

A radial velocity spectrometer for the Automated Planet Finder Telescope at Lick Observatory

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ABSTRACT

The Ken and Gloria Levy Spectrometer is being constructed at the Instrument Development Laboratory (Technical Facilities) of UCO/ Lick Observatory for use on the 2.4 meter Automated Planet Finder Telescope at Mt. Hamilton. The mechanical design of the instrument has been optimized for precision Doppler measurements. A key component of the design is the space-frame structure that contains passive thermal compensation. Determinate hexapod structures are used to mount the collimator, prism, and echelle grating. In this paper we describe the instrument mechanical design and some features that will help it detect rocky planets in the habitable zone.

Keywords: radial velocity spectrometer, hexapod, space-frame, echelle, Invar 36[®], determinate

1. INTRODUCTION

The Automated Planet Finder Telescope and Levy Spectrometer represents a seven-year, ten-million-dollar investment by the United States Naval Observatory, The National Aeronautics and Space Administration (NASA), The University of California Observatories (UCO), National Science Foundation, Ken and Gloria Levy, and Professor Geoff Marcy (U.C. Berkeley) for a dedicated, fully robotic system to find extrasolar planets. The PI for the project is Dr. Steven S. Vogt, and the Project Manager and lead engineer is Matthew Radovan.

The telescope and dome were purchased from EOS Technologies, Tucson AZ, and EOS Space Systems, Canberra Australia, in July 2003. Ground breaking at the site took place September 2005. In May 2010, UC began the final acceptance testing of the Automated Planet Finder Telescope, which is the first all-new telescope facility at Mt. Hamilton in the last 40 years

The Levy Spectrometer was designed at UCO by Professor Vogt. Every aspect of the design and construction of the spectrometer was done at UC Santa Cruz by the Technical Facilities Group. The scope of the project included the design, analysis, mechanical fabrication, optical fabrication, and the anti-reflective coatings for the spectrometer. The only two major exceptions are the cross-dispersing prism, which was polished by Zygo, and the R-4 echelle obtained from Newport Grating labs.

The Levy Spectrometer saw first light in the laboratory in December 2009. We are currently working on the final alignment of the spectrometer in preparation for deployment to the telescope in the 3rd quarter of 2010.

2. LEVY SPECTROMETER

The Levy Spectrometer is a high-resolution prism-cross-dispersed single object spectrometer designed to function at the Nasmyth focus of the 2.4 meter Automated Planet Finder Telescope. The instrument structure is a determinate space-frame made from Invar 36[®] with an Invar 36[®] optical table. The optical table is attached to the space-frame with six adjustable struts. The optical table provides the attachment points for all the small optics and stages. The space-frame also provides the attachment points for the collimator, the cross-dispersion prism, and the R-4 echelle. All three of these major components attach to the main structure via adjustable hexapod assemblies. The CCD dewar houses a 42-90 E2V CCD that is cooled with a Brooks Automation Cryotiger[®]. Signal from the CCD is recorded through the Lick

Observatory Universal Camera (UCAM) controller. The optical instrument is housed in an enclosure composed of fiberglass over 3" [75 mm] thick extruded polystyrene foam. The enclosure is sealed and positively pressurized with active thermal control. The total instrument volume is 112" x 48" x 50" [2.85 x 1.22 x 1.27 m].

2.1 Design Philosophy

The scientific requirement for radial velocity accuracy less than 1 meter per second drove all aspects of the mechanical design. The goal of this effort was to build a spectrometer with the highest possible spectral stability at the CCD.

To meet this requirement we set out to build the stiffest and most thermally invariant structure possible. The structural design drew on experience gained building the Echellette Spectrograph and Imager (ESI) for the Keck Telescope. ESI was the first attempt by UCO Technical Facilities to use this construction technique to build a spectrometer, and has been discussed in papers by Bigelow¹, Shenis², and Radovan³. The Levy Spectrometer represents a major advancement for UCO because most of the structure is constructed from Invar 36[®] to improve thermal stability.

Recognizing that there would be limitations of the design because materials other than Invar 36[®] are necessary for construction, we also designed a high-efficiency enclosure with active cooling control. . The enclosure is sealed and positively pressurized to keep the instrument clean. . It also contains multiple coolant circuits to address the unavoidable heat sources within the spectrometer.

The mechanical design of the instrument was integrated with the optical model to predict the thermal residual scale and focus changes. . The details of this process will be the subject of a paper to be presented at a later date by Professor Steven S. Vogt. The result was a passive solution using some of the hexapods to correct for the subtle changes to the optical components that are temperature dependant. This had a profound impact on the camera and prism hexapod structure as described below.

2.2 Optical Layout

The instrument optical layout is shown in Figure 1. Light enters the spectrometer through the fixed prism of the linear ADC, which also functions as a window to seal the instrument. 96 % of the photons pass through the pellicle and into the iodine cell and on to the slit plane of the instrument.

The remaining 4% of photons is reflected to the guider field lens to adjust the plate scale, and into a Princeton Scientific Photon Max 512[®] camera. The guider system also includes a corner cube and shutter that make it possible to see the slit plane and the 4% star image simultaneously. This feature is used for guider alignment only, so the corner cube shutter is closed during normal observation.

The slit stage has a single decker plate with a variety of rectangular apertures. The instrument shutter (not shown) is behind the slit plane and in front of the MaxMirror^{®4} fold flat. After the native f/15 beam from the telescope is folded it enters a relay system whose purpose is to speed the beam up to f/3. The f/3 beam then enters the field lens and collimator off-axis. After passing through the five-element, all-spherical collimator, the beam passes through the prism to the echelle and back through the prism a second time. The second pass through the collimator brings the beam to focus on the CCD after it is folded by a flat mirror.

The instrument has a calibration system with quartz lamps and thorium hollow cathode lamps filled with a mixture of 90% argon and 10% neon gas for wavelength calibration. A movable mirror (not shown) blocks the incoming beam from the telescope and directs the light from the calibration lamps into the iodine cell, after it is folded from the plane above the breadboard down into the main instrument optical axis.

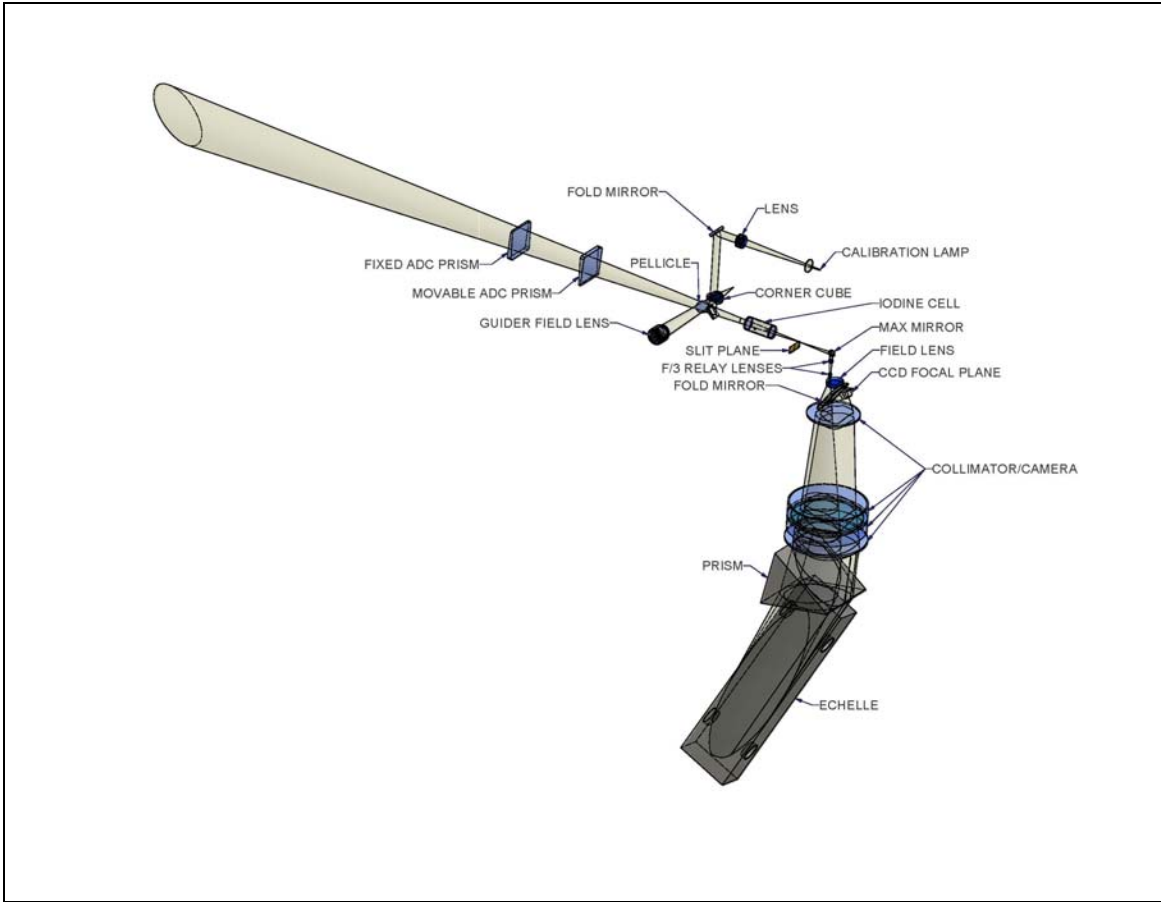


Figure 1. Levy Spectrometer optical layout.

2.3 Optical Table

The Invar 36[®] Optical table is 35½" x 35½" x 4.4" [900 x 900 x 112 mm] and provides the reference surface for the optical axis of the telescope. It contains the guider stage, calibration mirror, pick-off mirror stage, iodine cell stage, slit shutter, calibration lamp stage, the MaxMirror[®] fold flat, and the dewar stage (see Figure 2).

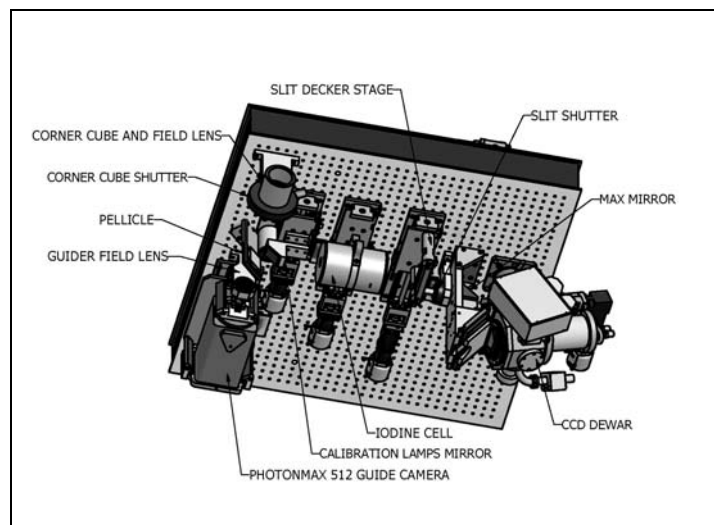


Figure 2. Optical table and components.

The opto-mechanical design of the guider stage, slit stage, and dewar compensates for the material properties of the components. Invar 36[®] and other materials were used in conjunction with specific mounting geometry to maintain the distance of the optical centerline from the breadboard, regardless of temperature. For the slit stage the execution of this design resulted in Invar 36[®] stand-offs holding an aluminum frame to which the aperture is attached. The length of the stand-offs and the aluminum frame were sized to compensate for the coefficient of thermal expansion (CTE) of the steel in the THK stage and both of its mounting plates, as shown in Figure 3.

The calibration lamps, CCD controller, and iodine cell produce significant heat in the instrument. To counteract the heat, liquid coolant is piped to the quartz lamps and CCD controller, and at a carefully controlled temperature to avoid condensing conditions in the instrument. All coolant lines are also heavily insulated. The iodine cell is heated to a temperature of approximately 55°C. This system is not actively cooled, but instead is heavily insulated to retain the heat used to elevate and maintain the cell's temperature. This effort resulted in an average power consumption of only 4 watts to maintain the set point of 55°C for an enclosure temperature of 0°C.

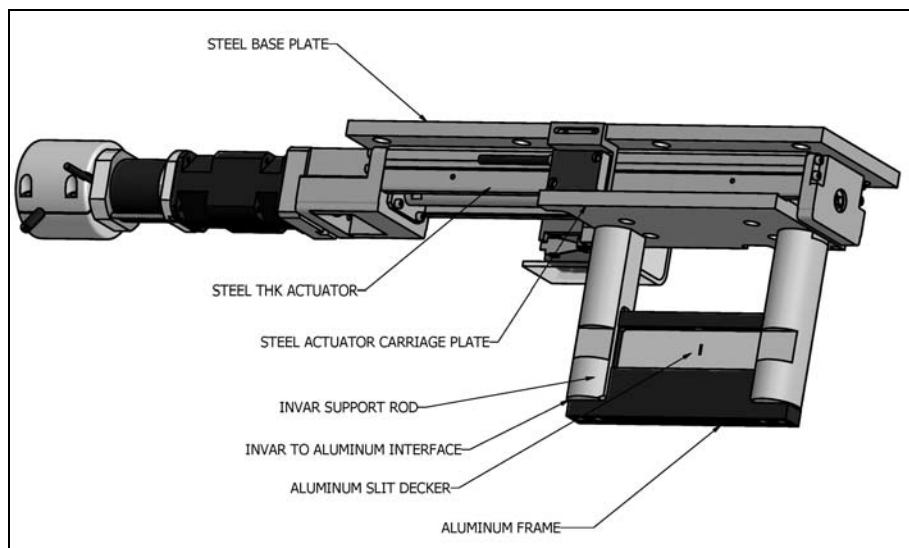


Figure 3. Slit stage.

2.4 Mainframe

The mainframe of the Levy Spectrometer is a determinate space-frame structure that consists of five all-Invar 36[®] hexapods. Optimization of the mainframe was an iterative process that began with a parametric CAD model of the hexapod structure with equal distances between nodes. Node positions were altered from this initial geometry until a physical configuration was found that fit around the optics and the beam bundle. Particular attention was paid to nodes above the camera, adjacent to the back of the prism, and near the echelle, because these nine nodal locations would also serve as the connection point from the structure to the respective optical components. Three connected hexapods form the core of the mainframe. The mainframe core supports the collimator, prism, and echelle. A fourth hexapod attaches the breadboard to the mainframe core. The fifth hexapod provides a determinate connection between the mainframe core and the telescope.

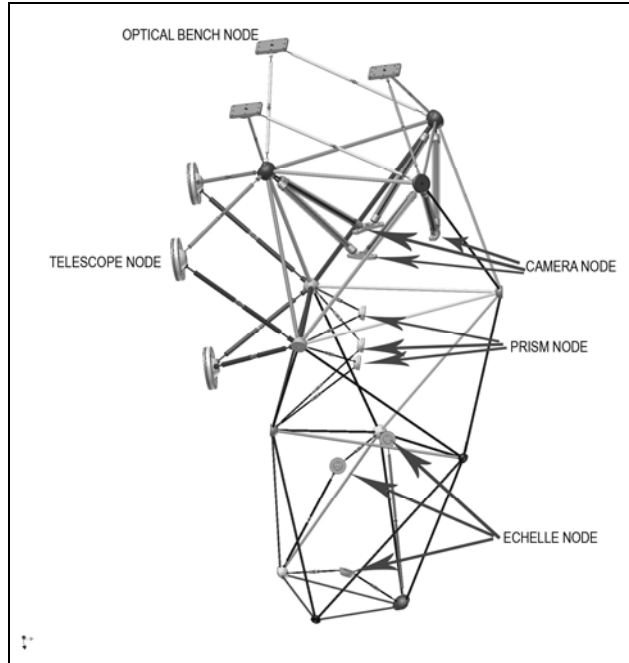


Figure 4. Mainframe

Once a base geometry was found that met the packaging requirements a simple finite element analysis (FEA) model was built. ANSYS was used for the FEA of the structure. The struts of the mainframe were modeled with LINK8 elements, which behave as spars and offer only axial stiffness. The prism and grating were modeled with SOLID45 elements. The camera was represented as a plate using SHELL63 elements. The thickness of this plate is the dimension of the flange at the camera's connection points. The density of the camera plate material was adjusted to reflect the full mass of the camera. Early on in the development of the FEA model it was determined that the rotational inertia of the camera was not important.

Concentrated masses were applied at mainframe element endpoints to reflect structural node point masses. The breadboard was initially modeled with plate elements (SHELL63) as well. This was later simplified to a triangular strut (LINK8) system at the three connection points with the mainframe and concentrated masses at these locations. The boundary condition was the three connection points to the telescope yoke. These three points were grounded in the three translational degrees of freedom.

The baseline design assumed all struts (core and core-to-telescope) were 3/8" [9.5 mm] diameter Invar 36[®]. For this structure, the fundamental first mode of 13.2 Hz was calculated from the FEA model. The second model and all subsequent models separated the telescope attachment hexapod from the instrument hexapod (core) so various combinations of strut diameters could be analyzed. The results are summarized in Table 1. Based on these results we choose 5/8" [15.9 mm] and 1/2" [12.7 mm] diameter struts for the telescope attachment and instrument core respectively as a starting point for the optimization.

		Core instrument struts				
		Dia. (in)	3/8	1/2	5/8	3/4
Core to telescope struts	3/8	13.2	-	-	-	
	1/2	-	16.8	17.8	18.2	
	5/8	16.5	18.5	20	20.9	
	3/4	17.7	19.6	21.7	23	

Table 1. Fundamental (first) natural frequency (Hz.)

The final optimization of the structure was done in an Excel spreadsheet. The loads on each strut calculated by the FEA model were used to check the axial deflection of all struts. This optimization process reduced the worst-case strut deflection from 0.0037" [0.094 mm] to 0.001" [0.025 mm].

Because all the nodes are welded in the structure, it was also important to check that the bending and torsional stiffness was low compared to the axial stiffness. If the ratio is not sufficiently large, moments will exist at the nodes when the structure deflects. The as-built structure has axial-to-bending stiffness ratios ranging from 300 to 3252. Three orthogonal vectors were checked to ensure the structure could be safely transported in any orientation. These additional design requirements increased the diameter of four of the six core-to-telescope struts from 5/8" [15.9 mm] to 3/4" [19 mm]. The changes to the instrument core were also significant. Five of the thirty-six struts didn't change. The others changed in size ranging from 5/16" [8 mm] to 3/4" [19 mm].

The last step of the design process was to rerun the FEA with the spreadsheet-optimized strut diameters to check the modal response. The resultant first mode was calculated to be 18.4 Hz, which compared favorably to the 18.5 Hz result for the 5/8" [15.9 mm] and 1/2" [12.7 mm] structure with which we started and also meet all the additional requirements.

Two of the five hexapods have adjustable length struts for alignment purposes. The struts to the optical table provide a means to align the optical axis of the bench to the axis of the camera. The other set of adjustable struts provides a means to adjust the instrument to the optical axis of the telescope. These struts were relatively large because they carry the entire mass of the instrument, and had axial-to-bending stiffness ratios as low as 300. This was a concern because deformations of the telescope could be transferred through the hexapod connection by strut bending. Since we would be adjusting these struts to align the instrument the nodes might also rotate as much as 2-3 degrees. The solution was to reduce the strut diameter at the node to create a flexure. The flexures are sized with sufficient factors of safety assuming the node rotation is 3 degrees. The impact on the total structural stiffness is very small since the flexure length is a small percentage of the strut length.

Because all the strut and node material is Invar 36[®], the structure was built as a weldment and heat-treated after assembly to ensure the Invar 36[®] achieved its low CTE value of 1.5×10^{-6} mm/mm/°C. During heat-treating, steel structures were substituted where the prism and echelle attach to support the nodes. The entire structure was elevated to a temperature of 1550°F for two hours in a vacuum oven then slowly cooled at a rate of 200 °F/hr. to 600°F in vacuum before nitrogen gas was purged into the furnace for the final quench.

The importance of proper heat-treating to obtain predictable CTE values for Invar 36[®] cannot be over-emphasized. Carpenter steel does not provide a CTE for Invar 36[®] in the annealed condition, as the value can change significantly due to the processing technique. Rod and sheet stock will have different CTE's before heat-treating. Heavy machining operations can also alter the CTE. The most reliable results are obtained by machining parts close to final sizing before heat treating, followed by light final cuts to get to the finished part size.

Node construction, assembly, and quality assurance proved to be a challenge during construction. Node spheres were manufactured in our instrument shop from invar rod stock ranging in size from 3" [75 mm] to 1-1/4" [32 mm] diameter. Each sphere had a reference flat with threaded hole for a stud. This provided a means to hold the sphere in the 5-axis mill for the final fabrication. For every node, a spot with a diameter equal to the mating strut diameter and a 1/8" diameter x 3/32" deep [3.2 x 2.4 mm] center hole oriented along the strut axis were machined on the sphere. The mating struts were cut to length with a matching 1/8" [3.2 mm] diameter hole deep enough for a small dowel pin and a spring. These pins maintained alignment on the flat spot face (see Figure 5). Springs were necessary to install the last one or two struts in each assembly because the structure is determinate. Once all 12 struts of the main hexapod were properly positioned and clamped, the structure was tack-welded using the tungsten inert gas (TIG) process. Early tests using Invar 36[®] as the fill material were unsuccessful. Better results were obtained using CF36 NILO filler rod for the final structure. After the first hexapod was assembled, the remaining units were added to the structure until complete. The total mass of the finished mainframe is 134.2 pounds [61 kg].

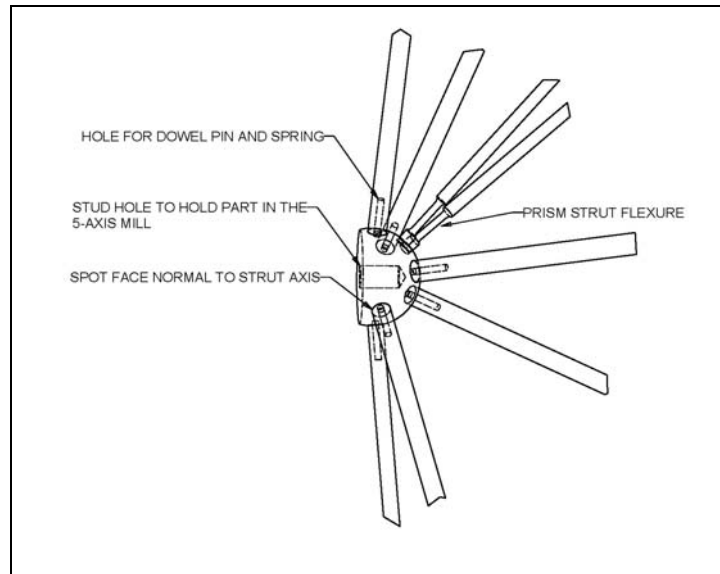


Figure 5. Typical node detail

The finished assembly was checked against the CAD model by making measurements on our large surface plate. True position of all nodes was estimated to be better than 0.040 inches [1 mm]. This error estimate was used later in the design process to set the range of motion requirements for the struts to the grating, camera, and optical bench.

2.5 APF Camera

The APF camera (Figure 6) body is of all-stainless steel (type 304) construction consisting of five optical elements arranged in two singlet assemblies on either side of a triplet that has a center element of calcium fluoride. The entire assembly weighs about 178.2 lbs. [81 kg] and is 23.1" [586.4 mm] long. The calcium fluoride element, 10.6" [270 mm] in diameter, is sandwiched between two 11.8" [300 mm] optics (I-BMS51Y). The radial clearance on either side of the CaF₂ is 0.013" [$\frac{1}{3}$ mm] and filled with an optical coupling fluid from Cargill Laboratories.

The camera design is simple. Gravity is constant and along the major axis. No active compensation with temperature is necessary. The largest optical element, 12.2" [310 mm] in diameter, is located below the triplet with a clearance gap of slightly over 0.078" [2 mm]. The smaller singlet, with its 7.87" [200 mm] element, is positioned 14.1" [358 mm] above the triplet.

Except for the calcium fluoride, all elements are potted in their cells with GE's RTV560. The non-silicone based Cargille 1160 optical fluid (a composition of mixed phthalate esters) was chosen, in part, for its compatibility with the RTV sealant. The RTV bond radial thickness dimension between optics and the stainless housings were sized with a procedure successfully used on the DEIMOS^{5,6} camera on Keck II and based on research by Fata & Fabricant⁷ and Lobdell⁸. Results were correlated and confirmed with finite element analysis. The RTV bonds were designed to accommodate a temperature swing of 25° C. The highest stress, just under 14 psi [0.096 Mpa], occurred in the small 7.87" [200 mm] (Element E) optical element. Figure 7 shows the stress along the mid-plane (from center to edge) of all four bonded optics at the worst case temperature difference.

A metal reservoir is used for volume compensation of the optical fluid, which is necessary for changes in temperature. A microscreen filter protects the fluid from contaminants in the atmosphere.

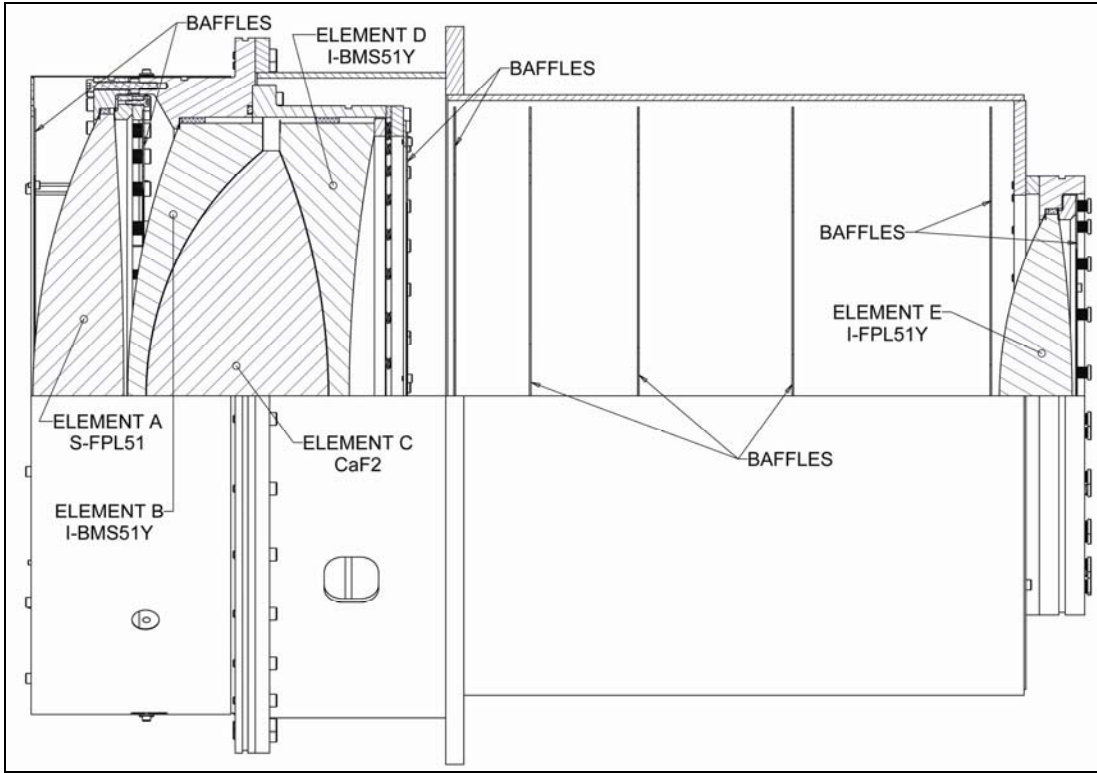


Figure 6. Camera showing cross-section of the interior.

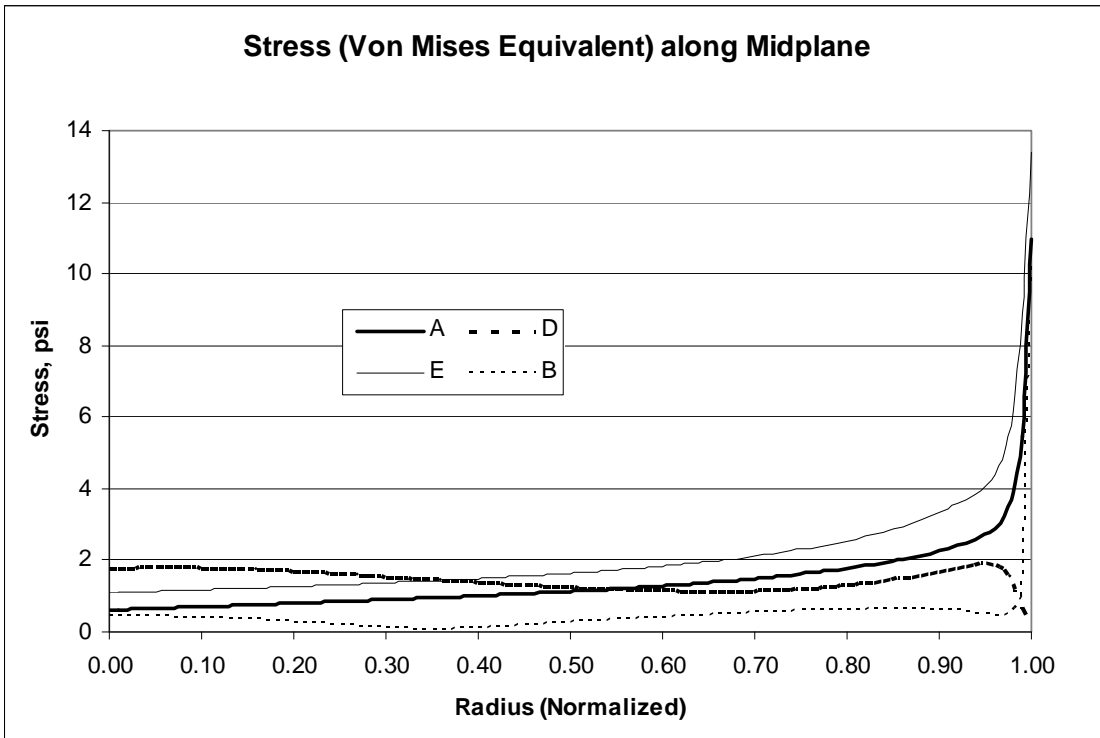


Figure 7. Stress in the optical elements (RTV potted in their housings) when cooled 25° C.

The camera is supported by a nonadjustable hexapod. The support is designed to provide passive thermal compensation for focus and scale change by pistoning the camera 0.0011" per °C [0.028 mm] along the optical axis. The implication of this requirement is that all six struts must be the same length. Additionally, the top mounting triangle of the mainframe and the mounting triangle formed by the three nodes on the camera barrel must be equilateral triangles. Geometric considerations limited the maximum node-to-node strut length of the camera support to 20" [508 mm]. This would have required the struts to have an effective CTE of 37.7×10^{-6} mm/mm/°C if they were simple spars. Most suitable metals for building hexapods struts have CTE's well below this value. Pure zinc (CTE 29.7×10^{-6}) was briefly considered but eliminated due to its poor structural properties and the unavailability of the material in rod stock.

The solution to the materials question was to build a folded composite strut from magnesium alloy AZ31 and Invar 36[®]. This composite rod acts as if the effective length is approximately twice the apparent strut length. The aluminum attachment block and stainless steel camera flange were included in the calculation to get the true node-to-node composite CTE value.

Figure 8 shows a cross section of the camera strut. One end of the three invar rods inside the magnesium outer tube is connected to the central magnesium strut with an invar disc. The other end of the three invar rods attaches to a magnesium cap, which is connected to the outer magnesium tube. We originally based the design on aluminum instead of magnesium and measured the assembly over a 110°C range in the lab. The resulting CTE-related growth was 9% less than predicted. We attributed the discrepancy to joint details, and modified the materials and their lengths as needed to improve the measured value to within 1% agreement.

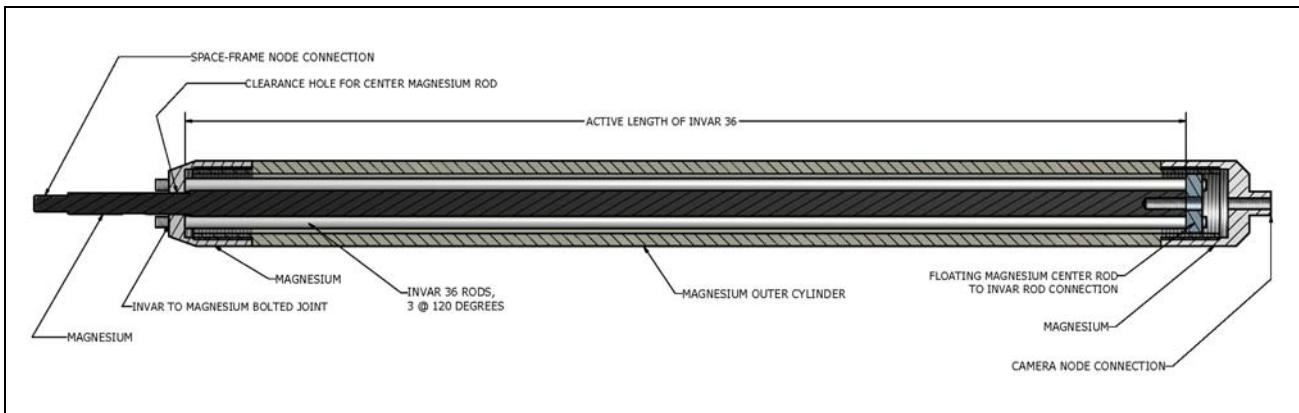


Figure 8. Camera strut section view.

2.6 Prism

The cross dispersion prism is made from Ohara BSL7Y glass. Zygo Corporation made the finished optic using magnetorheological polishing to adjust the prism faces to correct for material inhomogeneity. The prism is attached to the mainframe with six struts that can be adjusted in length via 1/4-28" Invar 36[®] turnbuckle assemblies with invar lock nuts. Two adjusters are made from 17-4 PH stainless steel whose greater CTE creates a temperature dependant rotation of the prism. This passive motion helps stabilize spectra changes that result from the echelle ruling pitch changing with temperature. The passive support provides 1/3 arc-sec per °C of rotation.

All adjusters were silver plated before the mainframe was assembled, and heat-treated to help prevent thread galling. Standard optical alignment techniques were used to check and position all assemblies with adjustable hexapods. Adjustments were made using the parametric CAD model to determine the strut length changes required for a desired motion. High accuracy was possible by attaching dial indicators for direct feedback across each turnbuckle assembly.

The hexapod assembly attaches to the node via a bolted connection. One half of this joint is made from Invar 36[®], to which the adjuster struts are welded. The mating half is made from 6Al-4V titanium, which is epoxied to the prism glass using a technique described by Laiterman in a separate paper presented at this Proceeding. The interface is close fit to provide precise and repeatable positioning. The Invar 36[®] node is held to the titanium puck by a bolted connection.

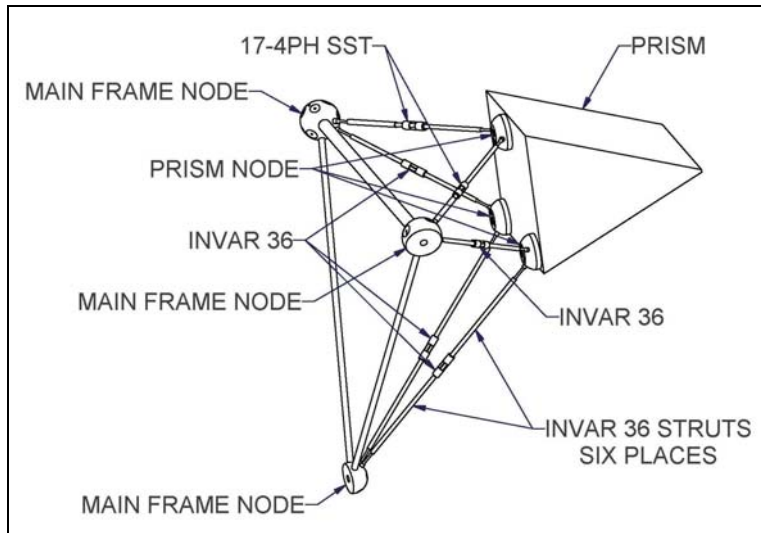


Figure 9. Prism hexapod assembly.

2.7 Echelle

The grating is fabricated on the surface of a Zerodur[®] block with dimensions 33.1" x 8.4" x 5" [840 x 214 x 125 mm]. The grating is supported by a hexapod system of Invar struts that can be adjusted with 10-28 threaded turnbuckles for precision alignment. The ends of the struts are reduced in diameter to keep bending stresses below the material yield point for the designed range of motion. The attachment points to the grating are through invar pucks epoxied to the surface of the glass. The detail of this interface is the same as for the prism connection. Figure 10 shows the grating in closer detail. There are two pucks on its back surface and one on the bottom end.

Although the grating is oriented almost vertically along its major axis, deflections and deformations of the echelle surface are still a concern. For this reason, the mainframe structure was optimized for all components and sub-assemblies in the instrument. The final design was analyzed with FEA. The peak-to-valley range of this deformation is less than 1/3 micron.

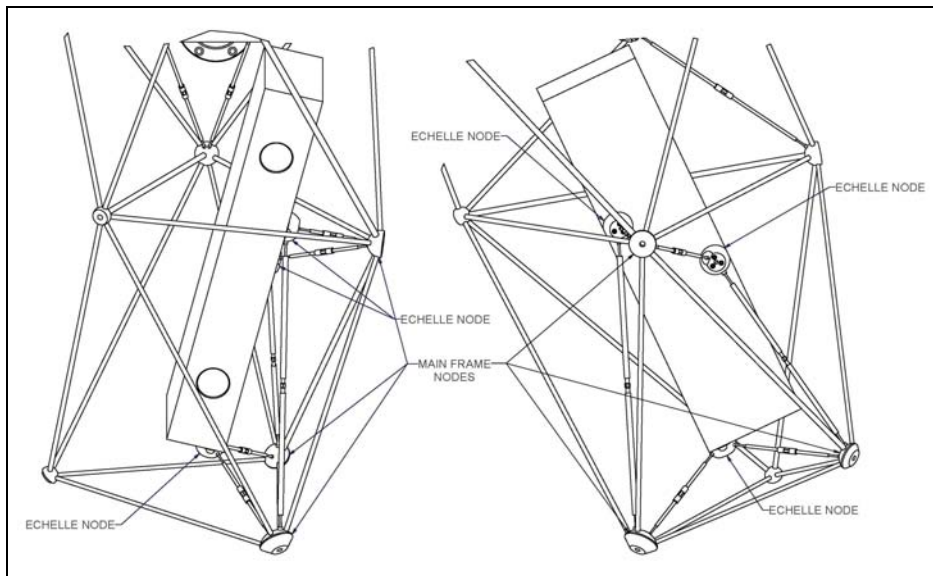


Figure 10. Echelle support, two views.

2.8 APF Dewar

The CCD dewar for APF houses the E2V 4092 (2k x 4k) CCD detector. We used a Polycold Cryotiger[®] closed cycle refrigeration head with P14 gas to cool the CCD. (The proprietary P14 gas puts the cold end very close to liquid nitrogen temperature, allowing adaptation to a liquid cryostat if necessary.) We equipped the dewar with an ion pump. The dewar has two polymer o-rings, one on the lid and one for the window/field flattener. All remaining vacuum seals are metal, including the valve. Volume constraints pushed for a low profile, low frontal area dewar design.

The result of the effort to minimize volume is a compact in-plane mounting and thermal isolation package for the detector. This structure has an Invar 36[®] carrier for the CCD, which is isolated from the aluminum support plate by a G10 flexure web frame. This frame holds the Invar 36[®] carrier at four locations. This is over-constrained, but its geometric symmetry minimizes thermally induced moments, and flexure due to (fixed) gravity loads is negligible. (Note that shrinkage in the G10 webs due to thermal gradients produces a bi-metallic diaphragm effect on the structure, limiting displacement of the CCD normal to the focal plane.) The support plate also carries a tantalum box with 1/4" [6 mm] thick walls to provide hemispherical radiation shielding from sources in and around the telescope. The tantalum box is closely packed around the CCD to minimize total mass. It is suspended on the warm side of the thermal isolation, however, to minimize heat load into the cryocooler. Figure 11 shows the CCD support package structure with and without shielding.

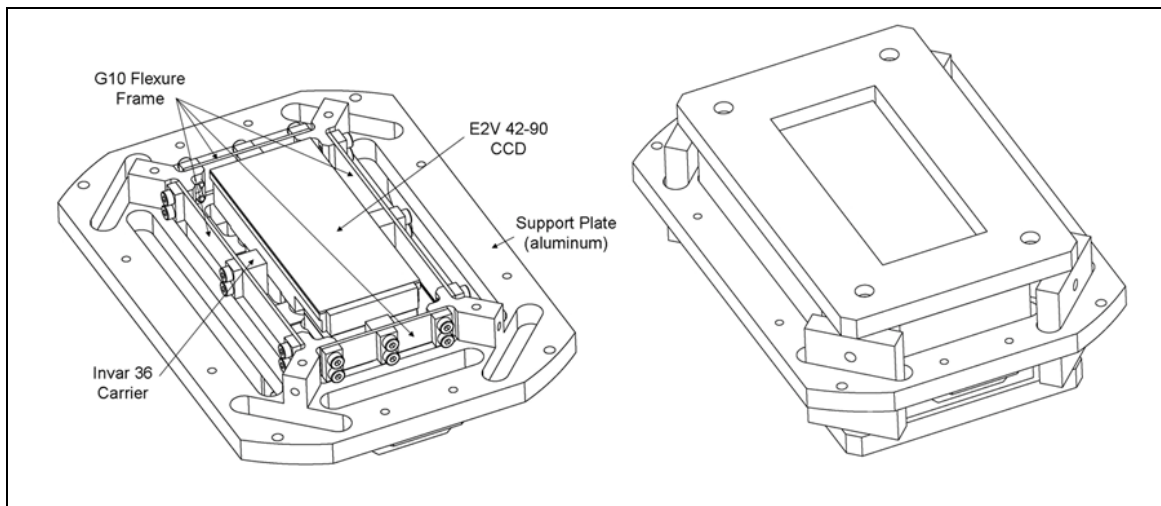


Figure 11. CCD thermal isolation and support structure (left); CCD support with tantalum radiation shielding (right).

The dewar window is also the plano-concave field-flattener for the system. Requirements for the distance of this optic from the CCD were driven by the optical design and were more stringent than an RMS stack-up of machining tolerance would have allowed. We used a long focus microscope on a three-axis stage to measure the assembled tilt and separation between the field-flattener and the CCD. After some adjustments, requirements were met. These measurements were made with the CCD at both room and cryogenic temperatures with no appreciable change.

2.9 Enclosure

The Levy Spectrometer instrument enclosure is constructed from 3" [75 mm] Styrofoam[®] covered with fiberglass cloth and epoxy resin. The structure is a three-piece assembly. The smallest section is fixed to the telescope fork and has pockets for the telescope-to-instrument hexapod nodes. The top and bottom moving sections weigh 50 and 100 pounds [22.7 & 45.4 kg] respectively and are guided by 30" [762 mm] and 60" [1524 mm] long ball bearing drawer slides that are attached to 5" x 5" [125 x 125 mm] tube steels. All parts of the enclosure assembly attach only to the telescope fork, which isolates them from the instrument. The inside of the tube steels contains lead counterweight to balance the assembly. The interface between the three parts of the enclosure has a labyrinth and foam silicone seal to keep the interface light and airtight. The enclosure air temperature is maintained with a water-to-air heat exchanger controlled via a PID interface. The enclosure is positively pressurized by a small fan that pulls dome air through a high-efficiency

particulate (HEPA) filter and a desiccant trap. Humidity and temperature is monitored in the enclosure and inside the dome to avoid drawing warm, moist air into the enclosure.

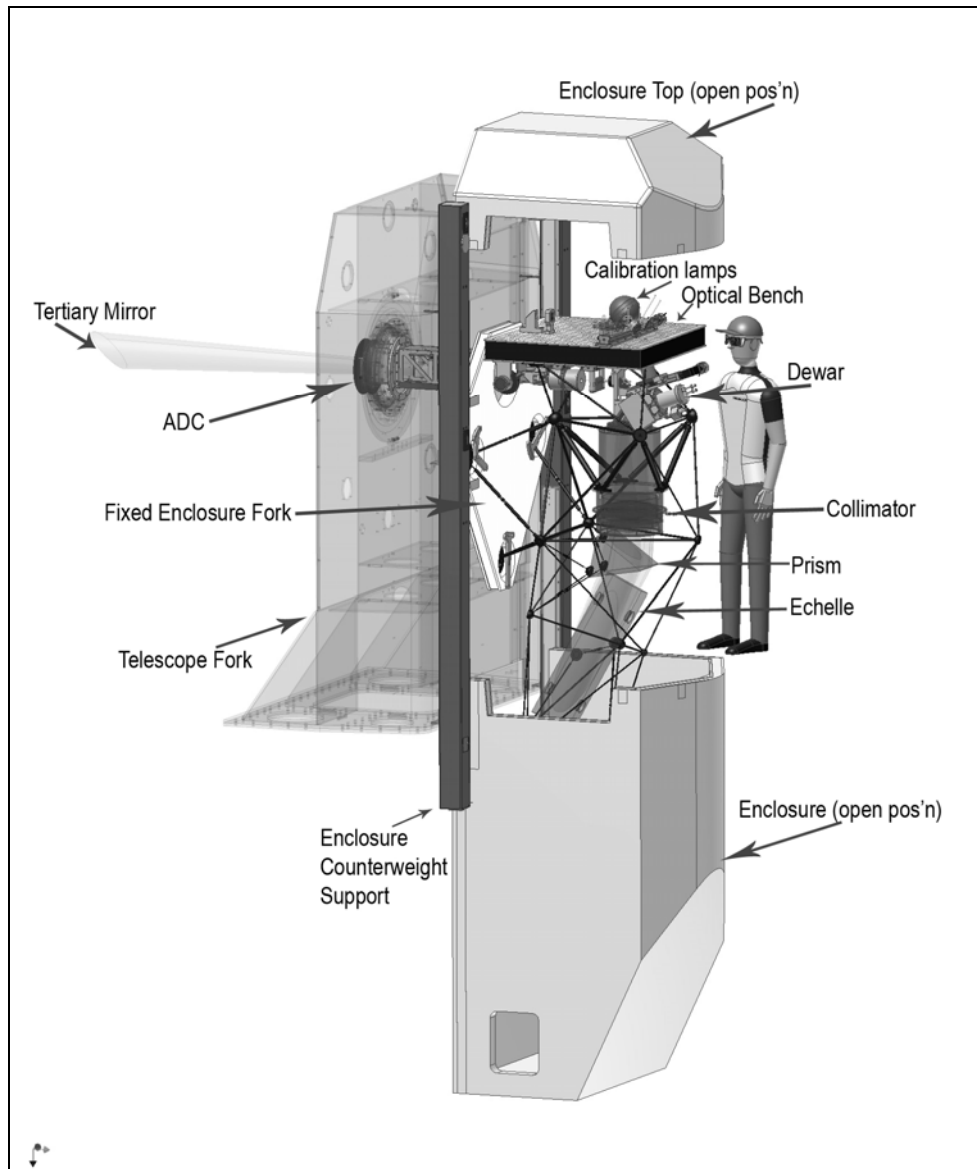


Figure 12. Levy Spectrometer and enclosure.

2.10 Conclusion

The Levy Spectrometer has been designed to produce the highest possible spectral stability. The space-frame structure is used in new ways to create passive compensation for the residual errors that have been predicted from an integrated optical and mechanical analysis. We expect to achieve radial velocity measurement accuracies better than 1 meter per second on the 2.4 meter Automated Planet Finder Telescope. In fall of 2010 this facility will begin dedicated observing to find earth analogs.

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