First-generation instrumentation for the Discovery Channel Telescope

Thomas A. Bida, Edward W. Dunham, Philip Massey, Henry G. Roe
Lowell Observatory, 1400 West Mars Hill Road, Flagstaff, AZ 86001, USA

ABSTRACT

The 4.3m Discovery Channel Telescope (DCT) has been conducting part-time science operations since January 2013. The f/6.1, 0.5° field-of-view at the RC focus is accessible through the Cassegrain instrument cube assembly, which can support 5 co-mounted instruments with rapid feed selection via deployable fold mirrors. Lowell Observatory has developed the Large Monolithic Imager (LMI), a 12.3' FOV 6K x 6K single CCD camera with a dual filter wheel, and installed at the straight-through, field-corrected RC focal station, which has served as the primary early science DCT instrument. Two low-resolution facility spectrographs are currently under development with first light for each anticipated by early 2015: the upgraded DeVeny Spectrograph, to be utilized for single object optical spectroscopy, and the unique Near-Infrared High-Throughput Spectrograph (NIHTS), optimized for single-shot JHK spectroscopy of faint solar system objects. These spectrographs will be mounted at folded RC ports, and the NIHTS installation will feature simultaneous optical imaging with LMI through use of a dichroic fold mirror. We report on the design, construction, commissioning, and progress of these 3 instruments in detail. We also discuss plans for installation of additional facility instrumentation on the DCT.

Keywords: Discovery Channel Telescope (DCT), Large Monolithic Imager (LMI), Near Infrared High Throughput Spectrograph (NIHTS), DeVeny Spectrograph, Lowell Observatory

1. INTRODUCTION

The 4.3m Discovery Channel Telescope (DCT), an f/6.1 Ritchey-Chretien (RC) design, is fully operational at the Happy Jack site in Northern Arizona (elevation 2361m)[1]. The telescope is ultimately capable of supporting instrumentation at the Cassegrain, Prime Focus, and Nasmyth foci. The initial suite of instruments will be implemented at the Cassegrain focus, supported by an instrument interface assembly that can hold 5 co-mounted instruments, and which provides integrated RC correcting optics for one 0.5° diameter wide-field of view instrument, and relay and/or dichroic optics for 4 smaller-field (3 arcmin diameter field of view) instruments[2]. In this paper we present progress reports on development of three facility instruments for the DCT, the Large Monolithic Imager (LMI) (Section 2), the Near Infrared High-Throughput Spectrograph (NIHTS) (Section 3), and the DeVeny Spectrograph (Section 4). We also present an update on the planned installation of a partner-supplied facility NIR imaging spectrograph (RIMAS, GSFC and U. Maryland) (Section 5).

2. THE LARGE MONOLITHIC IMAGER (LMI)

2.1 Instrument description

The Large Monolithic Imager (LMI) is the workhorse optical image for the DCT[3]. It is designed around a single large charge coupled device (CCD), the largest that is possible with current production lines, rather than a mosaic of CCD's, in order to avoid the problems associated with the gaps between devices that mosaics suffer from. This enables, for example, studies of galaxies down to extremely faint surface brightness limits, without the difficulties posed by changing sky levels while dithering to fill in the gaps between CCD chips. The use of a single CCD also provides many additional advantages, such as a greater uniformity of color-terms than one typically finds from chip to chip. To achieve the same level of photometric accuracy, each CCD chip in a mosaic must usually be treated as a separate instrument, greatly increasing the effort involved in reductions and analysis.

There were three science projects that motivated the decision to eschew a mosaic in favor of a single large device:

1) The faint outer halos of dwarf galaxies. The low density outer edges of galaxies are the last great frontier of galaxy evolution. LMI co-investigator (Co-I) Deidre Hunter is using LMI to image 42 dwarf irregular galaxies

that she and her LITTLE THINGS team has mapped in HI with the VLA. This ultra deep imaging (down to 30 mag arcsec^{-2}) will help answer how stars form in the very low density gas that is found in the outer regions of these tiny galaxies.

2) Physical properties of comets. For more than three decades, Lowell astronomers have conducted research aimed at learning the physical characteristics of comets as a family. Co-I David Schleicher is using LMI with narrow-band filters to determine the homogeneity (or lack thereof) of the nucleus of comets.
3) The masses of the most massive stars. Although very rare, massive stars have a disproportionately large effect on their environment. LMI principal investigator Philip Massey is using LMI to obtain light-curves of massive eclipsing binaries in nearby galaxies; combined with radial velocities, these data allow direct measurements of the these stars' masses.

LMI has been in operation on the DCT from Sept. 2012 to the present; its status and operation are detailed further in the DCT status paper and online[1,3]. It features an e2v CCD231-C6, with 6144 x 6160 15μm pixels, at a plate scale of 0.12 arcsec pixel^{-1} at the RC focal plane, yielding a 12.3' square field of view (FOV). The CCD is made of deep-depletion silicon, which largely eliminates interference fringing while increasing efficiency in the red passbands, and is coated with a 4-layer Astro AR coating, yielding quantum efficiencies (QE) of 43% at 350nm, 97% at 500nm, and 59% at 900nm. The device is controlled with a Leach Gen-III system, through a Linux PC-based server running the LOIS modular software package[4]. The CCD is operated with two separate sets of bias voltages and clocks to suppress residual images: one set during idling, and another higher-voltage set during integration[1]. Two CCD231-C6's were delivered to Lowell from e2v, and the 2nd device is in fact also science-grade and was utilized during early camera commissioning; the swap to the current grade-1 device occurred in February 2013.

A set of the Johnson-Cousins UBVRI filters and a set of the Sloan u'g'r'i'z' filters are kept mounted and available at all times. The former set was made by Andover Corporation and the latter by Asahi Spectra. In addition, we have a number of specialized filters, including a VR filter (used mainly for studies of faint KBO's), a set of nebula emission-line filters ([OIII]-5007A, H-α on and off-band filters), and a WFCAM Y-ish filter. These filters are all 120.65mm square and provide the full field of view of the CCD. A set of Hale-Bopp comet filters are also available, although their 100mm diameters introduce vignetting.

The opto-mechanical design and integration of LMI with the RC instrument support assembly (instrument cube) is shown in Figure 1. LMI is installed at the straight-through instrument cube port, behind the 2-element RC corrector and dual filter wheel. The two guider and wavefront sensor (GWAVES) probes patrol the annulus surrounding the CCD's FOV out to 0.6° corrected field diameter for guiding, and to 0.5° unvignetted field diameter for real-time wavefront sensing that provides feedback to the DCT active optical system. The future deployable dichroic mirror enables simultaneous LMI optical imaging with NIR spectroscopy with NIHTS or other mounted instrumentation. The 125mm square aperture Bonn shutter operates with 0.5% uniformity at 0.2s, with a minimum exposure time of 0.001s. The LMI dewar itself is a 235mm dia x 222mm long 6061-T6 tube, with a 165mm x 12mm thick fused silica dewar window installed in the front plate. The camera is cooled with a 16W Sunpower GT Stirling cycle cryocooler, to -120°C. The cryocooler head requires constant heat rejection, which is provided by the DCT facility glycol system, and the cooler is protected by a poweroff circuit if the flow is interrupted.

2.2 Instrument performance

As part of our commissioning work, we have monitored the gain and read-noise of the four amplifiers, as well as measuring the overall sensitivity of the system using standard stars. Two bias frames plus two flat-field exposures (using well-regulated lamps) provide the means for determining the gain and read noise using Janesick's method[5]. We find the values for both to be quite stable with time for all 4 operational amplifiers; typical measurements are shown in Table 1. Most observers are satisfied to use a single amplifier (most commonly A) for readout, as this takes only 22 seconds with the CCD binned 2x2.

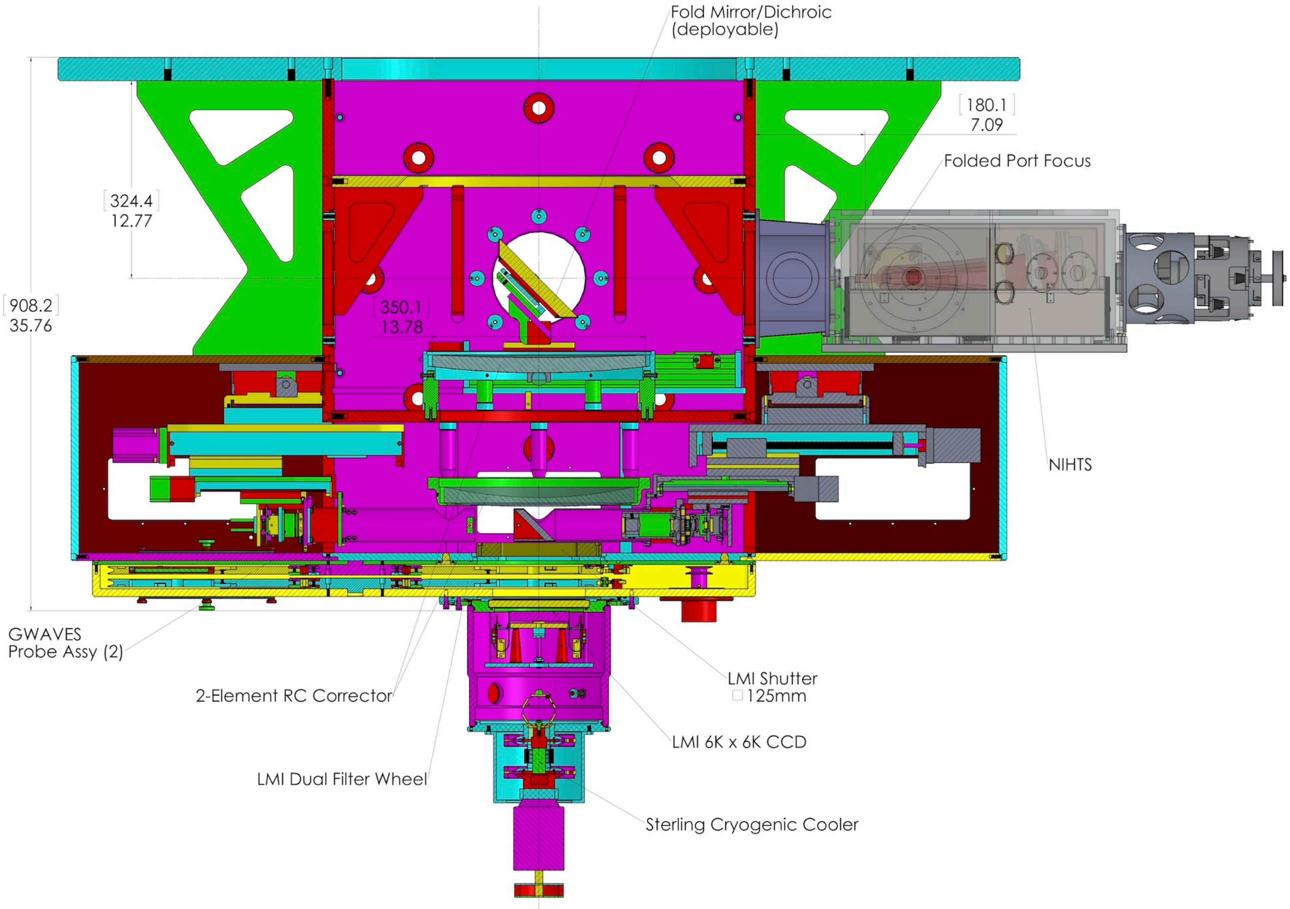


Figure 1. Cross section of the RC instrument cube, showing details of the LMI and NIHTS installations, and the supporting GWAVES components.

Table 1. LMI Science Grade CCD Performance			
Amplifier	Gain (e-/ADU)	Read noise (e-)	Mean bias level (ADU)
A	2.87	7.1	1060
B	2.75	6.9	1077
C	2.86	10.3	1067
D	2.68	6.9	1050

Standard stars were observed through all the filters. For the interference filters, we used spectrophotometric standards; for the Johnson-Cousins filters, Landolt standards, and for the Sloan filters we used standard Sloan fields. Count rates at 20th magnitude at an airmass of 1.0, integrated over a stellar profile, are shown in Tables 2 and 3. These values have all been incorporated in an exposure time calculator (ETC) available online[3].

Table 2. Photometric Filter Count Rates (Mag=20, airmass=1)			
Johnson Filter	Count rate (e-/s)	Sloan Filter	Count rate (e-/s)
U	60	u'	115
B	610	g'	715
V	590	r'	680
R	575	i'	500
I	410	z'	310

Table 3. Interference Filter Count Rates (Mag=20, airmass=1)	
Interference filter	Count rate (e-/s)
VR	490
Y-ish	19
H-α on	14
H-α off	65

The color-terms for the Johnson-Cousins filters are all modest (except for U) and quite stable. Typical transformation equations are:

u = U + 1.275 + 0.50 X - 0.112 (U-B)
b = B - 1.073 + 0.25 X - 0.039 (B-V)
v = V - 0.919 + 0.15 X + 0.028 (B-V)
r = R - 0.854 +0.10X + 0.029 (V-R)
i = I - 0.441 +0.07X - 0.021 (V-I)

The CCD electronics have not yet been optimized for linearity. Currently, there is a 3.5% deviation over the range 40000 to 52000 ADU. Over a more limited range, 20000 to 52000 ADU, deviations from linearity are only 1%. The deviations from linearity are quite reproducible, and a correction formula is available to observers, along with an IRAF routine that will apply these corrections.

With the broad-band filters excellent (<0.5%) flat-fielding is achieved with twilight flats. In contrast, large-scale 3-4% gradients are seen when flat-fielding with the calibration screen. An additional challenge for observers is a quilted pattern that occurs at shorter wavelengths due to the annealing process used by e2v. This pattern amounts to 9% at U, 2% at B, and is sub-1% at V. It flat-fields out well, but because of the color dependence of this, photometry through broad-band U requires some effort.

A major scientific driver for the LMI is the need to do surface photometry to very faint levels, i.e. m(B,V) ~ 30 mag arcsec^{-2}, in order to study the outer reaches of galaxies. Internal reflections within the LMI beam path produce ghost images on the CCD, which are introduced both from stars within the field and the sky background. We have developed a 2-element fused silica corrector that meets the stringent ghosting and astrometric requirements of the LMI and instrument cube assembly[2]. The largest average reflectance from witness samples of the AR coatings, applied by Infinite Optics, over 300-650nm is 0.78%, and that over 650-1100nm is 0.89%; transmission is 98.5% and 98.6% over these bandpasses, respectively. Preliminary analysis of on-sky images of a Vmag=2 star producing a 15mm pupil ghost of the proper size for a reflection between dewar window and filter surfaces, yields a ghost of brightness 23.2 mag arcsec^{-2}, and when scaled to Vmag=8 is approximately 31 mag arcsec^{-2}. This indicates that the optical design is sound with no surprises. We have also added 3 0.6° field baffles internal to the RC corrector assembly to block observed off-axis stray reflections from the lens cells and cube bulkhead; these baffles have proven to be highly effective[1]. The astrometric and imaging performance of the corrected RC focus over LMI's FOV have been measured utilizing M67 cluster data[1], and the distortion results show a maximum residual of less than 0.05% at the corner of the array, compared to the design goal of 1% and design actual of 0.03% over the LMI FOV. Imaging quality measured in the same data set is very uniform, with no systematic variation in the PSF diameter with radius from field center.

3. THE NEAR-INFRARED HIGH-THROUGHPUT SPECTROGRAPH (NIHTS)

3.1 Instrument description

The Near-Infrared High-Throughput Spectrometer (NIHTS, pronounced "nights") is designed to acquire low-resolution near-infrared spectroscopy of faint targets with simultaneous visible photometry via LMI. While the motivating science case for NIHTS is spectroscopy of faint outer solar system icy bodies (Centaurs & Kuiper Belt Objects), the capability will also be useful for a variety of other topics, including: 1) studies of asteroids, especially near-earth objects, 2) spectral light curves of outer planet irregular satellites, 3) efficient characterization of faint brown dwarfs, and 4) surveys of young stellar clusters.

NIHTS is a low-resolution high-throughput infrared spectrograph covering the wavelength range 0.9-2.4μm in a single, fixed spectral setting, at a resolution averaging 160. For simplicity of operation and data analysis, and spectral replication, NIHTS contains no moving parts. The science detector is a HAWAII-1 1024 x 1024 array. The slit assembly features an 80 arcsec long slit with several different slit widths (2, 3, 4 and 12 pixels) available along its length. The widest slit width is designed to allow accurate flux calibration, while the 3 and 4-pixel slits are closely matched to typical seeing at the DCT site (0.84 arcsec median image quality[6]). Different spectral resolutions will be rapidly selectable by dithering the telescope, and a typical observation is anticipated to involve a sequence of dithers both at the desired resolution and at the spectral energy distribution (SED) resolution for calibration purposes.

While observing with NIHTS, the GWAVES probes will acquire stars in a thin, 0.016 deg^2 annulus in the focal plane that is unvignetted by the dichroic fold mirror. Target acquisition is possible in the near-infrared with a Xenics InGaAs slit-viewing camera that is part of NIHTS, or in the optical with LMI; because the fold mirror to NIHTS is a dichroic beamsplitter, simultaneous optical imaging with LMI and near-infrared spectroscopy with NIHTS is enabled.

3.2 Optical design and components

The NIHTS optical design is based on that for the BASS instrument, a mid-infrared spectrograph developed for space-based astronomical observations[7]. The solid model for NIHTS is shown in Figure 2, which identifies the main optical sections of the instrument. First, the f/6.1 folded DCT RC beam enters the dewar through a fused silica window, focusing 62mm into the cryostat, then expanding into a 1:1 Offner relay system with a secondary stop that reimages the focal plane onto the multi-width slit assembly. The slit reflective surfaces fold the wide-field acquisition beam 45° through a second window out of the dewar into the external slit-viewing camera system. The diverging spectrograph beam passes through the slit jaws, and is then folded off of a gold coated flat into the ZnSe prism with front and back spherical surfaces. The once-dispersed beam returns from a spherical mirror, back through the prism and then the flat again folds the spectrum onto the HAWAII-1 detector, the surface of which is mounted at 25.9° to the beam in order to meet focus over the full spectral range. The final f-ratio is f/6.6, yielding a plate scale of 7.36 arcsec/mm, or 0.136 arcsec per 18.5μm pixel. The total path length through the spectrograph optics is 1650mm.

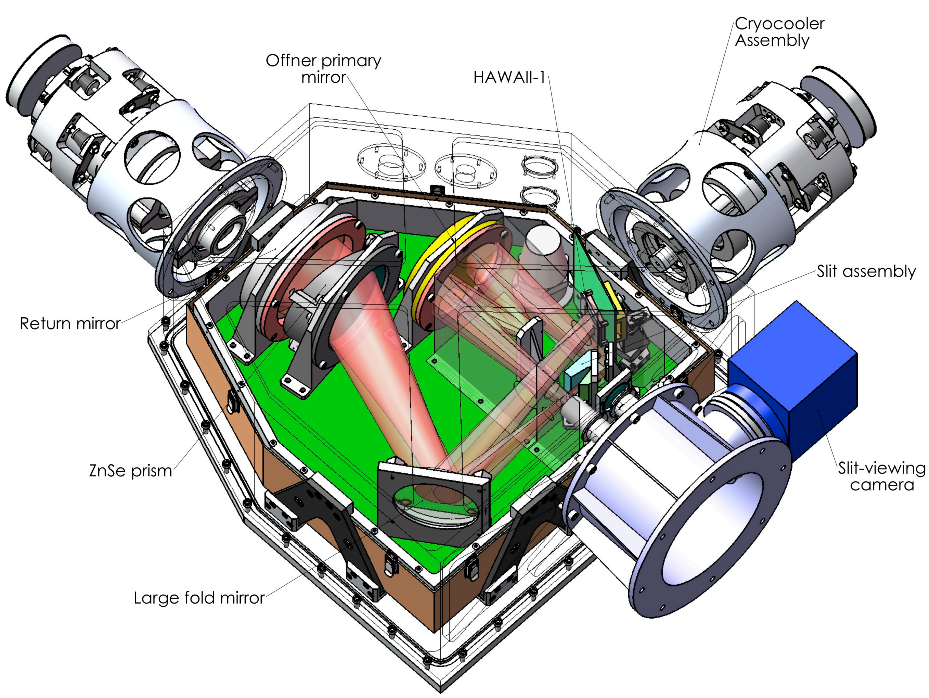


Figure 2. NIHTS solid model, with the dewar vessel shown in transparency and the upper shields removed, components discussed in the text noted, and the beam path highlighted in red. The dewar is approximately 24" wide along the diagonal.

The footprint of the spectral format overlain on the HAWAII-1 Astro-K-band quantum efficiency image is shown in Figure 3, with the resulting YJHK image quality and spectral characteristics shown in Table 4.

Custom optical elements include the fused silica Offner relay and return mirrors, ZnSe prism, and the fused silica dewar windows and slit-viewing camera field flattener; all were fabricated by Optimax Corporation. Commercial elements include the large and small fold mirrors, and several elements of the slit-viewing camera reimaging optics made of BaF2 and fused silica. Coatings for all of the optics have been applied by Infinite Optics.

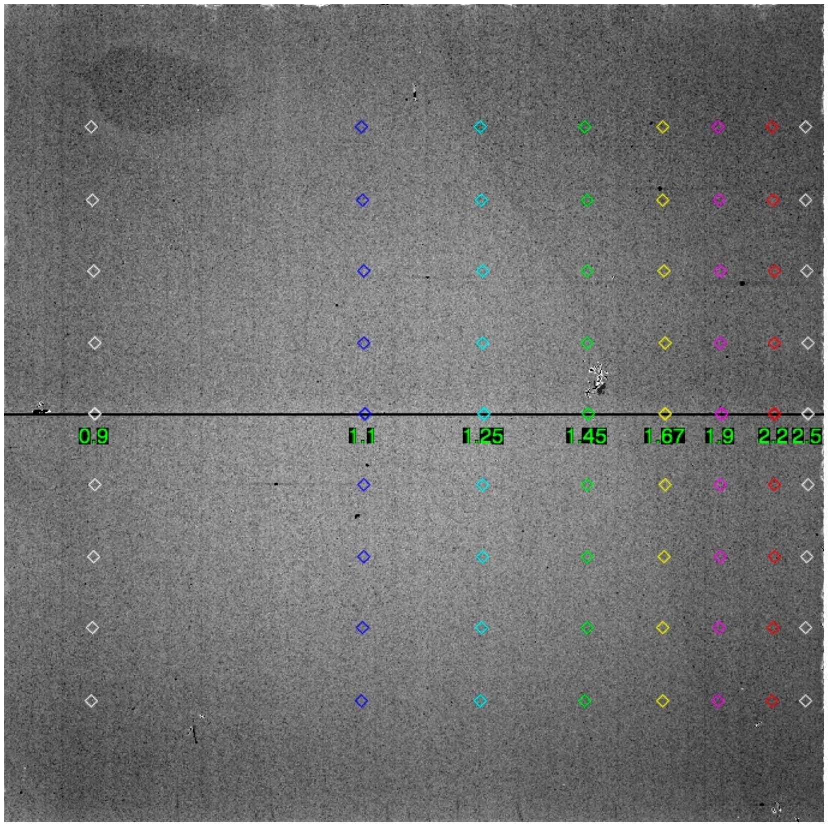


Figure 3. Image taken at Teledyne with HAWAII-1 Part 263 in K-band, illustrating the QE and defects of the array. The colored diamond pattern shows the layout of the NIHTS spectrum on the array, with wavelength points in microns labeled horizontally, and the seams between segments of the slit-jaw assembly delineated vertically.

Table 4. NIHTS Modeled Optical Performance

Wavelength (μm)	Spot radius (μm, 0' field angle)	Spot radius (μm, 0.6')	R (1 arcsec slit)
0.96	10.4	11.3	275
1.25	5.8	7.5	140
1.67	3.5	6.5	85
2.2	6.9	8.8	60

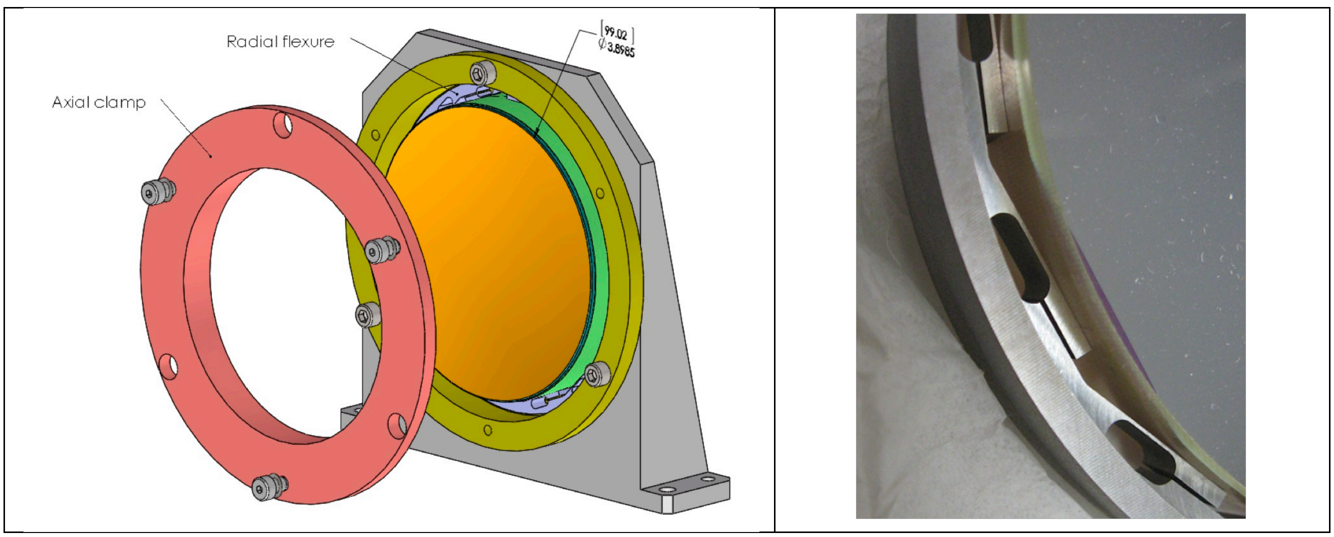
The dichroic beamsplitter for simultaneous optical imaging with LMI has been designed, consisting of an elliptical 180mm x 128mm fused silica blank, 10mm thick, with a 0.137° wedge angle on the back surface to eliminate astigmatism in the transmitted wavefront. The front surface will be coated to reflect NIR and pass optical light, with the back surface AR coated. The reflected FOV is 3 arcmin diameter, (larger than that required for NIHTS, but useful for other instruments) and through-beam images will have good optical quality over 2' FOV, with less than 1 pixel (15μm) FWHM image diameters in the B, V, and R passbands.

3.3 Opto-mechanical design

As mentioned previously, NIHTS produces a fixed-format spectrum that requires the optical elements and detector to be accurately secured to an optical bench, all located in vacuum and cooled to cryogenic temperatures. The 9.2 kg optical bench is fabricated from Mic-6 cast aluminum plate to minimize distortion during machining. We vacuum tested a piece of cast plate for out gassing prior to fabrication, and the material was found to be stable under vacuum conditions. The bench is suspended above the dewar bottom plate with 4 triangular G-10 supports, and shielded with 2.25mm thick Al sheet metal radiation shields, one attached to the bench and covering the optical assemblies, and the other a two-part floating shield fully surrounding the bench assembly.

Finite element analyses were conducted on the entire NIHTS model assembly to determine displacements of the cryotstat and internal elements under gravity and vacuum loads, mechanical resonance modes, thermal cycling, and material stresses, especially those imposed on the glass elements. The dewar structure top surface was predicted to deflect 0.8mm under vacuum, but the actual deflection was seen to be approximately1.5mm. The lowest resonant mode of the dewar structure was found to be 105Hz, compared to the Sunpower CryoTel GT coolers which oscillate at 60Hz. The cryocooler head will be installed in a custom vibration damper fixture as was done for LMI. Sunpower Inc. has also developed an active vibration damper for its cryocoolers which may be utilized in NIHTS if vibration proves problematic. Full results of these analyses will be detailed in a future comprehensive report on NIHTS.

The 3 large spherical powered components, the Offner primary mirror, the ZnSe prism, and the return mirror, are each supported by a radial flexure that is close fit into a sleeve, and retained with a floating axial clamp; the Offner primary mount model is shown in Figure 4a. The radial flexure rings, shown in Figure 4b, are a custom design for this project, consisting of a 6061-T6 Al ring with 16 wire cut spring restraints, designed to absorb expansion forces in the glasses during thermal cycles. A finite element analysis of the flexures revealed a maximum force of 150 PSI imparted to a fused silica blank over a temperature range of 80-293K, for a safety factor of approximately 66 in compression.



(a) **(b)**

Figure 4. a) The mounting of the Offner primary mirror is shown, with the axial clamp in exploded position. The radial flexure is shown in lavender within the transparent lens cell. b) Photograph of a test mirror installed in a development radial flexure ring, showing the detail of the flexure-glass interface. The individual flexure pad springs are 0.015" thick at the waist.

The optical alignment tolerances are maintained by the radial flexures, tight machining tolerances, and thermal expansion grooves for pins locating the optical mounts on the bench. The Offner relay and prism/return elements have decenter tolerances of 0.05mm (0.002"), with the tightest tilt tolerance of 0.015° required of the Offner primary and return mirrors, or 0.025mm across the mirror diameters. Element spacing tolerances are 0.05mm through the optical train, and the hole pattern in the optical bench was drilled for 295K positions. The detector mount provides focus and tilt adjustment through fine pitch ball-end screws and opposing spring plungers, and the mount will be fixed in place when the cryogenic focus position is determined. Precision-cut baffles located at focus, the Offner mirrors, enclosing the Offner relay assembly, and enclosing separately the slit optical section have been designed and will be fabricated and adjusted if necessary during cold testing in the laboratory.

The slit assembly features 8 fixed-width slit segments, requiring very high precision in fabrication. The assembly is shown in Figure 5. Each segment is 1.5mm long, ranging in width from 0.033mm to 0.5mm, and the polished reflecting jaws are oriented at 45° to the incoming reimaged f/6.1 DCT beam to direct the 1.65' x 0.9' acquisition FOV into the slit-viewing camera system. The slit blocks were fabricated with diamond machining by Durham Precision Optics.

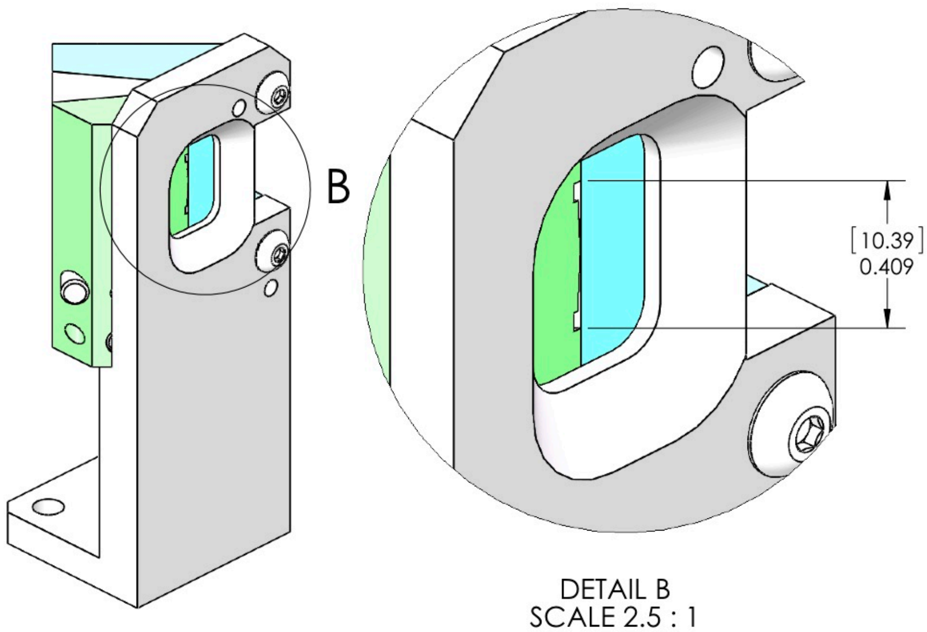


Figure 5. The NIHTS slit assembly model; the slit blocks are colored green and blue, and were diamond machined. The green block contains the 8-segment 35° slit knife-edges, and the blue block holds the 125° straight edge. Both blocks are highly polished for reflection of the acquisition field from the 12.5mm x 18mm front aperture 90° into the slit viewing camera system.

3.4 Detector and electronics

The HAWAII-1 HgCdTe focal plane array (Part 263) contains 1024 x 1024 18.5μm pixels, with 99.55% operability in the Astro-K band. It has a Teledyne-measured full well capacity of 160 ke-, readout noise of 23.6 e-, dark current of 0.07 e-/s, and a K-band quantum efficiency of 67.5% . The K-band QE map shown in Figure 3 reveals a number of dead pixel clusters, however, the NIHTS spectral format as shown fits very well on the array at the nominal position, with the large cluster just redward of 1.45μm falling in-between NIR bands, and other clusters in quadrant IV (upper right) lying close to the seams in between slit-jaw segments. There is +/- 5mm right/left motion available in the detector bracket should fine adjustments be necessary. The FPA will be controlled with a Leach Gen-III system through a Linux server, running the LOIS software. Temperature control of the array will be provided by a LakeShore 325 controller and a heater resistor mounted in the copper detector pedestal. Vacuum will be continuously monitored by a Lesker KPDR900 gauge and controller.

3.5 NIHTS status

At the date of this report, most of the major metal components for the spectrograph portion of NIHTS are fabricated, including the dewar structure, optical table, 1 cold shield, the optical and detector mounts, and many auxiliary parts. All of the spectrograph and slit viewing optics are in house and have been coated, and the detector was delivered in 2010. The dewar structure underwent vacuum testing in May 2013. Two Sunpower cryocoolers with vibration isolating mounts are ready for installation; we plan to initially run with one cooler and add the second cooler if more capacity is needed. The detector cold finger and 2 cold shield pieces remain to be fabricated prior to the first cold cycle, and the slit viewing camera assembly and cube interface mount require final design and fabrication. The dichroic beamsplitters are designed and identifying the coating is the next task. We plan to complete laboratory assembly and testing in early winter 2015, and begin commissioning NIHTS on the DCT in the first quarter of 2015.

4. THE DEVENY SPECTROGRAPH

The DeVeny Spectrograph is the former KPNO "White Spectrograph" that had a long career at the 84" telescope on Kitt Peak before being retired. Lowell Observatory obtained it from KPNO on indefinite loan and has modified it to use a CCD detector, along with a number of other changes, and since 2005 has operated it on the Perkins 72" telescope at Lowell with use of focal converting optics to match the spectrograph's f/7.5 design. We are now upgrading the spectrograph further for a new life on the DCT, including development of a deep depletion CCD camera, and adding remote motorized control of several stages. The DeVeny Spectrograph will be used on the DCT for several high-priority projects, including characterization of the basic physical properties of mission-accessible near earth objects to constrain their compositions and connection to other small bodies (N. Moskovitz), the astrophysics of red supergiants (P. Massey), and studies of the surface composition of icy bodies and comet compositions and dynamics.

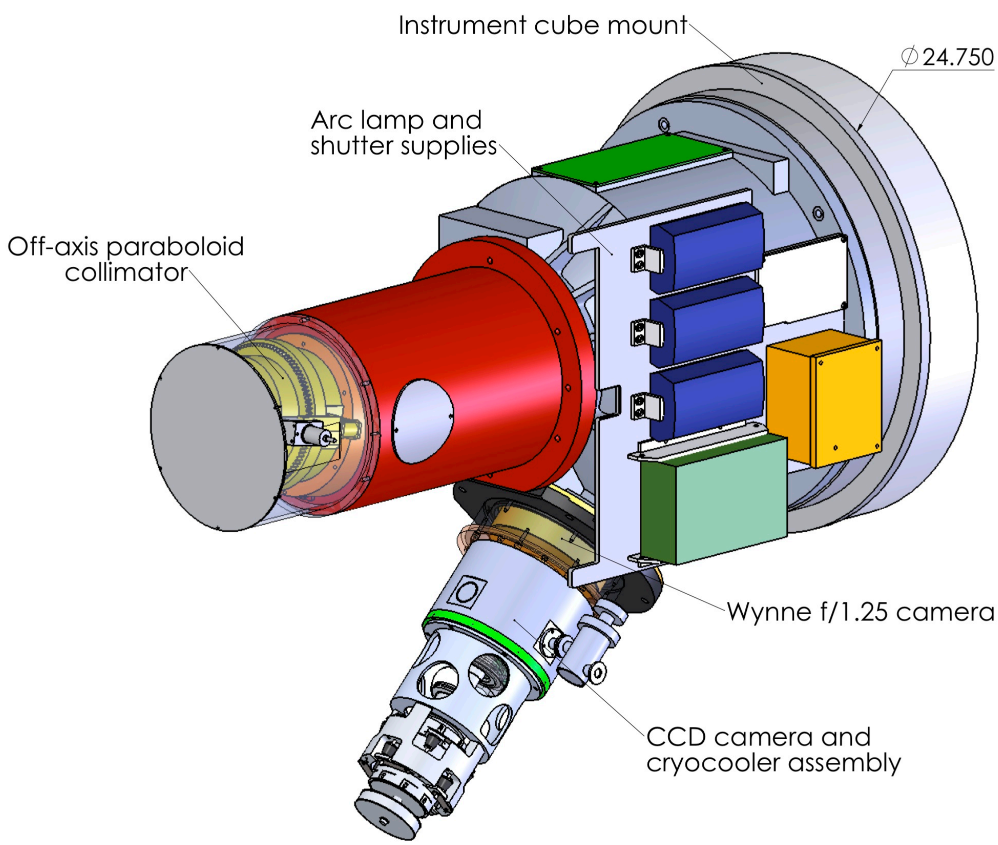


Figure 6. The DeVeny Spectrograph model, with key components noted. The CCD and motor control electronics are not shown for clarity.

The spectrograph assembly model is shown in Figure 6. The DeVeny provides low-resolution optical spectra at R500-4000 (2.5-pixel) over 3200Å - 1μm, with a 2' slit length at the f-converted DCT focal plane. The current grating complement includes 1200g/mm-5000Å, 400g/mm-8500Å, 2160g/mm 5000Å, and 300g/mm-5000Å 1st-order blazed ruled gratings; other stock rulings on 128 x 154mm blanks are commercially available. As part of the upgrade for DCT operations, the slit width, grating tilt, and collimator focus stages are being motorized for remote control, the slit via a motorized micrometer, the grating tilt with a gear-reduced stepper motor driving the internal helical/worm gears, and the focus with a gear-reduced stepper motor driving the 6.25" collimator spur gear. The instrument also includes pre and post-slit neutral density and order-sorting filters in manually-operated wheels, and a decker slide to manually adjust the slit length. The calibration lamp system includes Hg, Ne, Ar, and Cd lamps under remote control.

A new focal converter was designed and fabricated to convert the DCT f/6.1 beam to f/7.5 for spectrograph input. It features a 2-element achromat, utilizing a custom bi-convex CaF2 spherical lens and a commercial fused silica plano-concave lens in series, located 35mm ahead of the spectrograph top plate and 85mm ahead of the slit. Image quality at the slit is predicted to be 5.8μm RMS spot radius over 3500Å - 1μm on-axis, and 8.2μm at 0.9' field radius, with the plate scale at 6.55 arcsec/mm. A custom weak plano-convex fused silica lens located 16mm behind the slit focal plane serves to locate the telescope pupil at the grating. Other existing optical components include the 133mm f/7.5 off-axis parabolic collimator, and the f/1.25 Wynne camera. The camera has two powered reflective surfaces and a series of weak fused silica refractive corrective surfaces, however, the camera secondary mirror introduces a central obscuration in the camera. The final plate scale is 25.4 arcsec mm^{-1}, or 0.38 arcsec per 15μm pixel. Image quality delivered by the system is predicted to be 7.3μm RMS spot radius on-axis at 5000Å, and 12.3μm at 0.9'.

We have developed a new CCD camera for the DCT upgrade, centered around an e2v CCD42-10 deep depletion device with the 4-layer Astro AR coating, containing 2048 x 515 15μm pixels. The advent of a deep depletion device on the DeVeny Spectrograph will be impactive with the large reduction of fringing redward of 7000Å. Two science-grade CCD's were delivered; we installed device -08 which has a measured QE of 63.3% at 3500Å, 93.7% at 5000Å, and 58.8% at 9000Å. The CCD is operated in a dual-clocking mode like LMI, with the clocking run in deep depletion mode when integrating and readout, and inverted mode at lower clock levels when idling between exposures. A transition mode is also implemented when switching between the two above modes to keep the maximum clock swing within safe limits. The camera is also controlled with a Leach Gen-III system, Linux server, and LOIS. It is cooled with another Sunpower CryoTel GT cooler, but with a Gen-2 controller which features a higher degree of software control. This cryocooler is nearly too efficient for this application, where the lightweight CCD mount is thermally isolated from the dewar structure with G-10 standoffs and brazed stainless steel tube supports, the latter also providing high stiffness; the CCD cools from +20°C to -110°C in only 80 minutes with the cooler operating at minimum power. The cooldown temperature gradient on the CCD is a maximum of 4°C min^{-1}, within the specification of 5°C min^{-1}. The CCD is currently operating in the laboratory with a gain of 1.5 e- ADU^{-1} and read noise of 4.75 e-; there is pickup noise evident which should be suppressed on the telescope with proper grounding. The deep depletion CCD support was utilized on the Perkins installation as well, yielding only 1 pixel (15μm) overall instrumental flexure for operation from zenith to horizon.

At the date of this report, the focal converting optics are complete with the application of AR coatings pending, and the CCD camera has been fully assembled and tested in the laboratory. Designs are progressing on the motorized stages and controls, and the cube interface and handling fixtures. Assembly, modifications, and testing will occur from Aug.-Nov. 2014, with installation on the DCT targeted for Nov.-Dec. 2014.

5. DCT PARTNER INSTRUMENTATION

Under development at NASA Goddard Space Flight Center, in coordination with the DCT partnership with the University of Maryland, is the Rapid Infrared Imager-Spectrometer (RIMAS, A. Kutyrev (PI)). RIMAS is designed for gamma-ray burst afterglow observations with photometric and spectroscopic coverage of the YJHK bands[8], utilizing two 2048 x 2048 HAWAII-2RG detectors in two independent channels under full cryogenic operation. The instrument will be semi-permanently installed at one of the large instrument ports on the RC instrument cube, requiring connection to a closed-cycle He compressor located in the DCT telescope power room through existing plumbed copper He lines connecting to flexible hoses running through the telescope wraps to the Cassegrain instrument assembly. RIMAS is a large and sophisticated instrument, nearly the span of the instrument cube itself, and includes several cryogenic mechanisms. It will be selected via deployment of a NIHTS-type dichroic beamsplitter when gamma-ray bursts are targeted, allowing for simultaneous RIMAS and LMI observations.

ACKNOWLEDGMENTS

These results made use of the Discovery Channel Telescope at Lowell Observatory. Lowell is a private, non-profit institution dedicated to astrophysical research and public appreciation of astronomy and operates the DCT in partnership with Boston University, the University of Maryland, the University of Toledo, and Northern Arizona University. LMI construction was supported by grant AST-1005313 from the National Science Foundation. NIHTS is funded by grant NNX09AB54G from NASA's Planetary Astronomy and Planetary Major Equipment programs. The upgrade of the DeVeny optical spectrograph has been funded by a generous grant from John and Ginger Giovale, and the new CCD was purchased and installed with a grant from the Mt Cuba Astronomical Foundation. The DCT is sited on land in the Coconino National Forest of the US Forest Service, and we are pleased to recognize their willingness to work with us.

REFERENCES

[1] DeGroff, W. T., Levine, S. E., Bida, T. A., Cornelius, F., Collins, P. L., Dunham, E. W., Hardesty, B., Lacasse, M., Sweaton, M., Venetiou, A. J., Zoonemat Kermani, S., Massey, P., Foley, M. L., Larson, H., Sanborn, J., Strosahl, S., Winner, R., and Pugh, T., "Status and performance of the Discovery Channel Telescope from commissioning into early science operations", Proc. SPIE 9145-82 (2014).

[2] Bida, T. A., Dunham, E. W., Nye, R. A., Chylek, T., and Oliver. R. C., "Design, development, and testing of the DCT Cassegrain instrument support assembly", Proc. SPIE 8444-192 (2012).

[3] Massey, P. L., Dunham, E. W., Bida, T. A., Hunter, D. A., and Schleicher, D. G., "A large monolithic imager for the Lowell Observatory 4.2-meter Discovery Channel Telescope", http://www.lowell.edu/dct_instruments_lmi.php#, (2012).

[4] Taylor, B. W., Dunham, E. W., and Elliot, J. L., "Performance of the Lowell Observatory Instrumentation System", Proc. SPIE 5496, 446-454 (2004).

[5] Janesick, J. R., [Scientific charge-coupled devices], SPIE Optical Engineering Press, Bellingham, WA (2001).

[6] Bida, T. A., Dunham, E. W., Bright, L. P., and Corson, C., "Site testing for the Discovery Channel Telescope", Proc. SPIE 5489, 196-206 (2004).

[7] Warren, D. W., Hackwell, J. A, and Gutierrez, D. J., "Compact prism spectrographs based on aplanatic principles", Opt. Eng. 36, 1174-1182 (1997).

[8] Toy, V. L., Kutyrev, A. S., Lyness, E. I., Muench, M., Robinson, F. D., Lotkin, G. N., Capone, J. I., Veilleux, S., Moseley, S. H., Gehrels, N. A., and Vogel, S. N., "Detector driver systems and photometric estimates for RIMAS", Proc. SPIE 9147-105 (2014).