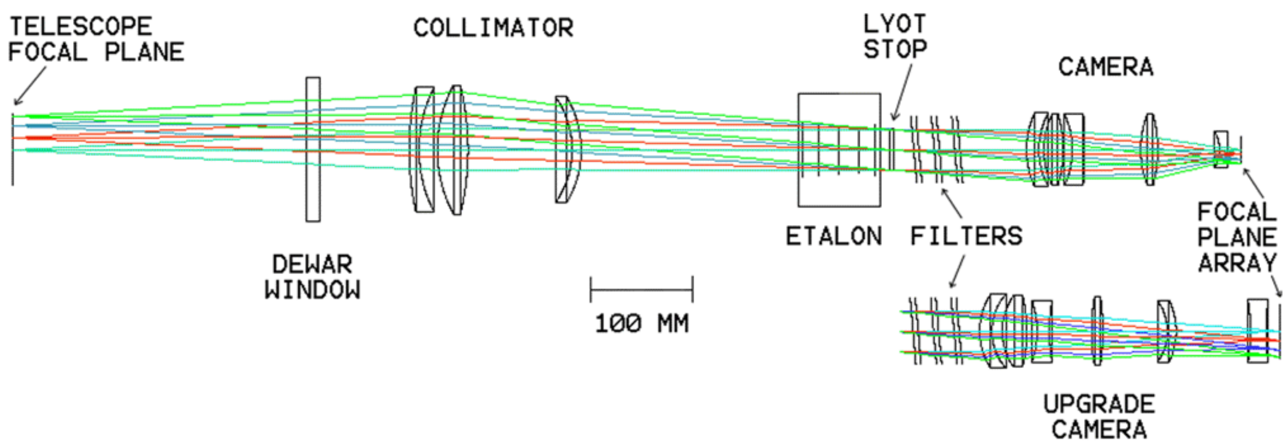

Figure 2. NIC-FPS optical layout showing both camera and upgrade camera.

2.1 Collimator and camera

A three element collimator will use IR-grade fused silica, CaF_2 and ZnSe elements. The first element of the collimator is located 384 mm behind the telescope focus. This distance allows the f/10.35 beam to expand to close to the pupil size of 40 mm. No corrector lens is required in front of the telescope focus. The pupil is located ~301 mm behind the collimator, with the exact value determined by the as-built design (*i.e.* to accommodate manufacturing and alignment tolerances). The space provides ample room to insert the etalon into the collimated beam (see below). The angular magnification at the pupil is the ratio of the primary diameter to the pupil diameter, or 85×.

The 0:39:1 camera has five elements. The materials, in order, are ZnSe, CaF_2, fused silica, CaF_2, and fused silica. These are distributed in a triplet, followed by a singlet and a field flattener. Possible ghost images are minimize by the design of the corrector lens in front of the focal plane array (FPA). The back surface of the corrector is convex towards the FPA, which 13 mm away. This combination enlarges any spot image reflected off from the FPA, to the corrector and back, to about 6.6 mm in diameter. Thus, the ghost image is spread over an area >40,000 times that of the original spot size. Assuming a 2% reflection off the FPA and corrector, the ghost image intensity is reduced by a factor of 10^8, or 20 magnitude per pixel.

The collimator and camera lenses will be mounted in separate aluminum optical tube. Each tube is mounted to the cryogenic optical bench, with the contact area sized to regulate the cool down rate. The individual lens mounts will be based on the Ohio State University Imaging Sciences Laboratory's cryogenic collet fingers design. In this design, the circular lens holders have regularly spaced axial cuts to form spring fingers. The flexure of the collet fingers accommodates all differential contraction between the lenses and the mounts without slippage. A ledge built into the ends of the fingers positions the lens along the optical axis. Small pads of epoxy adhesives hold the lenses into their holders. Optical alignment tolerances of the elements (i.e. decenter and tilt) have been keep at, or looser than those provided by the collet finger design. Spacing between lenses have been kept to a minimum of 5 mm to ease assembly.

The image quality of the baseline design is close to the diffraction limit. RMS spot diameters are kept below the pixel size at all wavelengths and positions on the detector. Spot diagrams are shown in Figure 3. The 80% diffraction encircled energy diameters are listed in table 1. No refocusing is necessary over the operational wavelength range.

Table 1. 80% Diffraction Encircled Energy Diameter

Wavelength (µm)	Best (µm)	Worst (µm)	Diffraction limit (µm)
0.90	11.9	17.4	11.3
1.30	16.7	20.0	16.5
2.00	27.4	37.0	25.2
2.40	32.4	39.7	30.3

The best and worst encircled energies are not necessarily the center and corner fields, respectively. At 2.00 and 2.40 µm, the 80% encircled energy level falls far out on the wings, hence a small change in image quality results in a large change in diameter. Manufacturing and alignment errors will slightly increase the diameters.

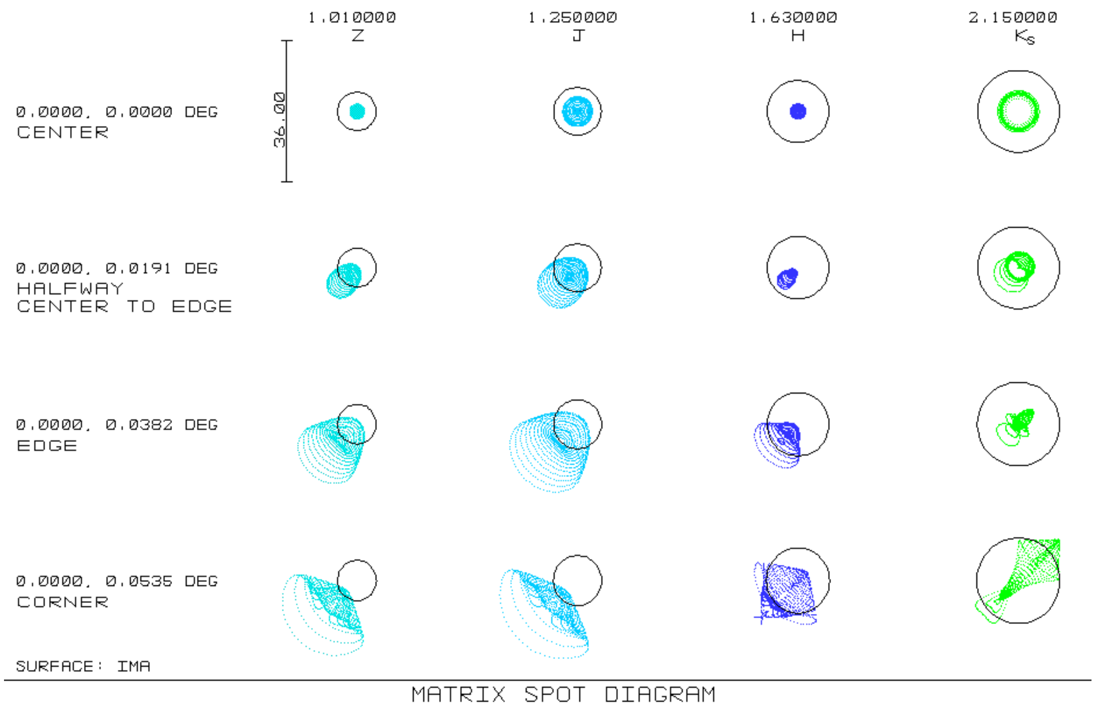

Figure 3. Spot diagrams at Z, J, H and K_s central wavelengths. The 36.00 µm bar represents two pixels, or 0.54". The circles represents the Airy disk diameters at the respective wavelengths.

The "Mauna Kea Filter Set"[1,2] J, H and K_s filters were ordered from Barr Associates as part of the Gemini filter consortium. The central wavelengths are 1.250, 1.635, and 2.125 µm, respectively. Our use of this widely accepted standard filter set will greatly ease photometric calibration by allowing ready use of the existing standard star lists established by UKIRT and other observatories. A Z filter is also planned to partially match the Sloan Digital Sky Survey Z' filter bandpass. The detector's short-wavelength cutoff will, however, limit the overlap of the Sloan and NIC-FPS Z filters. Two additional filters for the etalon will be available at commissioning. Further filters will be added when available.

2.2 Optical upgrade

With improvements to the dome air circulation and mirror supports, the seeing at 2 µm is expected to reach the 0.4 to 0.6" range. Adaptive optics is also being considered. These upgrades will occur several years after NIC-FPS's commissioning. As a result, we expect that the 0.27" pixel^{-1} scale will slightly undersample the seeing. With this in mind, we generated a preliminary design for a 2048 × 2048 FPA. The upgrade includes a new f/8.1 camera with a ~0.14" pixel^{-1} scale, effective focal length of 27600 mm. The edge-to-edge field of view increases from 4.6' to 4.8', and corner-to-corner from 6.4' to 6.8'. Field points beyond 3.2' from center will be slightly vignetted by the collimator.

The upgraded camera has six elements, with a major design restraint being the filter wheel to FPA distance. The upgrade camera is longer than the baseline camera. To allow for this extra length, the first camera lens can be mounted to within millimeters of the third filter wheel. We can fit the new camera onto the bench without moving the FPA. This, however, results in marginal field curvature and geometric distortion performance. Excellent image quality, and minimal geometric distortion is achieved by allowing the FPA to move back along the table by about 36 mm.

2.3 Etalon

We will use a Queensgate (now IC Optical Systems) EC50WF Fabry-Perot etalon provided by Rice University. The etalon can operate from room temperature down to a cryogenic 77 K for near-infrared work. The wavelength range is 1.5 to 2.4 µm, with addition sensitivity peaks from 0.9 to 1.4 µm. The cold cavity spacing is ~250 µm. At wavelengths near 2 µm, the spectral resolution is 10,000, and velocity resolution is ~30 kms^{-1}. The measured finesse is 36, and the free spectral range is 0.008 µm, or 0.4% at 2 µm wavelength. This etalon has a 50 mm clear aperture through the water-free fused silica windows.

The etalon will insert into the collimated beam before the stationary Lyot stop by use of a linear actuator. The front surface of the etalon vignettes the off-axis fields by <10%. This design minimizes the impact to the imaging mode. The optical alignment of collimator, Lyot stop and camera are not affected by the presence of the etalon. The insertion of the etalon defocuses the pupil at the Lyot stop, but no appreciable degradation in image quality and minimal vignetting of the off-axis fields. The etalon is not tilted.

Operational wavelength ranges are set by the availability of narrow bandpass order sorter filters. At commissioning, filters for the 1.64 µm Fe II and the 2.12 µm H_2 1-0 S(1) lines will be available. The narrow free spectral range of the etalon limits the FeII bandpass to 4.86 nm or 890 kms^{-1}, and the H_2 bandpass 8.10 nm or 1140 kms^{-1}. These bandpasses contain only one weak OH line each. Off-band filters that are shifted redward of line center will be added as funding becomes available.

In NIC-FPS, the etalon is feed with a 40 mm diameter, collimated beam. The velocity shift V at angle T away from the optical axis is given by:

$$V = 130\ (D/d)^2\ T^2$$

where V is in kms^{-1} and T is in arcminutes. D is the diameter of the telescope in meters and d is the diameter of the collimated beam through the etalon in centimeters. For the 3.4 m ARC telescope and 40 mm beam, the velocity shift is about 94 kms^{-1} at 1', and 376 kms^{-1} at 2' from center. Assuming we observe objects in 10 velocity slices (etalon cavity spacings) of 30 kms^{-1} each, we would cover a 300 kms^{-1} range, over a 3.6' diameter field.

Wavelength and flat field calibration of the etalon will be initially preformed through the telescope. Illumination is provided by line emission and continuum lamps mounted around the front of the telescope with their light reflecting off the primary mirror cover. Options for an instrument mounted calibration are being made should off-the-telescope calibration be required.

2.3 Detector

We will use a Rockwell Hawaii H-1RG 1024 × 1024 pixel HgCdTe array. The pixel pitch is 18 µm. The "R" in H-1RG stands for the 4 columns of reference pixels that are located around the perimeter of the array. The reference pixels reduces the active area to 1016 × 1016 pixels, and will allow us to determine the bias and dark current contribution to the raw image. The "G" stands for guide mode in which the electronics perform a rapid, non-destructive readout of a "postage stamp" sub-array of programmable size and location. In principle, the guide mode could be used to guide the ARC telescope to augment of the facility's off axis guider. The guide mode will most commonly be used to observe bright stars or planets.

The H-1RG quantum efficiency is expected to be >65% over 1-2.45 µm. It supports two read-outs modes, slow, low readout noise and fast, higher noise mode with selectable gain. The very low dark current and readnoise will permit the long exposures, up to 20 minutes, required for the R = 10,000 spectroscopy of faint, extended sources. For bright objects, the rapid read-out mode and deep well depth will minimize the likelyhood of saturation.

We have estimated the 5σ detection limit for various integration times (see Table 2). Integration times are for time on target only, and do not include overhead from readouts or sky subtraction. Detection limit assumes 50% system transmission, 70% detector quantum efficiency, 0.5 electrons s^{-1} dark current and 10 electron read noise. The sky glow is taken as the nominal value from Kitt Peak[3]. Estimated sky saturation times for J, H, K_s bands are about 50, 5 and 5 seconds, respectively. Sky subtraction will be performed by nodding the telescope. ARC's secondary is currently not configured to reliably chop at short time scales.

Table 2. Estimated 5σ detection limit in a 4×4 pixel aperture

Band	1 second	1 minute	1 hour
Z	18.7	21.0	23.5
J	18.0	20.3	22.5
H	16.7	18.9	21.2
K_s	16.0	18.3	20.5

3. MECHANICAL

NIC-FPS's exterior dimensions are 0.50 m diameter by 2.1 m long. Overall weight is estimated at 220 kg. NIC-FPS consists of three sections, warm, optical bench, and LN2 reservoir, see figure 3. The warm section is a 0.54 m long spacer between the telescope and the dewar, and is at ambient air pressure and temperature. The telescope focal plane is located within the warm section. Light baffling, hermetic electrical connectors and vacuum fittings are also located in the warm section. The optical bench and LN2 reservoir are described below.

The dewar shell and optical bench are designed to ease access without disturbing the hermetic electrical connectors, LN2 fill and vacuum fittings.When not mounted to the telescope, the instrument will be placed on a cart and rolled away from the Nasmyth port. This cart provides support to allow the removal of the dewar shell for servicing of the optical bench.

3.1 Dewar

The dewar shell is a single, 1.5 m long piece extending the length of both the optical bench and the LN2 reservoir. There is a large diameter O-ring sealed flange at each end. For maintenance of the bench, the dewar shell is broke at the front O-ring seal. The LN2 reservoir is mounted to the back wall of the dewar shell. The shell, thermal shield and reservoir are removed as a unit. This design introduces a thermal break between the back of the optical bench and the reservoir. Metallic springs form the thermal connection between the bench and the reservoir.

The reservoir is a right circular cylinder of 30 l volume, and has an on-axis fill/vent tube. Since NIC-FPS is mounted horizontally to a rotator, the reservoir can only be half filled. We estimate that 15 l of LN2 will provide approximately 36 hour of hold time. A polished dewar interior wall and a single layer heat shield are used to reduce the radiative heat load. A Kapton sheet resistive heater attached to the LN2 reservoir will allow a rapid, safe warm-up. A getter will remove water from the system. A vac-ion pump is an option should it be needed to hold vacuum for one year without the aid of an external pump.

3.2 Optical bench

The optical bench is cantilevered from a G-10 ring as those found in Ohio State University's TIFKAM and University of Florida's FLAMINGOS. The G-10 ring serves as both a structural support and thermal insulator. The alignment of the cantilevered bench is unaffected by the removal of the dewar shell.

The optical bench serves two functions, as a mount for the optics and a thermal conductor between the G-10 ring and LN2 reservoir. The optical bench is made rigid by two beams of 10 cm deep, and a lip around the bench's edge of 2.5 cm deep. These beam resist gravitational deflection when the bench is horizontal. The bench itself resist gravitational deflection when the bench is rotated 90° to vertical on the Nasmyth port. We estimate that the bench flexure is less than 90 µm when rotating 90°. This translates to an image shift of less than one pixel.

The NIC-FPS design of mounting the LN2 reservoir behind the bench results in a thermal gradient along the length of the bench. The primary heat load is through the window and G-10 ring in front, whereas the heat sink is the LN2 reservoir at the rear. We estimate that the steady state temperatures for the collimator and the camera are near 90 K and 80 K, respectively.

3.3 Filter wheels

Three filter wheels with seven slots each are used to provide seventeen filters positions, one blocker (for dark frames) and three opens (one in each wheel). The wheels will be arranged in a pair and a single, with these setting on opposite sides of the bench. Cryogenic stepper motors will drive the wheels through a pinion gear in contact with a spur gear located around the wheel's circumference. Roller detents in contact with the wheel's circumference will determine the final positions once the motors are turned off. An absolute position encoder will be implemented by three microswitches riding in code groves machined into the wheel's face. The 65 mm diameter filters will be held in cells to allow them to be removed individually using captive hardware. The general layout of the filter wheels, bearing, detents and absolute position encoders are based closely on the Imaging Sciences Laboratory filter wheel design.

3.4 Support electronics

To maintain good seeing within the dome, there is an unvented 10 W heat dissipation limit set on each instrument. Meeting this limit requires most of the support electronics be mounted on the intermediate level, just below the observing level. These electronics include the controllers for the etalon, stepper motors and vacuum gauge. The FPA readout electronics will be mounted to the dewar's exterior.

To connect the instrument to the support electronics, the NIC-FPS cables will be run through the "candy cane" cable run next to the altitude bearing. This cable run is about 15 m. Fiber optics form the link between the controllers to the computer and control rooms 100 m away. NIC-FPS will normally remained "powered-up", even when not attached to the telescope.

ARC is currently developing a new telescope and instrument control software. NIC-FPS will be the first new instrument with control software written to conform with the new software.

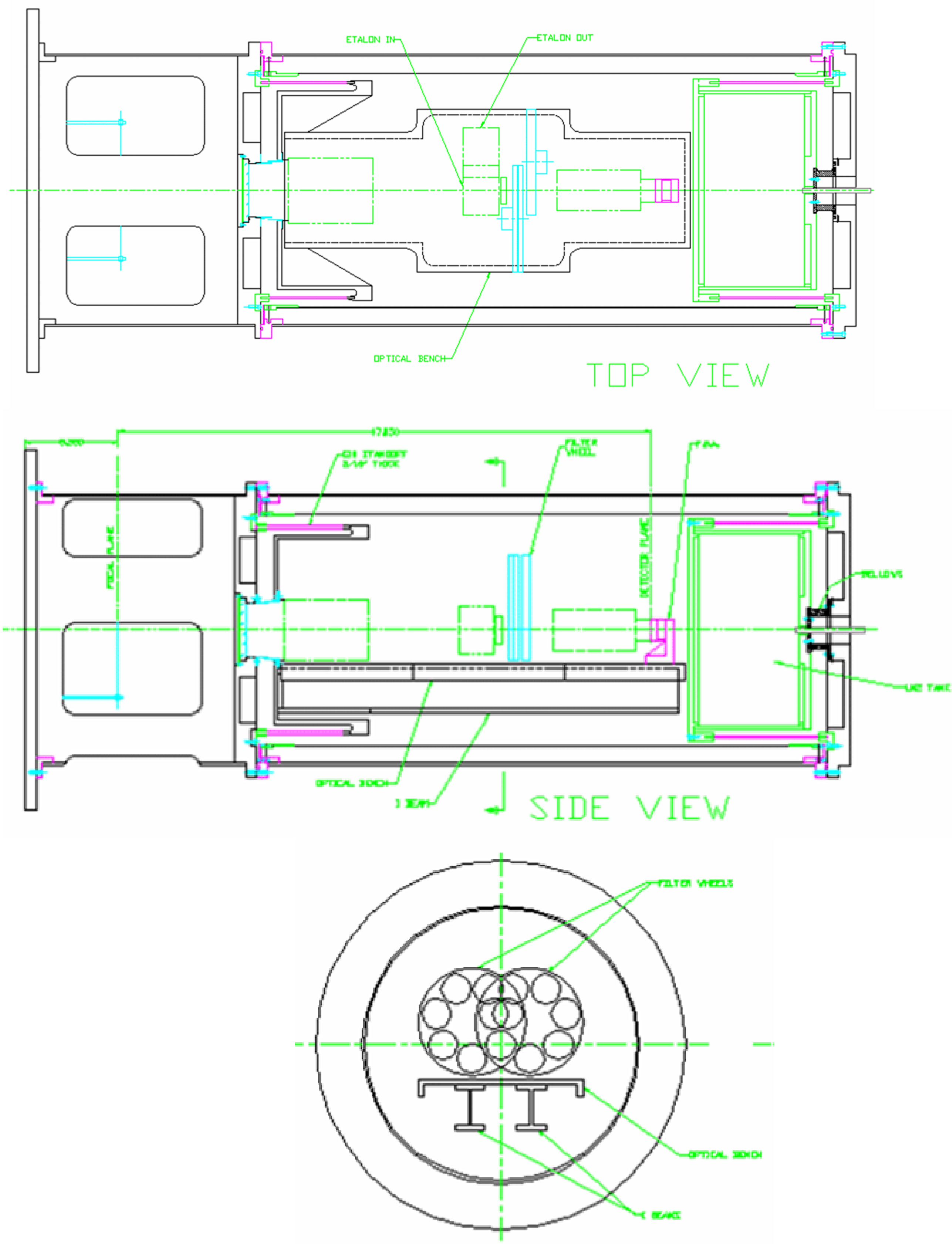

Figure 4. Dewar and optical bench layout.

4. ACKNOWLEDGEMENTS

We would like to acknowledge David Fischer, Chris Stewart, Art Olsen and Gary Emerson of Ball Aerospace with their extensive assistance with the optical and mechanical design work. We would like to acknowledge the help of Thomas O'Brien of Ohio State University on the design of the optical mounts and filter wheels. We would deeply appreciate Richard Elston's donation of spare G-10 ring from FLAMINGOS.

5. REFERENCES

1. Simons, D. A., A. Tokunaga, "The Mauna Kea Observatories Near-Infrared Filter Set. I. Defining Optimal 1-5 Micron Bandpasses," *PASP* **114**, pp 169 (2002).
2. Tokunaga, A., D.A. Simons, W.D. Vacca, "The Mauna Kea Observatories Near-Infrared Filter Set. II. Specifications for a New JHKL'M' Filter Set for Infrared Astronomy," PASP **114**, pp 180 (2002).
3. Joyce, R.R., "Observing with Infrared Arrays," Astronomical CCD Observing and Reduction Techniques, Ed. S.B. Howell, *ASP* **23**, pp 258 (1992).