The Carnegie Planet Finder Spectrograph: a status report

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ABSTRACT

The Carnegie Planet Finder Spectrograph (PFS) has been constructed for use with the Magellan telescopes at Las Campanas Observatory in Chile. PFS has been optimized for high-precision measurement of stellar radial velocities in order to support an ongoing search for extrasolar planets. PFS uses an R4 echelle grating and a prism cross-disperser in a Littrow arrangement to provide complete wavelength coverage between 390 and 620 nm distributed across 58 orders. Spectral resolution is 38,000 when using a 1 arcsec slit. An iodine absorption cell is included in the pre-slit module to allow the superimposition of well-defined absorption features on the stellar spectra. To improve velocity stability, the echelle grating is enclosed in a small vacuum tank with the cross-dispersing prism acting as the vacuum window. The spectrograph is mounted on an invar optical bench that is surrounded by an insulated enclosure with circulating liquid temperature control. Fabrication and assembly have been completed, and testing will soon be underway. Delivery to Las Campanas Observatory is scheduled for late 2008.

Keywords: spectrograph, spectroscopy, echelle, high resolution, radial velocity, iodine cell, extrasolar planet

1. INTRODUCTION

The Carnegie Planet Finder Spectrograph (PFS) will enable a long-term observing program at Las Campanas Observatory (LCO) capable of monitoring stellar radial velocities with a precision of about 1 m s^{-1}. The scientific motivation and goals for PFS were described by Crane et al.[1](hereafter C06).

PFS is shown in Figure 1. The spectrograph is mounted on an optical bench that sits on three flexure-topped fiberglass posts, approximately twelve inches above the instrument cart. When the spectrograph is in use, the cart sits on a static, three point kinematic mount on the Nasmyth platform of the 6.5m Magellan Clay telescope. When not in use, casters attached to the cart allow the instrument to be rolled away to a storage area. The bench spectrograph is surrounded by an insulating enclosure with an embedded thermal control system (Section 4). A pre-slit assembly (Sections 2.1, 3.1) is cantilevered off of the optical table and sits entirely outside of the insulating enclosure. Electronic control devices are housed in a large box attached to the instrument cart, near the ground.

This paper provides updates on design changes and describes several assemblies and subsystems that have been completed since the publication of C06.

2. OPTICAL DESIGN

A description of the PFS optical design and fabrication was given in C06. The optical layout for the full system is shown in Figure 2. The primary spectrograph optics remain as described in C06, but the pre-slit optical design has been changed in order to push the mechanical pre-slit assembly (Section 3.1) outside of the insulated and temperature controlled volume.

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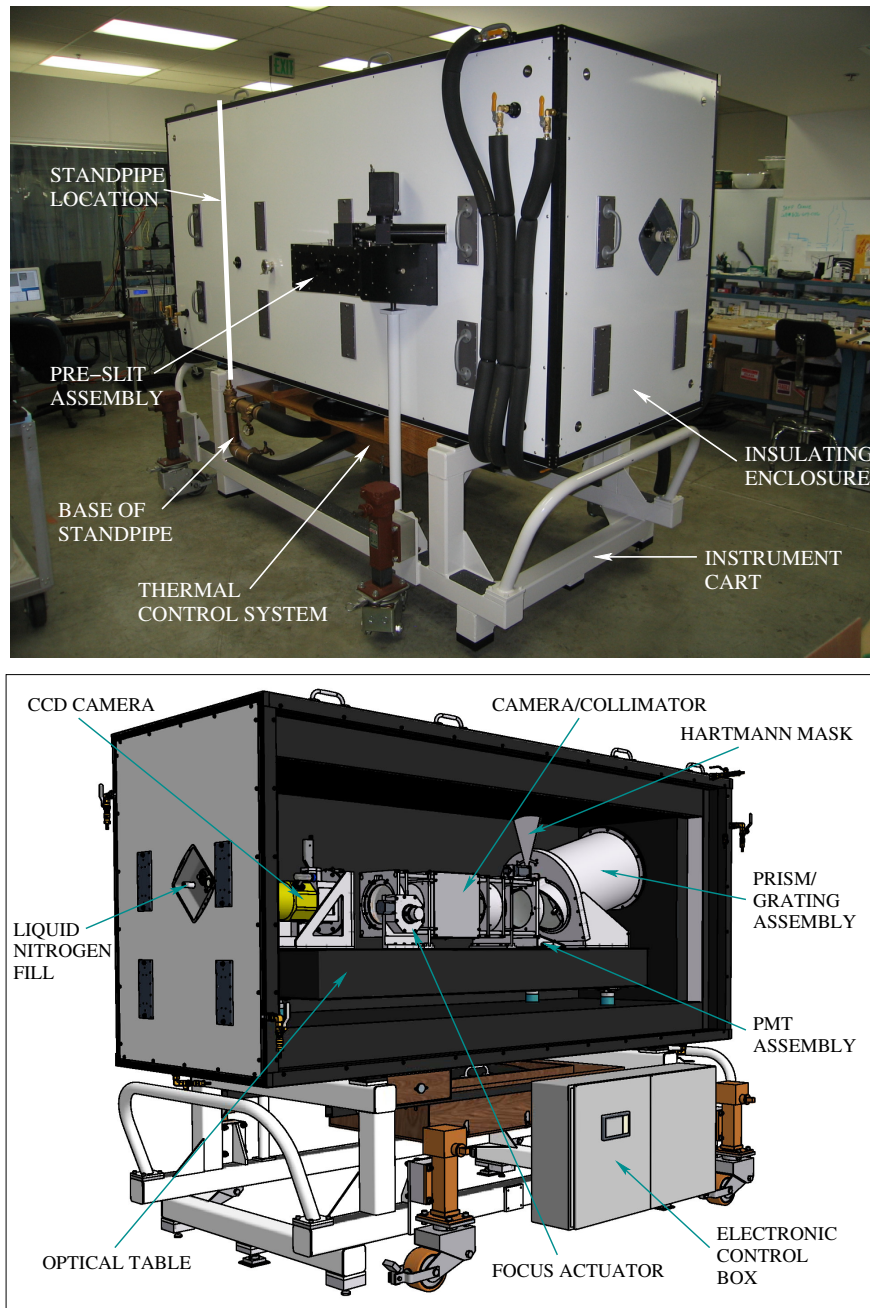R.P.B.: E-mail: paul@dtm.ciw.edu, Telephone: 1 202 478 8866

Figure 1. PFS is shown from two angles. The thermal control system standpipe is not shown in the top photo, but its intended location has been indicated. One side of the insulation has been removed in the lower image. Because the inside of the enclosure is black, it is difficult to produce clear photographs showing the spectrograph components, which are anodized black. For that reason, a CAD rendering has been generated with the table-mounted assemblies drawn in gray.

2.1 Pre-Slit Optics

The pre-slit optics (Figure 2) perform several functions. First, the diverging F/11 telescope light is converted to F/5 to match the focal ratio of the spectrograph. This is accomplished using two stock achromatic doublet lenses and a third doublet composed of a stock bi-convex lens and a custom meniscus lens. The latter have been glued together using Sylgard-184, an optical RTV made by Dow Corning.
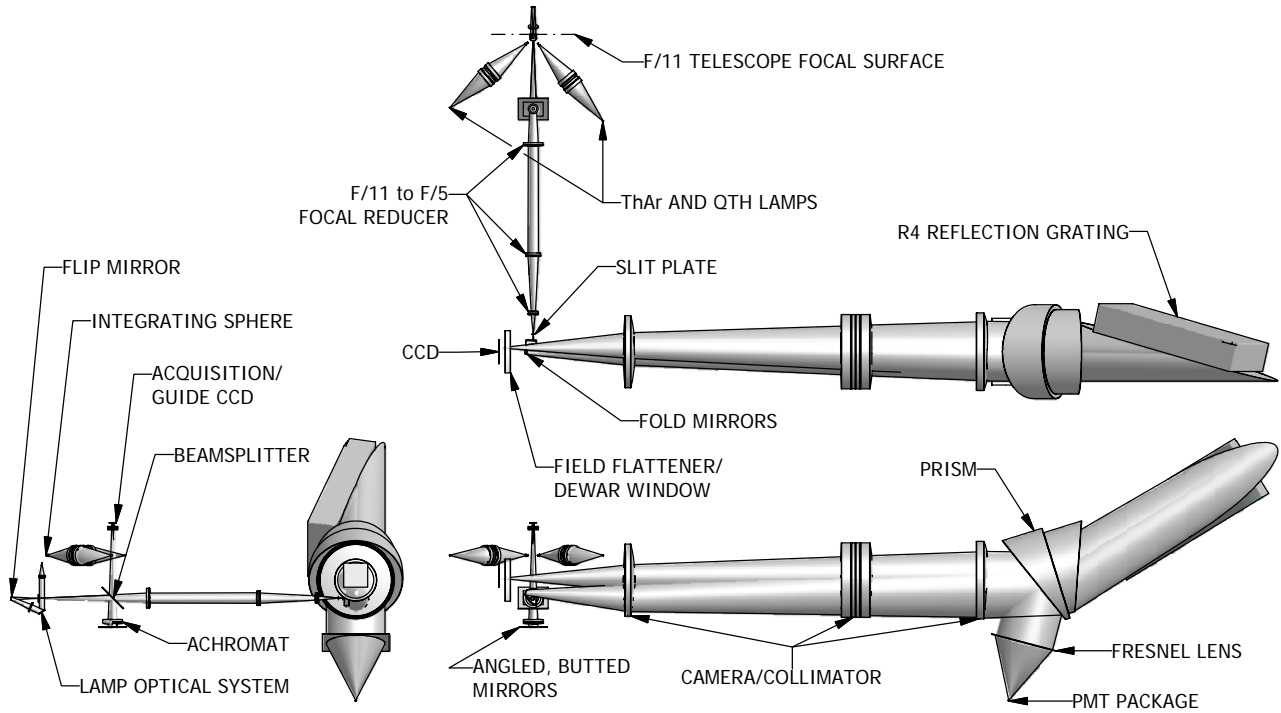
Figure 2. The full PFS optical layout is shown in three projections. The solid beam represents 5000 Å light.

After the light has diverged past the telescope focal surface and before it arrives at the first lens of the focal reducer, it passes through a fused silica window that has an anti-reflection coating on only one surface. The window therefore acts as a beamsplitter with reflectivity determined entirely by Fresnel reflection. About 4-5% of the light is reflected downward through a collimating, stock achromat toward two symmetrically rotated plane mirrors that split the pupil into two halves upon reflection. The reflected, collimated light is then focused by the same doublet through the beamsplitter and onto an acquisition and guide camera CCD. These images of the target star, each produced using half of the telescope pupil to either side of the slit, can be used to actively guide on the target and monitor telescope focus (See Figure 4 of C06). In this way, slit and pupil illumination is maintained throughout the exposure.

About 95% of the target's light is transmitted through the beamsplitter and focally reduced to F/5 where it encounters a reflective slit plate. The slit plate is described accurately in C06, except that the substrate has been changed so that the construction is now nickel-plated beryllium copper photo-etched in a bi-metal process. Except for the target light that passes through the slit, the remainder reflects from the slit plate face and passes through the focal reducer in reverse before reaching the beamsplitter a second time. 5% of the light reflected from the slit plate is in turn reflected by the beamsplitter toward the acquisition camera, forming an image with a 38 arcsec field of view.

A Thorium Argon hollow cathode lamp is available for wavelength calibration, and a quartz lamp is used for flat fielding and order tracing. Light from either of these lamps may be injected into the spectrograph using a common system. A set of symmetric, stock achromats is positioned in front of each lamp to collect the light and transfer it into an integrating sphere. The diffused light emerging from the integrating sphere is collected and focused at F/11 onto the telescope image surface when a flip mirror is engaged near the entrance to the pre-slit assembly. This optical system was also designed using stock optics.
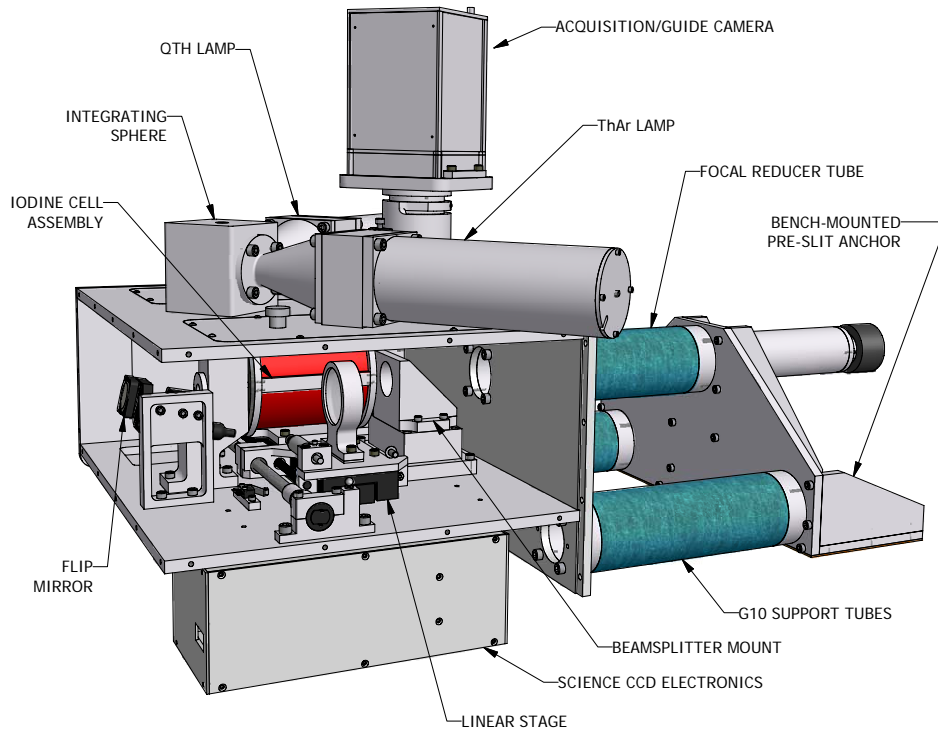
Figure 3. A rendering of the PFS pre-slit assembly is shown. The side and front walls of the assembly have been removed for clarity. The assembly is cantilevered from the optical table, with the G10 support tubes extending through holes in the wall of the insulating enclosure.

2.2 Coatings

C06 described the anti-reflection (AR) coatings applied to the custom spectrograph optics. The AR coatings for the stock optics were chosen from those among the optical vendors' catalogs that best match the PFS wavelength range. These catalog coatings were judged to be adequately efficient, so custom coatings were not required.

The cross-dispersing prism has a high-quality AR coating applied to its rear surface as described in C06. The front surface has been coated with magnesium fluoride in order to intentionally allow a 1-2% reflection to feed a photomultiplier (Section 3.3) for exposure monitoring.

3. MECHANICAL DESIGN

The mechanical design of the PFS support structure, camera/collimator assembly, and prism and grating mounts was described in C06. A preliminary design of the pre-slit assembly was also described, but was changed when the pre-slit optical design was revised.

3.1 Pre-Slit Assembly

The pre-slit assembly is shown in Figure 3. In addition to containing the focal-reducing optics, the pre-slit assembly houses calibration lamps, the acquisition/guide camera, a motorized flip mirror, and a motor-driven linear stage that moves the iodine absorption cell into and out of position. The iodine cell must be maintained at a temperature of 65°C. To maintain the instrument's thermal control, all of these sources of heat must be kept outside of the insulating enclosure. The pre-slit optical design was optimized specifically to accomplish this.

The pre-slit assembly is cantilevered about nine inches away from the optical table using three G10 fiberglass tubes. Arranging the tubes in a triangular pattern provides rigidity, and the use of fiberglass ensures good thermal isolation of the pre-slit assembly from the optical bench. Suspending this assembly away from the table
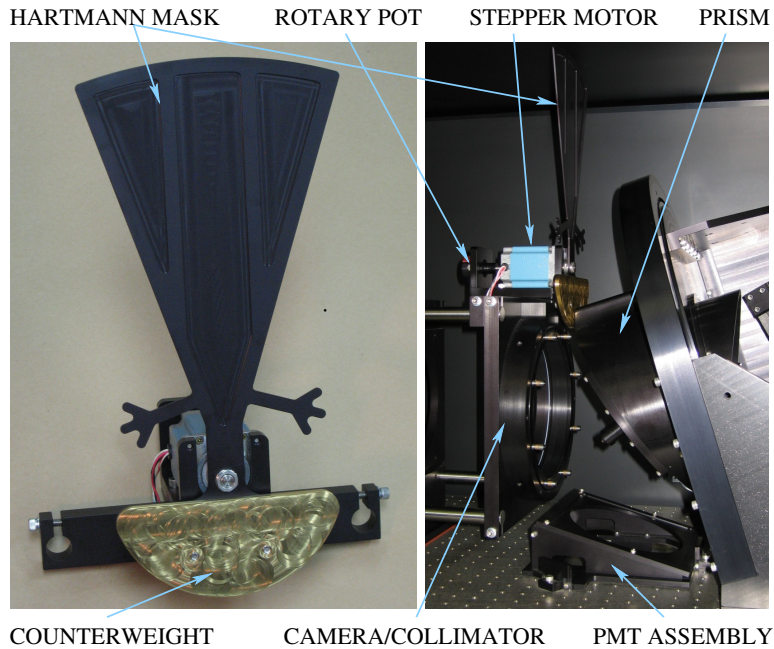
Figure 4. The Hartmann mask assembly is shown by itself and attached to the spectrograph. The assembly attaches to the camera/collimator frame and enters the collimated optical beam between the camera and the cross-dispersing prism. The mask is shown rotated to its "off" position in the photo on the right.

shifts the center of mass of the table and table-mounted component system away from its optimal position. To correct this, a rigid steel column has been installed between the instrument cart and the underside of the pre-slit assembly, with a compression spring providing a compliant interface between the two. The spring force pushes up on the assembly, shifting the table's center of mass back toward its optimal position. The central G10 tube contains the focal reducing optics and provides an optical path into the insulating enclosure. The other two tubes are used to pass wires from the electronic control box to the electrical components attached to the optical table.

Behind the entrance aperture at the front of the pre-slit assembly, a motorized flipper holding a flat mirror is used to enable the calibration lamp system. Beyond that sits a small tower containing the optical system that transmits light from the integrating sphere to the focal reduction system. A ball bearing linear stage driven by a lead screw coupled to a DC motor sits beyond the optic tower and contains three stations. In the first, the iodine cell is mounted in a cylindrical assembly, wrapped with thermal tape and insulation. The second station is blank, and the third contains a BK7 window that has the same optical path length as the iodine cell. During observing runs when the iodine cell is in use, the telescope will be focused on the slit through the cell. When the observer wishes to take exposures without the cell, the pyrex window will be used in order to avoid having to refocus the telescope. The blank position on the linear stage can be used if any observer wishes to use PFS without the iodine cell. Absolute feedback of the position of the linear stage is provided over the full travel length by a linear potentiometer, and two switches trigger a motor shut-off if the stage is mistakenly driven to either extreme end of the allowable travel.

The beamsplitter, pupil-imaging achromat, and offset, butted mirrors are potted in a fixed, precisely machined assembly at the rear of the pre-slit assembly enclosure. The beamsplitter feeds a camera that is mounted on a tube sitting vertically above the pre-slit assembly. Camera focus is adjusted manually using a push-pull screw system and then locked down.

The calibration lamps are mounted in individual tubes and attached with their optical systems on the top of the pre-slit assembly enclosure. This eases replacement of the lamps. The integrating sphere is also mounted on the top of the enclosure, with its output port pointed down and into the enclosure.
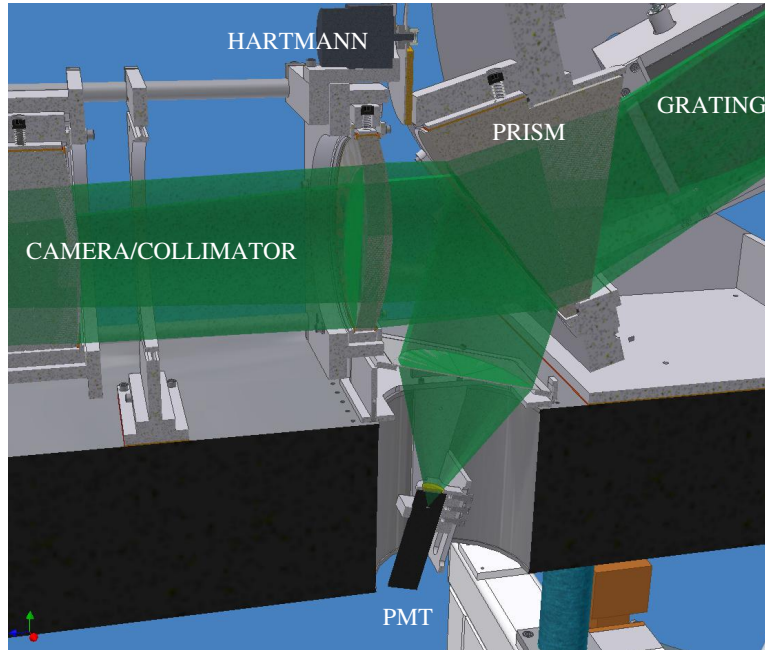
Figure 5. The PMT assembly is shown in cross-section. The beam shown represents 5000Å light. The assembly can also be seen in Figure 4.

3.2 Hartmann Mask

A Hartmann mask will be used used to check the internal spectrograph focus (Figure 4). The PFS Hartmann mask is a large leaf shutter that is attached directly to the shaft of a stepper motor controlled by a micro-stepping controller. The mask alternately blocks either the left or right half of the collimated light beam between the camera and the cross-dispersing prism. The leaf is nonsymmetric about the rotation axis, so a counterweight has been attached to center the load on the motor shaft. In this way, the leaf is balanced when stopped and no power is required to stabilize it. This will minimize heat dissipation. The position of the leaf is measured absolutely by a rotary potentiometer that is coupled to a rear shaft on the stepper motor. Although the leaf is sized so that an integral number of steps is required between the positions blocking the left and right halves of the optical beam, microstepping will be used during rotations to minimize vibrations. This is important because the assembly is attached directly to the camera/collimator frame (see C06).

3.3 Photomultiplier Assembly

A photomultiplier tube (PMT) is required to monitor exposure levels. This allows the observer to calculate the exposure-weighted mean exposure times necessary to apply the appropriate barycentric radial velocity correction to each spectrum. Constantly monitoring the exposure level is also necessary in order to provide feedback control of the CCD's time-delayed integration (Section 3.4).

The PFS PMT assembly (Figure 5) is fed by 1-2% of the target's collimated light, reflected from the front surface of the cross-dispersing prism. This light passes through a simple Fresnel lens mounted just above the surface of the optical table. The custom table was fabricated to include a hole through the full thickness with diameter seven inches. The Fresnel lens collects and focuses the light onto the PMT package. The active area of the photocathode is 22 mm in diameter, so even the poor focus provided by an inexpensive Fresnel lens is adequate.

3.4 CCD Camera

Especially at the level of precision sought for PFS velocity measurements, sub-pixel inconsistencies in the measured intensity distributions of the spectra and flat-fields can have significant, deleterious effects. To combat this,
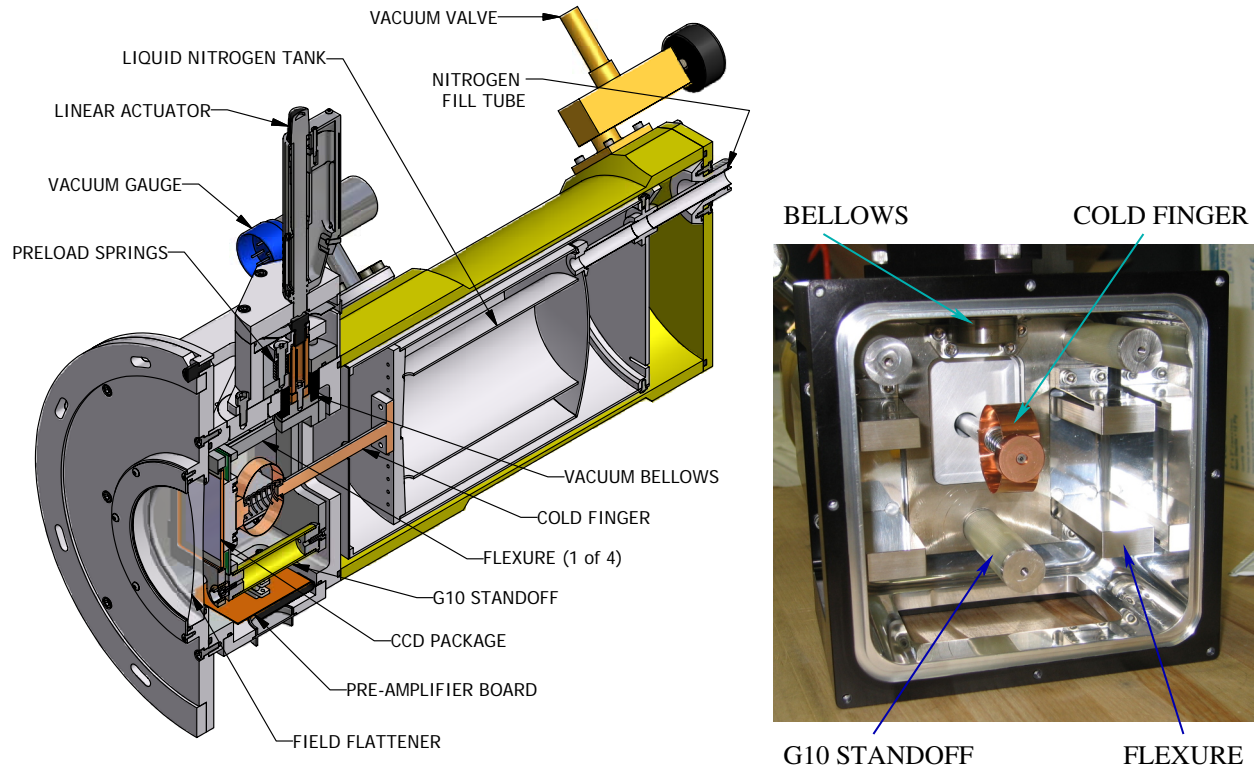
Figure 6. The PFS CCD camera is shown in cross-section. The inside of the CCD head is also shown prior to the placement of the CCD package and electronics.

PFS exposures will be executed using time delayed integration (TDI) at the CCD. The CCD will be physically translated in the cross-dispersion direction during each exposure, with well-timed charge shifts in the opposite direction. This will effectively produce an output image where every image pixel has been averaged over many physical CCD pixels. In this way, the effects of sub-pixel variations will be minimized through averaging. The timing of the shifts must be slaved to the output of the PMT so that each physical pixel that contributes to each final image pixel receives equal weight.

The camera's entrance window is a field flattener. It was therefore not an option to translate the entire assembly since the optical alignment of the flattener with respect to the rest of the system would be disturbed. The CCD must therefore be physically translated inside the evacuated camera head attached to the liquid nitrogen dewar.

The CCD camera is shown in Figure 6. The detector, which is a 4064×4064, 15μm pixel, back-illuminated and broadband AR-coated CCD, is attached to an invar platen with a header printed circuit board (PCB) and embedded heat sink seated at its rear face. A spring-loaded copper puck with attached copper straps presses against the back side of the heat sink, thermally coupling it and the CCD to a cold finger that is bolted to the cold plate of the liquid nitrogen dewar. The platen is attached to three G10 fiberglass post assemblies using threaded shafts, the adjustment of which allows precise tuning of the distance between the detector plane and the field flattener. The G10 posts provide thermal isolation of the CCD from the camera head, which is at ambient temperature. The posts are attached at their bases to a structure that is mounted within the head on stainless steel flexures. This whole assembly is moved using a screw-driven linear actuator that is mounted on the outside of the vacuum enclosure and mechanically coupled to the flexure mount through an edge-welded vacuum bellows. There is a combination of forces acting on the assembly including gravity pulling the flexure assembly down, atmospheric pressure pushing on the vacuum bellows, and resistance from various flexures. These are balanced by three compression springs outside of the vacuum that preload the linear actuator minimally at the top of the

TDI motion.

Inside the CCD head, in vacuum, wires from the header PCB are attached through connectors to a pre-amplifier board mounted on a removable side plate. Communication between the pre-amplifier and the pressurized world is through a multi-pin, hermetically sealed round connector. A cable assembly connects this to the CCD electronic controller "saddlebag" on the outside of the insulating instrument enclosure, mounted to the underside of the pre-slit assembly (Figure 3).

The liquid nitrogen dewar is filled from and vented to the outside of the insulating enclosure. The fill tube is wrapped with insulation to minimize thermal draw on the heat inside the enclosure.

4. THERMAL CONTROL

C06 briefly described a plan to passively modulate the temperature of the bench spectrograph by dampening the effects of sudden, external temperature changes using a thick layer of rigid foam insulation. That plan has been abandoned in favor of active, closed-loop thermal control. To ease the thermal control problem by limiting heat flow to one direction, a setpoint temperature (preliminarily 25°C) above the changing, ambient dome room temperature will be used. The PFS thermal control system is effectively a radiant heater with the spectrograph enclosed within it. The spectrograph will "see" an isothermal world and equilibrate to it.

4.1 Insulating Enclosure

The spectrograph is surrounded by an insulating enclosure in the form of a rectangular box. The box is supported by a frame made of square aluminum tubing. The horizontal members of the frame are integrated into the box's "floor" and "roof". Both the frame and the floor of the box are attached directly to the steel instrument cart, with the optical table's G10 support columns passing through holes in the floor. The floor and two sides of the insulating box are intended to be de facto permanent. The roof and the other two sides of the box can be independently removed to allow access to the spectrograph, with one large side intended as the primary access side (this is the side shown removed in Figure 1).

Each side of the box is an assembly of multiple layers (Figure 7). The outer layer is a $\frac{1}{16}$ inch thick aluminum sheet painted on the side facing outward. A four-inch thick layer of square edge, Dow Corning Styrofoam is glued to the sanded and cleaned inner surface of the aluminum. A sanded and cleaned $\frac{1}{8}$ inch thick aluminum sheet is then glued to the other face of the Styrofoam. This sheet acts as the heat sink for the radiant heating system. Aluminum plates are then attached to the outside face sheet. These serve both as bases for removable handles and as spreaders for threaded nylon rods that are tensioned to squeeze the outer aluminum sheet and inner heat sink together, with the Styrofoam sandwiched between them. Bendable aluminum tubing is attached to the heat sink using copper pipe straps that are riveted to the aluminum. A thermally conductive silicone adhesive is then dispensed along each side of the tubing to increase the thermal coupling between the tube and the plate. Finally, the glued, clamped tubing is covered tightly with thick, adhesive-backed aluminum tape that provides further thermal coupling to the sheet. The ends of the tubing run through cutouts in the outer $\frac{1}{16}$ inch sheet so that they can be accessed from outside the enclosure. In between the tubes clamped to the $\frac{1}{8}$ inch sheet, $\frac{3}{4}$ inch thick Styrofoam is glued to the aluminum sheet. On top of this layer, a three inch thick layer of Styrofoam is glued. The heat sink is therefore insulated from the dome room by four inches of Styrofoam and is also insulated from the instrument by almost the same amount. All of the exposed Styrofoam is covered with black Formica sheets to protect it from damage, protect the spectrograph from flaking Styrofoam, and provide a dark interior to the enclosure.

The floor and the roof of the enclosure are integrated with the square aluminum frames. The outer face sheets of these two panels are riveted to the horizontal aluminum framing members to create solid units. Each edge of the insulating panels is stepped so that when the box is assembled, there is no direct path for light to enter the enclosure. Also, the edges of the insulating walls' aluminum face sheets are sized to overlap the frame and bolt to it.

Each side of the enclosure has two aluminum tubes protruding from it. One is the input and one is the output for the heating liquid. The tubes are terminated with ball valves and quick-release nozzles. Rubber hoses wrapped in insulation and terminated by quick-release connectors attach each panel's input and output to the thermal control system.
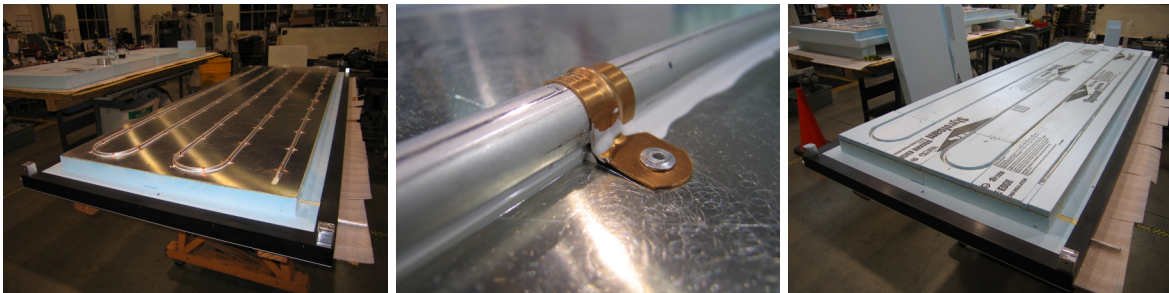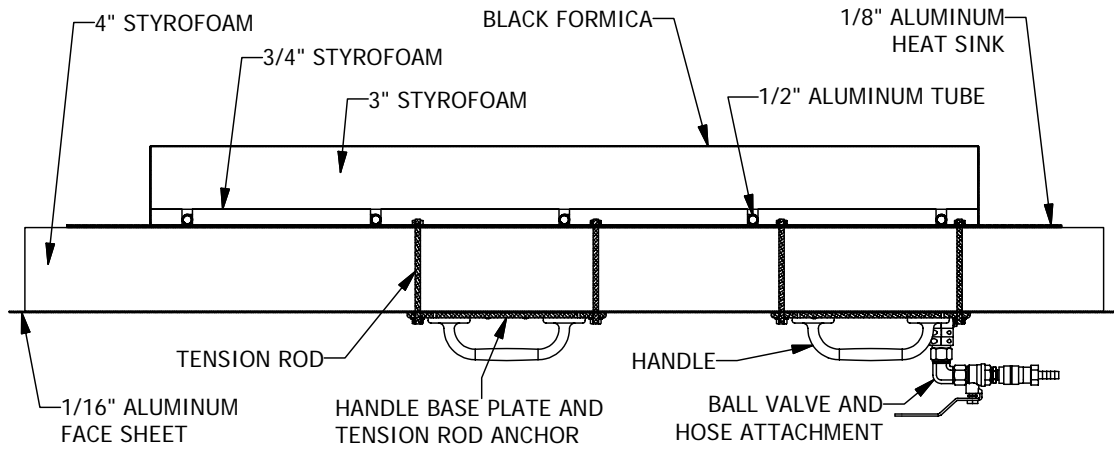
Figure 7. A cross-section of an insulation wall and several assembly photos of the insulation roof are shown. In the left photo, roof assembly has been completed through the application of the thermally conductive silicone adhesive. The middle photo shows a copper pipe clamp riveted to the aluminum heat sink, with dried adhesive trimmed up to, but not beyond, the clamp. The right photo shows the panel after the next two steps have been completed: wrapping of the tubes with aluminum tape, and gluing of the $\frac{3}{4}$ inch Styrofoam.

4.2 Thermal Control System

Most of the remaining thermal control system is assembled inside a wooden box that is lined with styorofoam to minimize heat loss (Figure 8). This box is mounted to a wooden structure that is attached to the instrument cart beneath the insulating enclosure.

Heat is transferred through the system using a corrosion-inhibited glycol solution. The glycol is nominally pumped at about one gallon per minute, but the rate is adjustable by regulation of the DC voltage applied to the pump. After the pump, the glycol passes through a liquid flowmeter that provides flow feedback to the control system. Next it passes through a section of copper pipe wrapped in resistive, thermal tape. This is the primary means by which the glycol is heated to the setpoint. The glycol flows past an immersed temperature sensor and into a manifold where it is distributed via insulated hose to the six sides of the insulating spectrograph enclosure. After it passes through the tubes of the enclosure, it returns via hose to a manifold that sends it past another temperature sensor and into a thick section of pipe exterior to the insulated wooden box (Figure 1). The flow slows due to the larger pipe diameter, and air bubbles have the opportunity to escape upward through a tube that acts as a standpipe and is exposed to atmospheric pressure. This is also where the system is filled. Past the debubbler, the liquid returns to the pump.

Temperature control will be accomplished using a proportional-integral-derivative (PID) loop. The controlled quantities are the voltage applied to the thermal tape and the speed at which the pump is run. PID loop feedback is provided using several temparature sensors inside the insulating enclosure as well as sensors monitoring the temperatures of the glycol going to and coming from the enclosure.
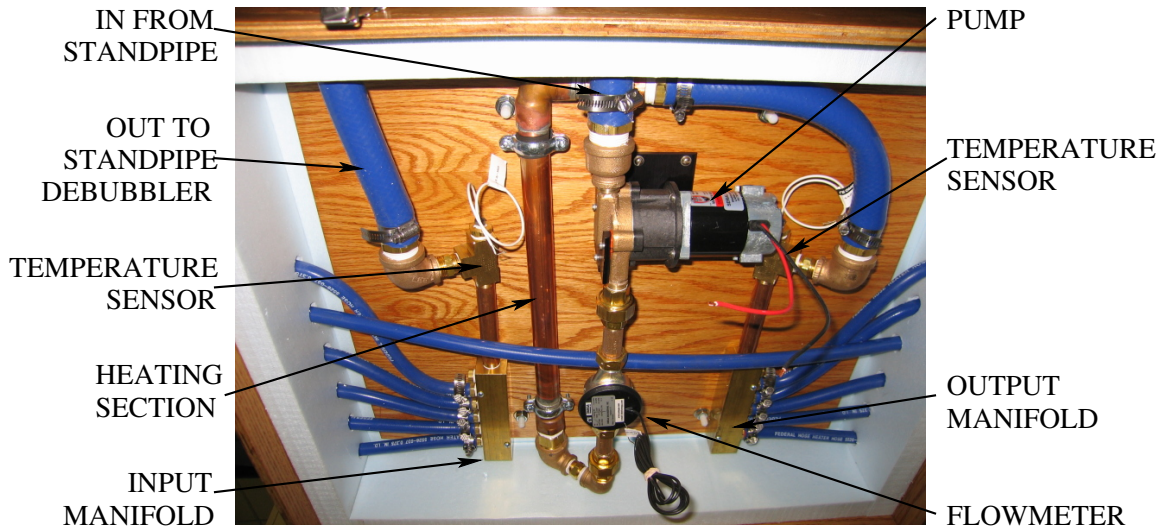
Figure 8. The PFS temperature control system is shown inside its insulated box mounted to the instrument cart beneath the insulated spectrograph enclosure. When this photo was taken, the heat tape had not yet been wrapped around the copper pipe and the wiring had not yet been completed. Note that only five hoses are attached to each manifold because the two insulating end panels are connected in series to match the total flow length to that of the larger panels.

5. STATUS

PFS is mechanically assembled and its optics are fully mounted. The electronic components are currently being wired and the instrument-level control computer is being programmed. At the same time, a top level graphical user interface is being written. All of these should be complete by mid-July. After a period of testing, the instrument will be shipped to LCO with first light possible by the end of 2008.

ACKNOWLEDGMENTS

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