Status and performance of Lowell Observatory's Discovery Channel telescope and its growing suite of instruments

Stephen E. Levine, William T. DeGroff, Thomas A. Bida, Edward W. Dunham, George H. Jacoby

Stephen E. Levine, William T. DeGroff, Thomas A. Bida, Edward W. Dunham, George H. Jacoby, "Status and performance of Lowell Observatory's Discovery Channel telescope and its growing suite of instruments," Proc. SPIE 10700, Ground-based and Airborne Telescopes VII, 107004P (6 July 2018); doi: 10.1117/12.2312380

Event: SPIE Astronomical Telescopes + Instrumentation, 2018, Austin, Texas, United States

Status and performance of Lowell Observatory's Discovery Channel Telescope and its growing suite of instruments

Stephen E. Levine[a,*], William T. DeGroff[a], Thomas A. Bida[a],
Edward W. Dunham[a], George H. Jacoby[a]

[a]Lowell Observatory, 1400 West Mars Hill Road, Flagstaff, AZ 86001, USA

ABSTRACT

Lowell Observatory's Discovery Channel Telescope (DCT) is a 4.3-m telescope designed and constructed for optical and near infrared astronomical observation. The DCT is equipped with a cube at the RC focus capable of interfacing to five instruments along with the wave front sensing and guider systems at the f/6.1 RC focus. Over the period 2016 through mid-2018 the instrument cube ports were fully populated as several instruments new to the DCT were brought on-line (NIHTS, IGRINS, EXPRES). The primary and secondary mirrors of the telescope were re-aluminized, and the coating process modified. The facility operational modes have been refined to allow for greater flexibility and faster response to unexpected science opportunities. This report addresses operational methods, instrumentation integration, and the performance of the facility as determined from delivered science data, lessons learned, and plans for future work and additional instruments.

Keywords: DCT, Discovery Channel Telescope, Lowell Observatory, Telescope and systems performance, System status

1. INTRODUCTION

Lowell Observatory's Discovery Channel Telescope (DCT) is a 4.3-meter optical and near infrared telescope. The DCT has been in full science operation since the beginning of 2015 with an instrument assembly (the "instrument cube") at the f/6.1 Cassegrain focus that is capable of carrying up to five instruments. Since mid-2016, we have had a full complement of instruments available (as will be discussed below). See Ref. 1 for an overview of the basic site and facility parameters, and Refs. 1–3 for prior performance assessments.

In this contribution, we provide a summary of the facility and instrument progress over the past two years, the work on improving and preseving the mirror coatings and aspects of the whole that we believe contribute substantially to making the facilty operate efficiently and flexibly.

2. INSTRUMENTATION OVERVIEW

One of the original goals for the DCT was that users would be able to make use of multiple instruments within one night, including the option to switch quickly between instruments. The current DCT Cassegrain instrument cube can carry up to five instruments,[4] as well as two guider and wave front sensor probes. Four instruments are visible in Fig 1, and the left panel of Fig. 2 gives a clearer sense of the available volume. Because of the telescope design, the available instrument volume and total carrying capacity is somewhat limited. The cube, all five instruments and any ancillary components can weigh at most 1,500 kg, and fit within a cylindrical volume that is roughly 3-m in diameter, 1.05-m deep with a spherical cap 0.3-m deep. Operationally, this trade-off has worked out well. One added complication is that the guider/wavefront sensor probes are enclosed, and take up the lower potion of two of the cube sides; we have one straight through port, two large ports and the two small ports available for science instruments.

Each of the four side port instruments has a fold flat that can be inserted into the optical beam within the cube to direct light to that instrument. When all four flats are retracted, the beam passes to the LMI on the straight through port. Each fold flat can be optimized for the instrument it feeds. Switching between instruments requires only a few minutes during which we reposition the flat(s) and update the telescope instrument definition.

---

[*] Corresponding author: E-mail: sel@lowell.edu

Ground-based and Airborne Telescopes VII, edited by Heather K. Marshall,
Jason Spyromilio, Proc. of SPIE Vol. 10700, 107004P · © 2018 SPIE
CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2312380

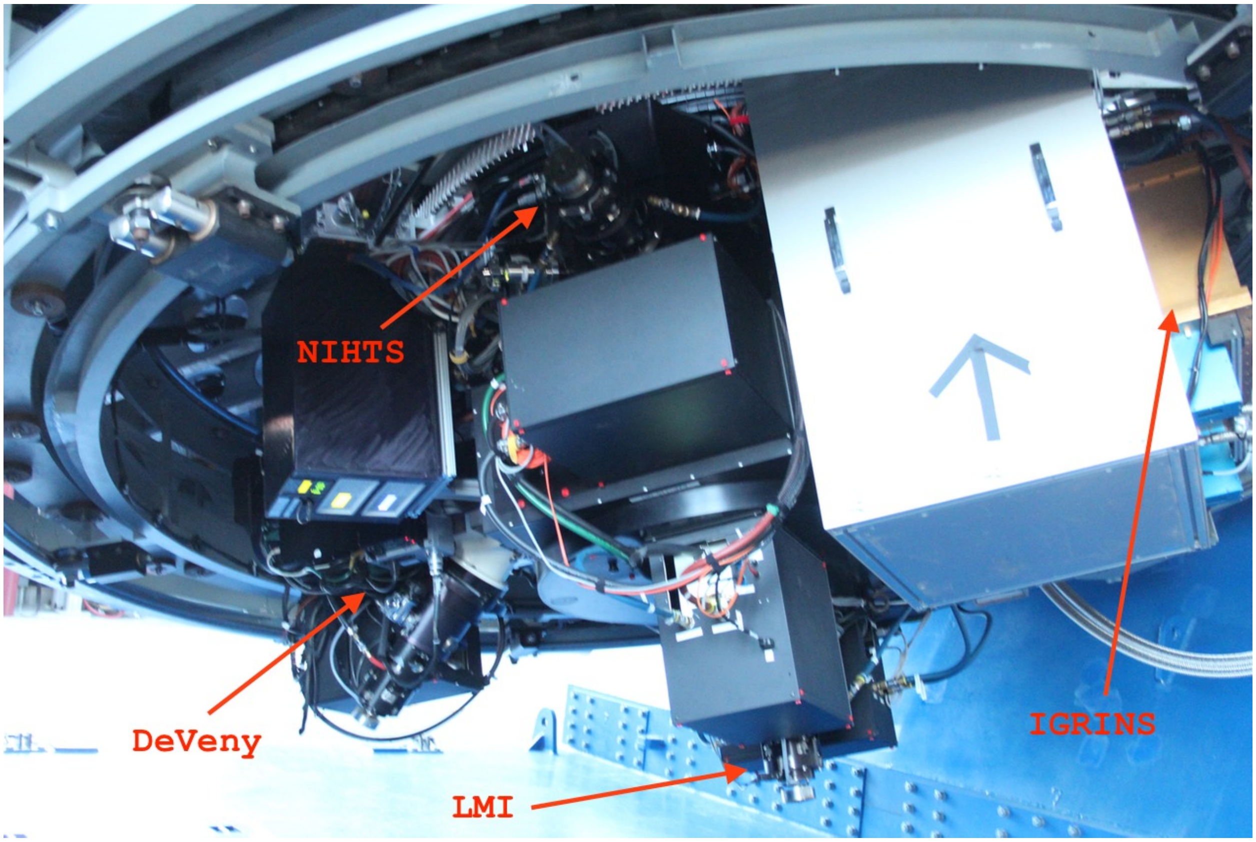


Figure 1. Four instruments mounted on the DCT instrument cube. From left to right are the DeVeny optical spectrograph, the NIHTS near-IR spectrograph, the LMI optical imager and the IGRINS near-IR spectrograph. The fifth instrument which is not visible because it is on the far side of the cube is the EXPRES high resolution optical spectrograph front end module.

2.1 LMI, DeVeny and NIHTS

The primary optical imager is the Large Monolithic Imager (LMI), which covers a $12.'3 \times 12.'3$ field of view with $0.''12$ pixels.[5] The instrument uses a 125mm Bonn University linear blade shutter, which allows for exposures that are as short as 10^{-3} sec, although in practice are usually no shorter than 0.1 to 0.2 seconds to minimize non-uniformities. A filter wheel assembly with two 10 slot wheels allows us to carry up to 18 filters at one time; typically we use 17 and a dark slide. Unless we have an unusually large request for particular non-standard filters, our UBVRI set, our SDSS u',g',r',i',z' set and our astrometric VR filter are always in the filter wheels. That still leaves another six slots, which are usually filled with a variety of narrow band filters.

The first optical spectrograph was the refurbished DeVeny optical spectrograph. The DeVeny was in use for many years at Kitt Peak National Observatory, and known as the White Spectrograph. It came to Lowell on long-term loan. It was refurbished and used on the 1.8-m Perkins telescope at Lowell's Anderson Mesa site, before being upgraded and moved to the DCT. This venerable instrument provides spectra over the wavelength range 3,200Å to 1micron, with resolving power between 500 and 5,000.[5] There are ten gratings available for use, listed in Table 1. It was upgraded during 2016 and 2017 to motorize the grating tilt mechanism, the collimator focuser and the slit width controls. At this point, with the exception of selection of order sorting and bandpass filters, the instrument can be completely operated by computer.

The most recently installed Lowell instrument is the Near IR High Throughput Spectrograph (NIHTS).[5] NIHTS covers roughly 0.9 to 2.4μm in one exposure at an average spectral resolution of 160 (see Ref 6 for

Table 1. Available gratings for the DeVeny spectrograph.

g/mm	Blaze Wavelength (Å)	Dispersion (Å/pix)	R (2.5 pixels measured at the blaze wavelength)
150	5000	4.3	450
300	4000	2.17	920
300	6750	2.17	1250
400	8500	1.66	2850
500	5500	1.33	1500
600	4900	1.14	1400
600	6750	1.14	2370
831	8000	0.80	4000
1200	5000	0.58	3450
2160	5000	0.33	5250

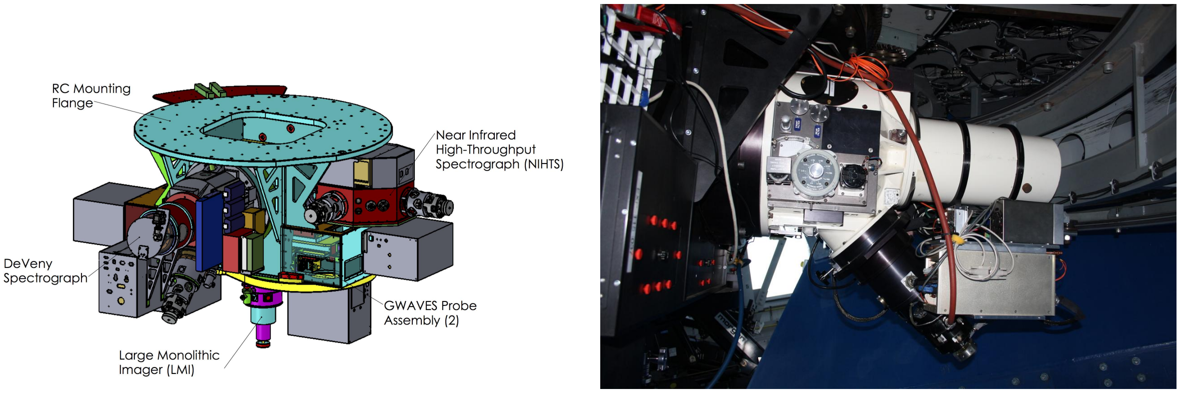


Figure 2. *Left:* The three dimensional model, from Ref 4 (Fig. 5) showing the instrument cube and how instruments fit on it. The location of one of the guider/wavefront sensor assemblies is visible through the cutaway panel below NIHTS on the right side of the cube. *Right:* The The DeVeny optical spectrograph mounted on one of the large ports on the DCT instrument cube.

instrument details). The instrument was assembled in the Lowell shop in late 2015, and saw first light on the DCT at the end of November 2015. Commissioning was delayed and recommenced in 2017. NIHTS is now in science operations, with modest work continuing to improve the instrument software controls. NIHTS is mounted on one of the small folded ports of the RC instrument cube. It has no moving parts, making it relatively easy to maintain and to calibrate. In 2017, the fold mirror that feeds NIHTS was replaced with a dichroic,[6] allowing us to do near IR spectroscopy with NIHTS and optical imaging with LMI simultaneously (see Fig 3). Because of the mounting of the dichroic, the usable area on LMI (shown in Fig 3) is reduced, but still exceeds $4' \times 6'$.

2.2 POETS and DSSI

Because of the availability of ports, DCT is able to host modest sized “traveling” instruments with minimal difficulty. Examples of this include the POETS (Portable Occultation, Eclipse and Transit System)[7] occultation camera and DSSI (the Differential Speckle Survey Instrument).[8] These have brought high temporal and spatial imaging capability to the DCT in compact packages. Both of these instruments are small enough to fit on a small port, and can be installed in a day. Because they fit on the cube, additional infrastructure to support these instruments is minimal (i.e., they can use the facility’s guider, instrument rotator, wavefront sensor).

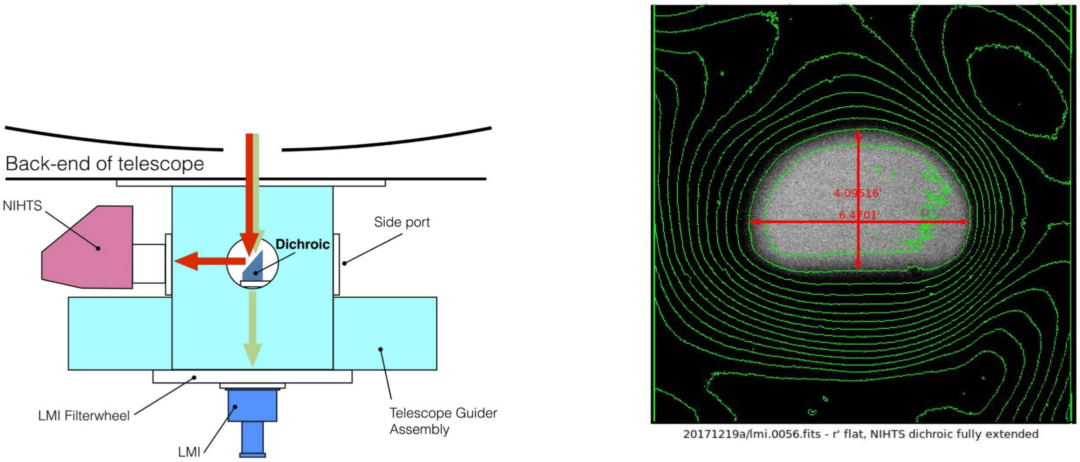


Figure 3. *Left:* Schematic showing the path that light from the telescope takes to both NIHTS (on the left) and LMI (at the bottom). Wavelengths longer than roughly 1μm are reflected towards NIHTS, those shorter are passed through to LMI. (Graphic courtesy of N. Moskovitz.) *Right:* An LMI flat in SDSS r' with the NIHTS dichroic inserted into the optical beam. The dichroic has been inserted to full extension (242.1mm). The central region in grey is roughly $4' \times 6'$ in size (marked in red). The flat field signal decreases reasonably steeply outside the central region. The green contours are at 500 ADU intervals between 15,000 and 25,000 counts.

2.3 IGRINS, EXPRES, and RIMAS

In addition to the Lowell instruments described above, and the portable visiting instruments, through mutual agreements, DCT has hosted, and is hosting the Immersion GRating INfrared Spectrograph (IGRINS) and the the new high resolution optical spectrograph EXPRES. We are awaiting as well the Univerity of Maryland and Goddard Space Flight Center's Rapid Infrared Imager/Spectrometer (RIMAS).

IGRINS came to the DCT in the fall of 2016 for the first of three roughly six month long visits. The instrument had already been in use at McDonald observatory and was known to perform well. Further details on IGRINS are presented in Refs. 9–11. What was involved in bringing it to the DCT and its performance there are discussed in more detail in Ref. 12. Suffice to say that IGRINS, when available at DCT, was one of the most heavily requested instruments on the telescope. Because of the very compact design of IGRINS, we were able to fit it on the DCT instrument cube, just (see Fig. 1). It covers the full H and K bands at a resolution R $\sim 45,000$ making for a powerful combination. IGRINS will return to the DCT for its third six month visit in September of 2018.

To support IGRINS, we have also installed an additional flat field bank with much brighter lamps. The original system was designed for optical imaging and low resolution spectroscopy, not high resolution near IR spectroscopy. We patterned the bulb choice after those in use at McDonald. That system has turned out to be useful for other instruments as well, including NIHTS and the DeVeny spectrograph.

As part of an agreement with the Yale Exoplanet Laboratory, their new Extreme Precision Spectrograph (EXPRES) has come to the DCT. EXPRES is capable of R $\sim 150,000$ resolution over much of the optical regime. The capabilities of the spectrograph were reviewed in Ref. 13. The spectrograph portion of the instrument is housed in a vacuum chamber that is thermally and vibrationally isolated from the DCT facility in a modified portion of the DCT laboratory space. Fig. 4 shows the spectrograph before closing up the vacuum container. The instrument front end module which houses the fiber feed and tip-tilt stabilization assembly is mounted on a small port on the DCT instrument cube. On-sky commissioning of the instrument began in December of 2017. Over the course of the first half of 2018, commissioning work has been transitioning over to science observing. By the end of 2018, EXPRES will have been scheduled for 50 nights, typically in quarter and half night increments.

During the second half of 2018, the instrument will be available to the broader DCT partnership for limited use for science beyond the primary exoplanet search project. In 2019, the instrument is expected to be available to the DCT user community as a general science instrument.

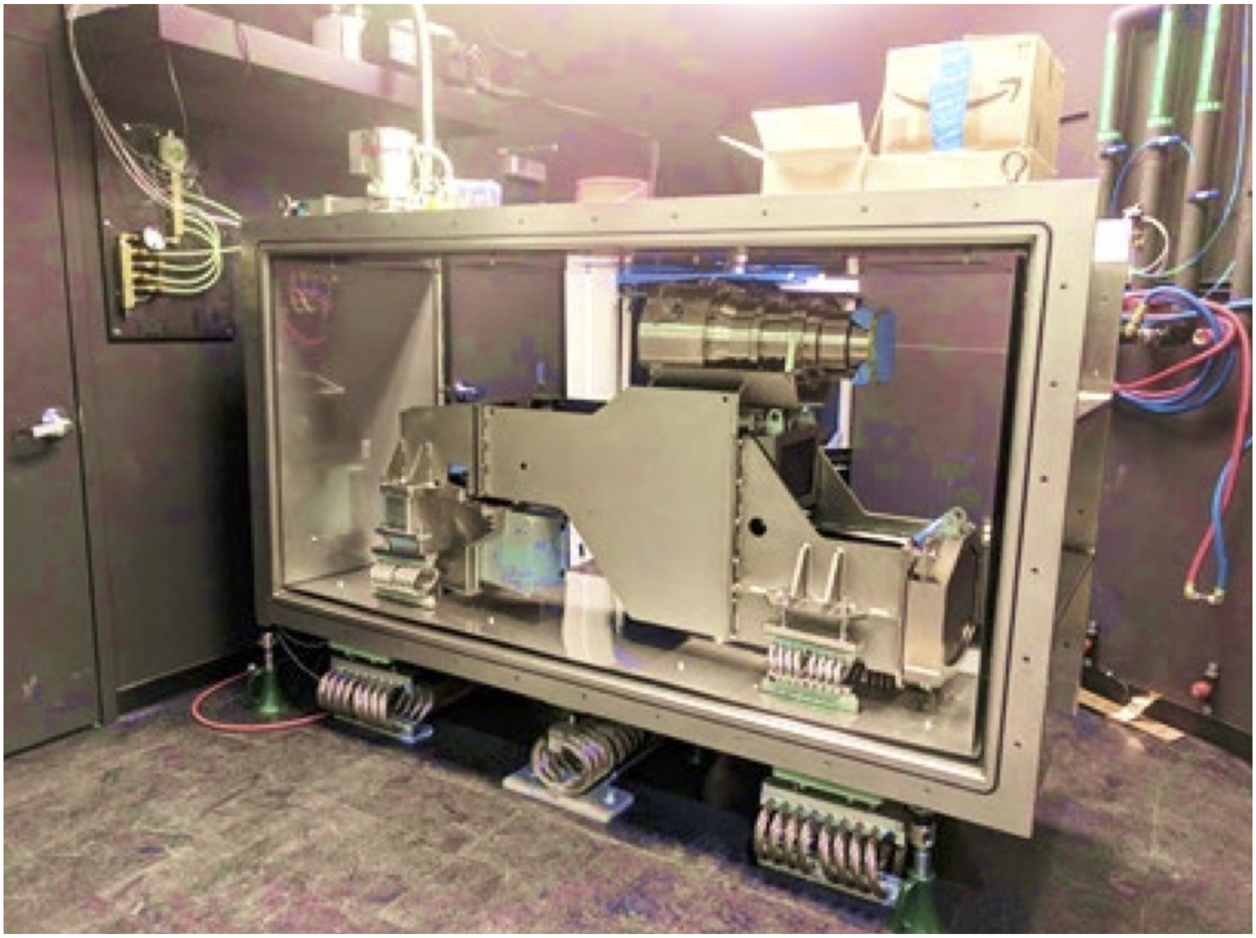


Figure 4. The EXPRES spectrograph in the spectrograph room before the vacuum chamber was closed up.

The Rapid Infrared Imager/Spectrometer (RIMAS) is nearing completion at the Goddard Space Flight Center. The most recent progress is discussed in Refs 14, 15; additional background can be found in Refs. 16–20.. RIMAS is a dual beam near infrared instrument capable of imaging over a 3′ field of view, and low and medium resolution spectroscopy. Pending the delivery of the second high resolution grism, we are expecting to see RIMAS at the DCT in the middle of 2019.

3. MIRROR COATING

Over the past two summers, we have recoated both major optical elements of the DCT. The original coatings were in use for roughly 5.5 years each. Periodic CO_2 and water cleanings helped to prolong the useful life of the coatings. Considering both the ages of the coatings, and the need for systemic constancy for the primary EXPRES observing program over its planned 5 year term, we chose to recoat both mirrors before the installation and commissioning of EXPRES.

In July 2016, the DCT primary mirror was stripped and recoated. When originally coated (January 2011), we discovered that the coating was non-uniform and overall, much thinner than expected. The coating system

Table 2. 2016 Primary mirror witness sample coating thickness.

Sample	Location	Average thickness (nm)
1 – 2 RID	M1, ID, North	78.9
3 RID	M1, ID, West	77.9
1R	M1, OD, NE (P1)	55.6
2R	M1, OD, NW (P2)	74.8
3R	M1, OD, SW (P3)	69.6
4R	M1, OD, SE (P4)	43.4
Overall Avg.		66.7

ID == Inner Diameter
OD == Outer Diameter

specification called for a nominal 100 nm thickness, uniform to ±5 %. Actual thickness, as measured by witness samples, was 40.2 nm to 77.5 nm, with an overall average of 61.3 nm. The decision in 2011 was to use the mirror as-is.

After discussion with the coating system manufacturer, we concluded that the cause of the non-uniformity and thin coating was not taking the filament firing to complete depletion, thereby leaving some aluminum on the filaments. Further, concern was expressed by others that the type of witness samples - microscope slides – were creating uncertainty in the actual coating thickness.

Therefore, when we re-coated in 2016, we used improved witness samples, and allowed more time for the filaments to deplete. The improved samples comprised 3/8-inch thick, 1/10th wave glass flats, with a razor blade overlaid on a prepared surface to allow accurate thickness measurement. Unfortunately, the thickness values in 2016 still reflected significant non-uniformity and less thickness than desired overall (see Table 2). Locations are described with respect the mirror as oriented in the chamber, with the corresponding position sensors (P1 - P4) listed for reference.

Before coating the DCT secondary mirror, we undertook several actions to better understand the coating system performance. This included measurements of filament zone currents and voltages (the filaments are connected with 6 parallel zones of 20 filaments each) in an attempt to correlate coating thickness and non-uniformity with the electrical performance of the filament grid. During the same time frame, we investigated coating chamber leakage, made changes to the configuration of crystal monitor feed-throughs, and investigated and resolved coating system computer bugs. Despite these tests and investigations, we could not reach a conclusive answer for the thickness non-uniformity and overall below-par thickness performance.

All of the afore-mentioned coating operations were conducted using filaments provided by the coating system manufacturer. Unrelated to the coating system performance, we wished to identify filaments that would minimize the cost of our coating operations. Following suggestions from the MMT organization, we began to test filaments produced by Midwest Tungsten Service, a company located in Willowbrook, IL. They produced filaments by winding an aluminum strand within the tungsten strands. This is in contrast to the filaments we used previously, in which aluminum was deposited on the surface of the filament coils only. The MMT Organization had been using the Midwest Tungsten filaments for several years with good results.[21] The new style filaments were less costly, and had shorter delivery lead time.

We began by conducting tests of individual coils in a bell jar test setup at the University of Arizona's Sunnyside facility, with MMTO engineers Ricardo Ortiz and Will Goble present for procedural guidance. The main focus of the bell jar testing was to determine the propensity for aluminum droplets to be produced - the DCT chamber is uplooking (filaments above the mirror); hence any falling droplets will produce splatter on the mirror surface. During individual filament tests in the bell jar, despite a variety of current ramp rates, including deliberate mechanical disturbance, we could not induce an aluminum droplet to fall from the filaments. This encouraging result convinced us to commit to a full-scale test in the DCT coating chamber.

Table 3. P/N 513H filament test results.

Sample	Location	Average thickness (nm)
P1-A	Radial dir. of P1, near chamber wall	78.7
P1-B	Radial dir. of P1, midway to chamber wall	106.7
P2-A	Radial dir. of P2, near chamber wall	85.4
P2-B	Radial dir. of P2, midway to chamber wall	111.0
P2-D	Radial dir. of P2, near chamber center	106.0
P2-D (NR)	Same as P2-D, but no razor blade.	81.8
P3-A	Radial dir. of P3, near chamber wall	80.2
P3-B	Radial dir. of P3, midway to chamber wall	108.6
P4-A	Radial dir. of P4, near chamber wall	85.2
P4-B	Radial dir. of P4, midway to chamber wall	113.1
Overall Avg.		95.7

P1 – P4 are as defined in Table 2

Table 4. 2017 Secondary mirror witness sample coating thickness.

Sample	Location	Average thickness (nm)
1	Northeast of M2 center	113.9
2	East	129.2
3	Southeast	138.7
4	Southwest	148.5
5	West	148.8
6	Northwest	141.6
Overall Avg.		136.8

The chamber was prepared for the full scale test by loading 120 Midwest Tungsten Service filaments, part number 513H. Since no mirror was loaded in the chamber, we took advantage of this to load additional witness samples in an effort to gain more data on coating uniformity. The coating thickness results are summarized in Table 3. Locations are defined with respect to the M1 position sensor locations, although M1 was not in the chamber during the test. The results showed overall coating thickness within acceptable limits, although individual samples indicate that we still have uniformity issues. Still, overall results were far better than earlier runs with the old style filaments, and all thickness values are above the limit at which the coating is opaque (60 nm).

Based on the full-scale test results, we decided to coat the secondary mirror with the 513H filaments. This coating run took place in July 2017. Witness samples were again used to assess actual mirror coating thickness, and results are summarized in Table 4. All witness samples were located near the mirror periphery, in the general direction indicated in the table.

The thickness results were surprising, as the procedure used for coating M2 was the same as used in the full-scale test. We speculate that the average coating thickness may be sensitive to the filament current ramp rate. Confirming this speculation will require additional testing, which may be attempted during the 2018 monsoon season when we will coat other mirrors from our Anderson Mesa facilities.

The impact of the greater-than-expected coating thickness for M2 is a reduction in reflectivity. This is readily seen by comparing the panels of Fig. 5. The left panel of Fig. 5 shows the M1 reflectivity shortly after the mirror was recoated in July 2016. Note the measured reflectivity is consistently greater than the specification requirement, represented by the blue data points. The right panel of Fig. 5 shows the M2 reflectivity, again after the mirror was recoated in July 2017. Its reflectivity is lower than the specification requirement (red points) and drops off more rapidly with wavelength. The reduced reflectivity is likely a result of a rougher surface finish resulting from excessive coating thickness.

The reflectivity curves demonstrate the criticality of controlling, and accurately measuring coating thickness during the coating process. We intend to refine our coating process, including possibly automating the deposition process, prior to future recoating of either of the DCT mirrors.

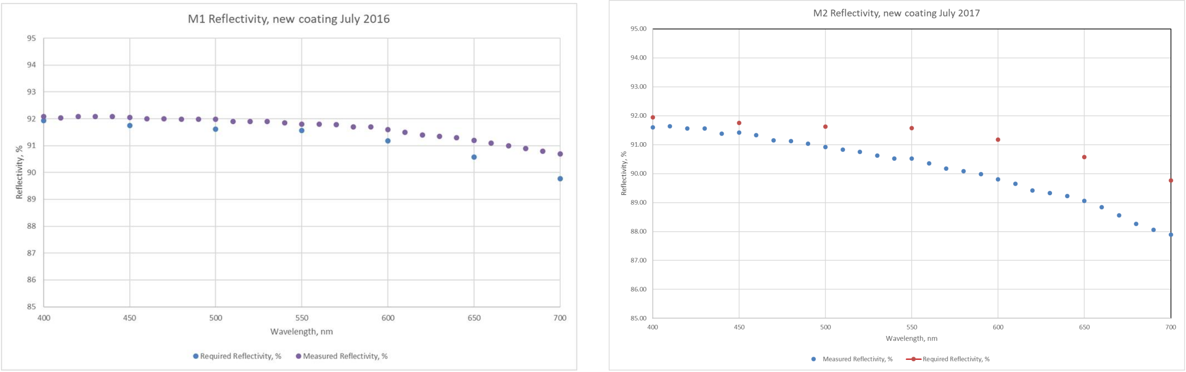


Figure 5. *Left:* M1 reflectivity with new coating in 2016. *Right:* M2 reflectivity with new coating in 2017.

4. OPERATIONAL EFFICIENCY

At this point, we feel that the DCT is operating efficiently, and providing a flexible array of both timing and instrumentation options to its user community. What has made this possible is the sum of a number of modest items which taken together make that aforementioned flexibility and efficiency possible. We've emphasized both terms because often you get one at the expense of the other.

On the facility operations side, DCT is not a “residential” observatory in the sense of having a full set of staff on-site at all times. This reduces our overhead significantly, at the expense of reaction time. However, the drive time to DCT from Flagstaff is under an hour. This means that if need be, we can respond to the unexpected in near real time with potentially the full array of staff skills. As a case in point, the primary mirror positioning depends upon three sacrificial pins that help define the mirror position in the $x-y$ plane, and provide a critical safety against over stressing the glass of the primary mirror. On the last several occasions when a pin has broken, our staff were able to get out to the site, replace the pin and have the facility back on-line for the second half of the night, rather than losing the entire night.

Daytime operations at the site have been worked out to make sure that procedures do not impede night time operations. Instrument swaps (which only happen a handful of times a year) are structured to be completed within a day, or to leave the telescope in an operational state mid-change over. Mirror cleanings (both CO_2 and water wash) have been worked out so they can be completed within one day. This is critical for us, as the water washes especially have proven to be very effective at preserving the reflectance of, and reducing the scattering from the mirrors.

The combined capabilities of the telescope mount and the mirror position systems provide for quick, repeatable pointing and motions between pointings.[1–3] Blind pointing is roughly $5''$. The mount pointing model has turned out to be both relatively simple and surprisingly stable. This means that observers rarely need to do more than very minor tweaks to setup their targets, and we do not need to devote large amounts of engineering time to maintaining the pointing model. Target acquisition is quite efficient, and for exposures less than five to ten minutes, guiding is not required. As part of the normal startup procedure every night, the operators check the pointing on at least three stars. This is quick, but also a good early warning of any issues with the mount model.

The ability to pursue Solar System science was an important driver behind a number of the DCT telescope requirements. The lower pointing limit is at zenith distance of $z = 85°$. Observations of comets, occultations of small bodies, observations of Mercury all have been made possible by this low limit. The zenith keyhole exclusion zone has a radius under a degree. The TCS control system was delivered with the ability to track at non-sidereal rates, and to track following an object ephemeris. The whole system is capable of successfully tracking at up to near earth object rates, with offset rates as high as $150'' \mathrm{s}^{-1}$. Fig 6 is an unguided, 120 second image of the Chandra X-ray Telescope, which was moving at roughly $9,930'' \mathrm{hr}^{-1} = 2.76'' \mathrm{s}^{-1}$ relative to sidereal.

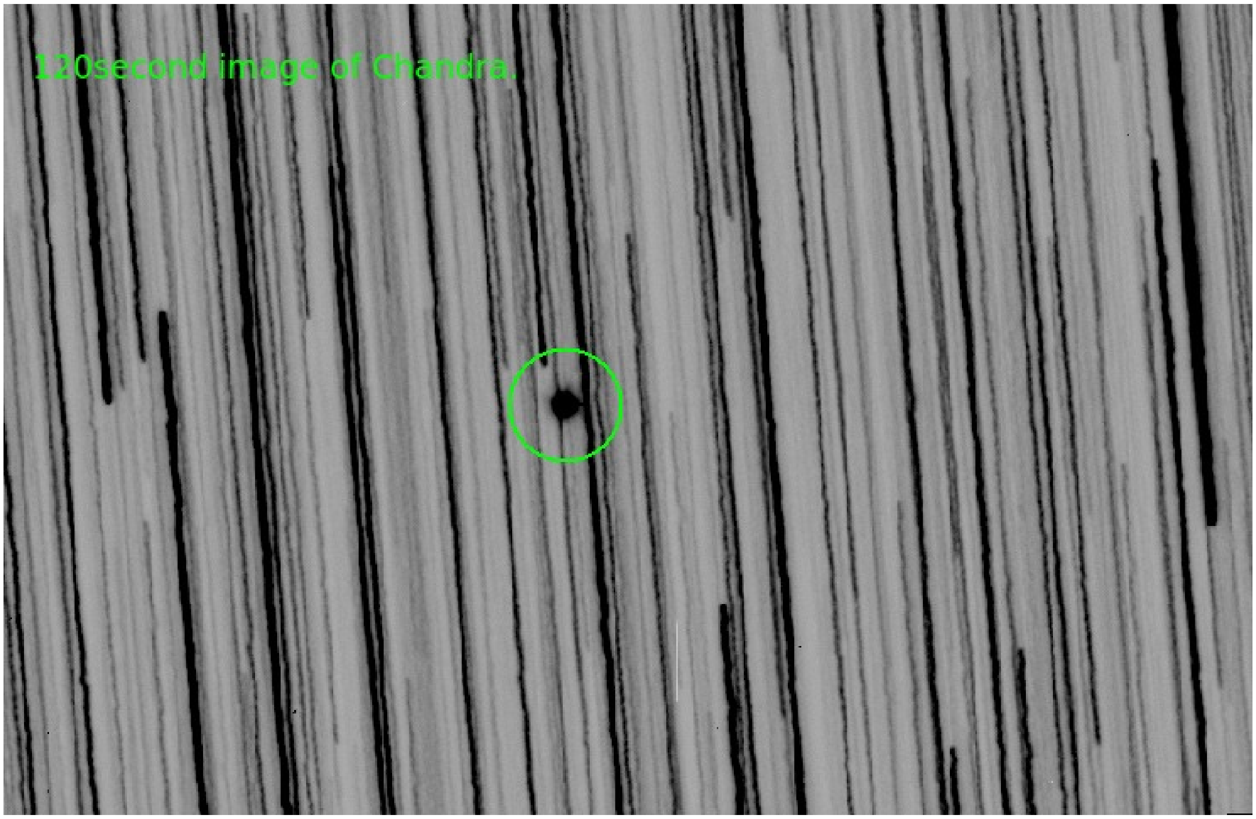
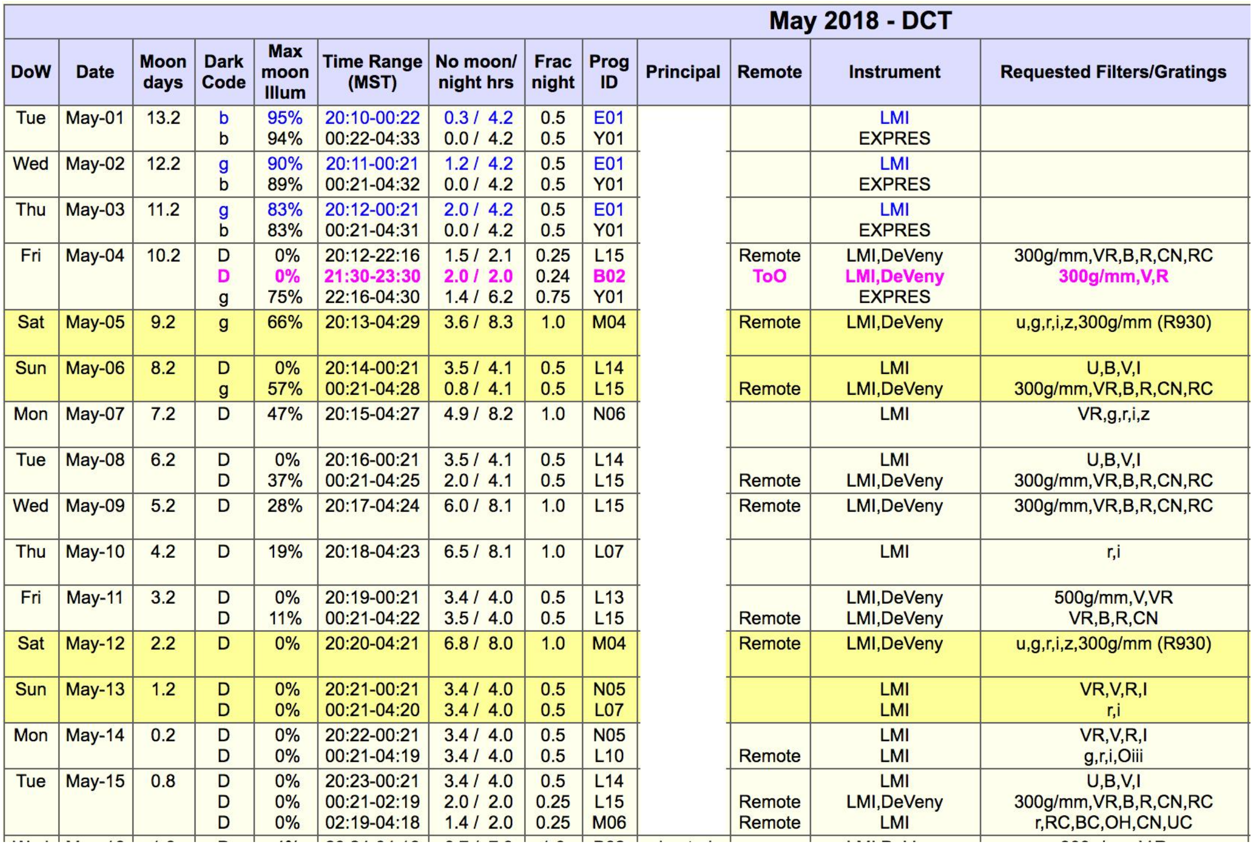


Figure 6. An unguided, 120 second image of the Chandra X-ray Telescope taken at the DCT. The satellite is moving at roughly $2.76'' \mathrm{s}^{-1}$ relative to the sidereal tracking rate. The DCT tracked it using the satellite's ephemeris. The rate differential with respect to sidereal is high enough that one pixel along each star trail is equivalent to 0.09 second sampling. The wiggles seen are atmospheric motion of the stellar centroids. The image of the satellite in the center is saturated in the core, but fitting the wings give an approximate image FWHM of $\sim 1\overset{''}{.}5$. (Data taken by T. Pugh and J. Sanborn.)

As noted in the initial sections of this paper, the DCT Cassegrain instrument cube can carry up to five instruments at one time. Switching between instruments is a simple operation, involving only the movement of a fold mirror in the instrument cube and software redefinitions for the new instrument zero points. The whole operation can be in done just a few minutes. This opens up the option for observers to use several instruments over the course of one observing session (e.g. one group regularly requests three instruments per night). In addition, because NIHTS uses a fold dichroic instead of a mirror, NIHTS and LMI can be used simultaneously. This flexibility also means that programs using different instruments can be scheduled for the same night without any issue.

For reasons of personnel and equipment safety, we do not replace filters or gratings during the night. Because the LMI filter wheels can carry as many as 18 filters at a time, the need to do so has not come up. It is possible to schedule programs with very different filter needs on the same night.

A two week portion of a recent DCT telescope schedule is shown in Fig. 7. Not only are multiple instruments in use most nights, but many nights are divided between two or even three groups. The magenta line in the schedule was a Target of Opportunity (ToO) interrupt that was called in that night. Having the multiple instruments available significantly expands the ToO options as well. Over the past two years, DCT has refined the scheduling quantum down to roughly 1/4 of a night. In fact, we have the ability to shift the schedule around at the fraction of an hour level if needed to facilitate the science programs. The biggest limitation on scheduling multiple programs in one night has turned out to be the limited amount of twilight time available for on-sky calibrations. Pragmatically, we tend to limit nights to two or three programs, unless the program calibrations are internal to the instrument or can be done during daytime or within the assigned observing block. We have begun to explore the possibility of more flexible scheduling for programs that need more, shorter observing blocks.



May 2018 - DCT

DoW	Date	Moon days	Dark Code	Max moon Illum	Time Range (MST)	No moon/ night hrs	Frac night	Prog ID	Principal	Remote	Instrument	Requested Filters/Gratings
Tue	May-01	13.2	b	95%	20:10-00:22	0.3 / 4.2	0.5	E01			LMI	
			b	94%	00:22-04:33	0.0 / 4.2	0.5	Y01			EXPRES	
Wed	May-02	12.2	g	90%	20:11-00:21	1.2 / 4.2	0.5	E01			LMI	
			b	89%	00:21-04:32	0.0 / 4.2	0.5	Y01			EXPRES	
Thu	May-03	11.2	g	83%	20:12-00:21	2.0 / 4.2	0.5	E01			LMI	
			b	83%	00:21-04:31	0.0 / 4.2	0.5	Y01			EXPRES	
Fri	May-04	10.2	D	0%	20:12-22:16	1.5 / 2.1	0.25	L15		Remote	LMI,DeVeny	300g/mm,VR,B,R,CN,RC
			D	**0%**	**21:30-23:30**	**2.0 / 2.0**	0.24	**B02**		**ToO**	**LMI,DeVeny**	**300g/mm,V,R**
			g	75%	22:16-04:30	1.4 / 6.2	0.75	Y01			EXPRES	
Sat	May-05	9.2	g	66%	20:13-04:29	3.6 / 8.3	1.0	M04		Remote	LMI,DeVeny	u,g,r,i,z,300g/mm (R930)
Sun	May-06	8.2	D	0%	20:14-00:21	3.5 / 4.1	0.5	L14			LMI	U,B,V,I
			g	57%	00:21-04:28	0.8 / 4.1	0.5	L15		Remote	LMI,DeVeny	300g/mm,VR,B,R,CN,RC
Mon	May-07	7.2	D	47%	20:15-04:27	4.9 / 8.2	1.0	N06			LMI	VR,g,r,i,z
Tue	May-08	6.2	D	0%	20:16-00:21	3.5 / 4.1	0.5	L14			LMI	U,B,V,I
			D	37%	00:21-04:25	2.0 / 4.1	0.5	L15		Remote	LMI,DeVeny	300g/mm,VR,B,R,CN,RC
Wed	May-09	5.2	D	28%	20:17-04:24	6.0 / 8.1	1.0	L15		Remote	LMI,DeVeny	300g/mm,VR,B,R,CN,RC
Thu	May-10	4.2	D	19%	20:18-04:23	6.5 / 8.1	1.0	L07			LMI	r,i
Fri	May-11	3.2	D	0%	20:19-00:21	3.4 / 4.0	0.5	L13			LMI,DeVeny	500g/mm,V,VR
			D	11%	00:21-04:22	3.5 / 4.0	0.5	L15		Remote	LMI,DeVeny	VR,B,R,CN
Sat	May-12	2.2	D	0%	20:20-04:21	6.8 / 8.0	1.0	M04		Remote	LMI,DeVeny	u,g,r,i,z,300g/mm (R930)
Sun	May-13	1.2	D	0%	20:21-00:21	3.4 / 4.0	0.5	N05			LMI	VR,V,R,I
			D	0%	00:21-04:20	3.4 / 4.0	0.5	L07			LMI	r,i
Mon	May-14	0.2	D	0%	20:22-00:21	3.4 / 4.0	0.5	N05			LMI	VR,V,R,I
			D	0%	00:21-04:19	3.4 / 4.0	0.5	L10		Remote	LMI	g,r,i,Oiii
Tue	May-15	0.8	D	0%	20:23-00:21	3.4 / 4.0	0.5	L14			LMI	U,B,V,I
			D	0%	00:21-02:19	2.0 / 2.0	0.25	L15		Remote	LMI,DeVeny	300g/mm,VR,B,R,CN,RC
			D	0%	02:19-04:18	1.4 / 2.0	0.25	M06		Remote	LMI	r,RC,BC,OH,CN,UC

Figure 7. A two week portion of the DCT telescope schedule in 2018.

Related to the finer time slicing of the schedule is the question of observing mode. DCT is predominantly a classically scheduled telescope in the sense that an observer is expected to take their own data. Since most of the DCT partners are not local, we have implemented remote observing protocols. These are also turning out to be popular with the local observers as it means they can productively use a 1/4 night time slot without having to spend two hours getting to and from the telescope.

One point worth noting is that unlike most other large telescopes, the DCT is the only facility at the Happy Jack site. Because there is no help nearby should there be a problem, our safety protocols require two people be on-site during operations. During classical observations, we have the TO and the observer. If the observer is remote, we schedule a second safety monitor to cover that time.

Our remote observing tools are kept as industry standard as possible. Observers use VPN to access the Lowell networks, and then VNC to access the user interface computers. This avoids developing and maintaining additional remote versions of the observing tools and also means that the visual experience is very similar whether the observer is on-site or off.

The facility instrument interface permits common instrument commands to the telescope like dithers and focus changes. Under normal circumstances, because the telescope cannot impact anything in the dome, we also permit instruments to command slews. Users can set up sequences that include long slews. Procedurally, the telescope operators confirm proper operation of the facility at the start of the night and only when they are satisfied do they release the telescope to the observers for commanding. The observer commandable slews sound simple (and they are), but they are also somewhat unusual and have proven to be a big time saver.

The efficient use of time at DCT has proven to be the product more of many modest things that have worked out well, rather than one overriding thing. All of this works because we have a dedicated crew who stay on top of the state of the facility.

5. FUTURE

As DCT goes forward, we are constantly evaluating ways to improve the productivity and image quality delivered by the facility. There are several facility upgrades that we are actively considering.

1. In order to support additional, and possibly larger, instruments, we have begun considering the design and implementation requirements for a tertiary mirror and mechanism to allow redirection of the optical path to the Nasmyth and bent Cassegrain ports.
2. We are already working on the next logical step in improving the image quality, which will be to implement closed loop correction to the AOS from the wavefront sensor.
3. A related step will be to design and implement a low order adaptive optics system to feed other instruments. Planning and design work have alraedy started on this.
4. Similarly, we will be looking into designing and installing an ADC for the through beam to LMI to help correct for differential refraction. This is particularly germane to DCT as many of our users work at large zenith distances.

ACKNOWLEDGMENTS

The performance of the DCT is due in large part to the dedication and hard work of the many people who were and are part of the team that designed, built and now operates the telescope. The engineering team members Frank Cornelius, Ben Hardesty, Mike Sweaton, and Georgi Mandushev were instrumental in the doing the coating chamber tests and analysis. We wish to thank Mike DiVittorio of the U. S. Naval Observatory - Flagstaff Station for sharing his witness sample recommendations and surface preparation techniques.

These results made use of Lowell Observatory's Discovery Channel Telescope. 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, Northern Arizona University and Yale University. The NSF funded the construction of the LMI (under grant AST-1005313). NIHTS was funded by grant NNX09AB54G from NASA's Planetary Astronomy and Planetary Major Equipment programs. The Mount Cuba foundation the dichroic beamsplitter coats and the upgraded deep depletion CCD for the DeVeny spectrograph. A wide range of upgrades to the DeVeny spectrograph were supported by John and Ginger Giovale. The Technology Committee of the Lowell Observatory Advisory Board was instrumental supporting the effort to bring IGRINS to the DCT. The DCT is sited on land in the Coconino National Forest of the US Forest Service, and we are delighted to acknowledge their willingness to work with us.

REFERENCES

[1] Levine, S. E., Bida, T. A., Chylek, T., et al., Status and performance of the Discovery Channel Telescope during commissioning, Proc. SPIE, 8444, 844419 15pp. (2012)

[2] DeGroff, W. T., Levine, S. E., Bida, T. A., et al., Status and performance of the Discovery Channel Telescope from commissioning into early science operations, Proc. SPIE, 9145, 91452C 18pp. (2014)

[3] Levine, S. E, DeGroff, W. T., Status and imaging performance of Lowell Observatory's Discovery Channel Telescope in its first year of full science operations, Proc. of SPIE, 9906, 9906-72 16pp. (2016)

[4] Bida, T. A., Dunham, E. W., Nye, R. A., et al., Design, development, and testing of the DCT Cassegrain instrument support assembly, Proc. SPIE, 8444, 844451 16pp. (2012)

[5] Bida, T. A., Dunham, E. W., Massey, P., Roe, H. G., First-generation instrumentation for the Discovery Channel Telescope, Proc. SPIE, 9147, 91472N 11pp. (2014)

[6] Dunham, E. W., NIHTS: the near-infrared high throughput spectrograph for the Discovery Channel telescope, Proc. SPIE, 10702, 10702-123 (this meeting) (2018)

[7] Souza, S. P., Babcock, B. A., Pasachoff, et al., POETS: Portable Occultation, Eclipse, and Transit System, PASP, 118, 1550–1557 (2006)

[8] Horch, E. P., Veillette, D. R., Baena Gallé, R., et al., Observations of Binary Stars with the Differential Speckle Survey Instrument. I. Instrument Description and First Results, AJ, 137, 5057–5067 (2009)

[9] Yuk, I.-S., Jaffe, D. T., Barnes, S., et al., Preliminary design of IGRINS (Immersion GRating INfrared Spectrograph), Proc. SPIE, 7735, 77351M (2010)

[10] Park, C., Jaffe, D. T., Yuk, I.-S., et al., Design and early performance of IGRINS (Immersion Grating Infrared Spectrometer), Proc. SPIE, 9147, 91471D 12pp. (2014)

[11] Mace, G., Kim, H., Jaffe, D. T., et al., 300 nights of science with IGRINS at McDonald Observatory, Proc. SPIE, 9908, 99080C 15pp. (2016)

[12] Mace, G., Sokal, K., Lee, J.-J., et al. IGRINS at the Discovery Channel telescope and Gemini South, Proc. SPIE, 10702, 10702-26 (this meeting) (2018)

[13] Jurgenson, C. A., Fischer, D. A., McCracken, T. M., et al., EXPRES: a next generation RV spectrograph in the search for earth-like worlds, Proc. SPIE, 9908, 99086T 20pp. (2016)

[14] Kutyrev, A. S., Capone, J. I., Toy, V. L., et al., RIMAS: near infrared cryogenic imager and spectrometer, Proc. SPIE, 10702, 10702-127 (this meeting) (2018)

[15] Kuzmenko, P. J., Little, S. L., Kutyrev, A. J., Capone, J., Optical testing and performance of large ZnSe grisms for the rapid infrared/imager spectrometer (RIMAS), Proc. SPIE, 10706, 10706-189 (this meeting) (2018)

[16] Kutyrev, A., Toy, V., Veilleux, S. et al., RIMAS - rapid reaction near infrared imager-spectrometer, AAS, meeting 223, #148.01 (2014)

[17] Toy, V. L., Kutyrev, A. S., Lyness, E. I., et al., Detector driver systems and photometric estimates for RIMAS, Proc. SPIE, 9147, 91472W 10pp (2014)

[18] Capone, J. I., Content, D. A., Kutyrev, A. S., et al., Cryogenic optical systems for the rapid infrared imager/spectrometer (RIMAS), Proc. SPIE, 9147, 914736 6pp. (2014)

[19] Toy, V. L., Kutyrev, A. S., Capone, J. I., et al., H2RG detector characterization for RIMAS and instrument efficiencies, Proc. SPIE, 9908, 99083I 8pp. (2016)

[20] Kuzmenko, P. J., Little, S. L., Kutyrev, A. S., Capone, J. I., Technique for diamond machining of large ZnSe grisms for the Rapid Infrared/Imager Spectrograph (RIMAS), Proc. SPIE, 9912, 99120C 12pp. (2016)

[21] Goble, W., Ortiz, R., Characterization of an integrally wound tungsten and aluminum filament for physical vapor deposition, Proc SPIE., 9912, 991238-1 8pp. (2016)