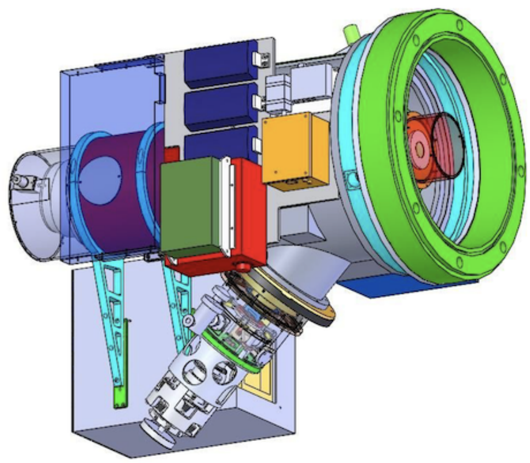
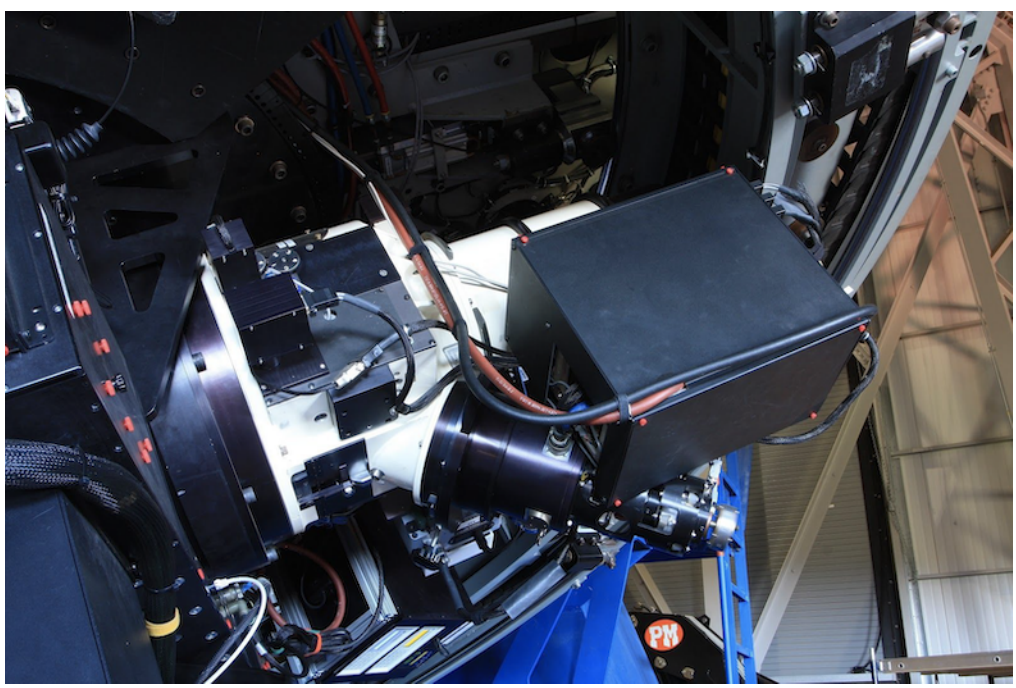
The DeVeny Optical Spectrograph User Manual

Lowell Discovery Telescope

T. Ellsworth-Bowers, T. Bida, T. Pugh, S. Levine

v1.7.1 10 May 2022





DeVeny Quick Reference

- Spectral Channel CCD
  - Detector: e2v CCD42-10 deep depletion device: 2048×512 13.5 μm pixels (27.65 mm $\times$ 6.91 mm)
  - Slit Length: $2.5'$
  - Pixel Scale: $0.34''$/pixel (spatial direction, unbinned)
  - Gain: 1.52 e^-/ADU
  - 16-bit ADC; Full-Well: $\sim$ 100k e^-
  - Read Noise: 3.2 ADUs, about 4.9 e^-
  - Typical bias level: $\sim$ 2370 ADU (ambient temperature dependent)
  - CCD Normal Operating Temperature: -110°C
  - Linearity: Linear to 97% of saturation ($\sim 63,500$ ADU)
  - Readout Time: 8 s
  - Dark Current: 4.5 e^-/h = 0.0013 e^-/s
  - Fringing: 1-3% fringe amplitudes, redward of 8000 Å
- Slit Viewing Camera
  - Model: Lodestar X2 by Starlight Xpress
  - Pixel Scale: $0.253''$/pixel (binned 2×2)
  - Image Size: 376×290 pixels
  - Field of View: $95'' \times 73''$
- Grating Complement
  - Collection of 10 gratings that were used with the KPNO White and Gold spectrographs
  - 128 mm $\times$154 mm plane reflection gratings
  - Range of spectral resolution from $R \sim 500 - 4000$
  - 1^{st} order blazed gratings
  - Motorized grating tilt angle stage to select central wavelength on the CCD
  - See Table 4 for specifications
- Calibration Lamps
  - For wavelength calibration, there are four remotely-controlled AC-powered pencil-style gas discharge arc lamps:
    * Neon ($\sim 5800 - 8600$ Å)
    * Argon ($\sim 6900 - 9700$ Å)
    * Mercury ($\sim 3300 - 5800$ Å)
    * Cadmium ($\sim 3200 - 5500$ Å)
  - The primary dome flat field calibration lamps are on the top ring of the secondary mirror support structure. Example flat field spectra from all gratings are shown in Figure 11.
- Data Reduction Software
  - PypeIt data reduction pipeline (Appendix H; https://pypeit.readthedocs.io/en/latest/)
  - IRAF (https://iraf-community.github.io/)
- Quick Start Guide: §3

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1 What's New?

May 2022: Version 1.7.1 – updated Confluence documentation links to conform to a Lowell server migration. Additionally, there are updates to the PypeIt instructions (Appendix H) to align with the v1.9.0 release of the data reduction pipeline, and updated line identification plots (Figs. 23-27)

February 2022: Version 1.7 of the DeVeny Manual released in conjunction with the addition of LDT/DeVeny to the python spectroscopic data reduction pipeline PypeIt – Appendix H has been added, containing instructions for reducing DeVeny data with this tool. A discussion of the flexure of the spectrograph has been added (Appendix F), including what must be done to obtain accurate wavelength and flux calibrations. Python-based versions of the `deveny_grangle` and `dfocus` observer tools are described in §4.2. In late 2021A, the second GG495 filter was removed from the spectrograph; replacement plan TBD.

March 2021: Version 1.6 of the DeVeny Manual released. Revised and updated with new figures, and content cross-linked for easy navigation. Includes a new Appendix G related to grating and collimator physics.

2020B: The original GG495 filter broke in September 2020. Fortunately, we had a second GG495 in our collection of filters from the KPNO Gold Spectrograph, and this has been installed. Collimator focus suggestions have been updated following an analysis of 2017-2020 focus data. To account for instrument temperature and the grating tilt angle, we present an equation for estimating the collimator focus. We recommend this estimate be used as the center of the focusing script range (see §4.2.7).

2 Overview of the DeVeny Spectrograph

2.1 Brief History and Configuration

The DeVeny spectrograph was built at Kitt Peak National Observatory (KPNO) and known as the White Spectrograph. It had a long career at the #1 36-inch and 84-inch telescopes there before being retired; Lowell Observatory acquired the spectrograph from KPNO on indefinite loan in 1998. A new CCD camera was built for it, and the instrument was further modified for installation on the 72-inch Perkins telescope in 2005. Following 8 years of service there, it was removed in 2013 for upgrades for installation on the LDT instrument cube. It has been in service since February 2015. The spectrograph was designed for f/7.5 telescope optics, and new re-imaging optics were designed and fabricated to match the spectrograph with LDT's f/6.1 beam.

The LDT/DeVeny Spectrograph system is a fully modern, cryogen-free instrument suited for remote operation. In addition to the f/ratio matching optics, the current instrument features a deep depletion version of the e2v CCD42-10 CCD (to reduce fringing in the red) mounted in a new dewar with a Stirling cycle cooler. A Lodestar X2 camera is situated to view the slit for target acquisition and telescope focusing, and is equipped with a filter wheel for use with bright targets. Motorization and remote control of the slit width, grating tilt, and collimator focus has been implemented. Four spectral calibration lamps (Hg, Cd, Ne, and Ar) are mounted on the spectrograph front plate and are remotely controllable.

The spectrograph provides low-resolution optical spectra at resolving power $R \sim 500 - 4000$ over a wavelength range from 3200 Å to 1 μm. The grating complement currently includes 10 1^{st}-order blazed gratings, from 150 g/mm up to 2160 g/mm (see Table 4 for details; other stock rulings are commercially available).

2.2 Software

The CCD detector is operated by a Gen III ARC (a.k.a. Leach) controller from a Linux computer. The software that interfaces directly with the controller is called lois, and the user interface software is called LOUI. Both lois and LOUI were developed at Lowell Observatory.

There are four fundamental software systems that the astronomer should be aware of at present. Each piece of software runs on a different computer, although the astronomer interfaces with them through one of the two astronomer computers, dual-screen iMacs named `dct-obs1` and `dct-obs2`.

- **LOUI (Lowell Observatory User Interface)**: The user interface by which the astronomer controls exposures and instrument setup (defining the type of exposure, exposure time, setting the grating tit and slitwidth, etc.). It runs on the iMac observer's computer (`dct-obs1/obs2`).

- **GoQuat / `slitviewg`**: The slit viewing camera controller that lets the astronomer view the focal plane of the telescope (focusing the telescope, placing the object of interest on the slit, sending position offsets to the telescope, etc.). It runs on the computer `vishnu`, with X-window GUIs forwarded to the observer's computer (`dct-obs1/obs2`).

- **lois (Lowell Observatory Instrument System)**: The guts-level system that actually runs the spectral-channel CCD controller, sets the micro-code, generates the FITS header, and does all the heavy lifting. It runs on the computer `deveny`. The only direct interaction the observer has with lois is to ensure it is running and initialized.

- **JOE (Java/Joint Operator Executive)**: The software "controller" that is in charge of all moving parts on the instruments. JOE needs to be running in order for LOUI and lois to talk to the motorized stages and obtain telemetry from the telescope control system (TCS) for header information. It runs on the computer `joe`. The observer does not directly interact with JOE, and generally only needs to be aware that this software is running in order to move any of the motorized stages. (There is an indicator showing JOE's health in the LOUI.)

3 Quick-Start Guide

1. Software – The DeVeny User Interface

   a. Start LOUI and restart lois (§4.1.1 - 4.1.3)

   b. Set storage pathway (§4.1.4)

   c. Check that JOE is running (§4.1.5)

   d. Update telemetry (§4.1.6)

   e. Take a test image to confirm everything is working (§4.1.8)

2. Spectrograph Setup

   f. Home and check grating tilt, slit width and collimator focus initial values (§4.2.1 - 4.2.3)

   g. Enable the spectral calibration lamps (§4.2.4)

   h. Confirm requested grating and filters (§4.2.5)

   i. Focus the collimator (§4.2.7)

   j. Take calibration images (bias, arc lamps, flats) (§4.3)

3. Slit Viewing Camera (`ssh -Y lois@vishnu.lowell.edu`)

   k. Start slit viewing camera, GoQat (§4.4.1)

   l. Set-up storage pathway (§4.4.1)

   m. Start IDL slit viewing GUI, `slitviewg` (§4.4.2)

   n. Take a test exposure (§4.4.2)

   o. Focus the telescope (§4.5)

4 At the Start of the Night

4.1 Setting Up the Software: The DeVeny User Interface and CCD Controller

The instrument user interface software (LOUI) is operated from `dct-obs1` or `dct-obs2` in the control room (or via VNC remotely). At present, the collimator focus routines do not function on `dct-to1`, so TOs doing engineering work should operate DeVeny from one of the observer computers. The camera control software (lois) runs on the host machine `deveny`.

The setup steps are outlined below, all of which should be done from either `dct-obs1` or `dct-obs2`.

1. Verify that the background support software applications are running:

   - If there is not already an open terminal logged into `deveny`, open a new terminal now.
   - Log in to `deveny` using ssh: `ssh obsdeveny@deveny` (the password is on the whiteboard or can be given by your TO)
   - Check the status of the various required processes: Type `st`. This will provide a status listing (see Figure 1). In particular, inspect the following two items:
   - Network Time Protocol (NTP) daemon: If there is a number listed after "`NTPD:`", that is the process ID number – the local NTP daemon is running. If there is NOT a number, the daemon needs to be restarted (check with your TO; they will do this, or they will contact a member of the instrument group). NTP is what makes sure the `deveny` computer clock is properly synchronized to UTC.
   - Sequestor process: If there is a number after "`Sequestor Proc:`", it is ok. If sequester is NOT running, the host machine will need to be rebooted (check with your TO; they will do this, or they will contact a member of the instrument group). The sequestor process is a memory management process needed for CCD data handling and must be running for proper operation.

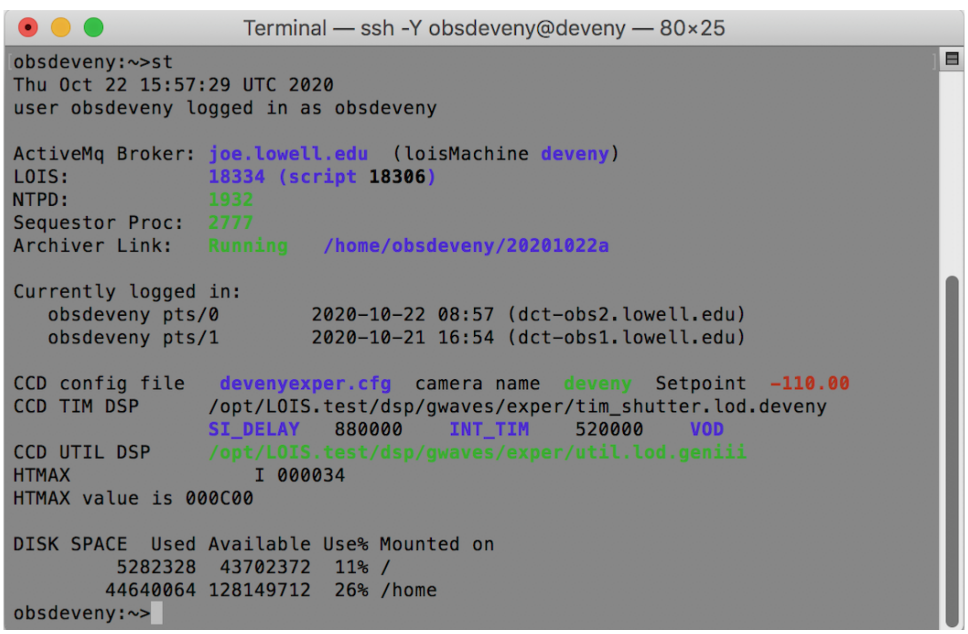


Figure 1: Results of an `st` command run in the `deveny` terminal window when all process are running (lois, NTDP, and Sequester Proc). All processes have process IDs.

2. Start the user interface LOUI:

   - If there is a DeVeny LOUI already running in the dock, exit it.
   - Double-click the "DeVeny LOUI" icon on the `dct-obs1/obs2` desktop.
   - Figure 2 shows the layout of widgets in the LOUI. Many observers find it helpful to "detach" the Facility Summary tab (upper left) as a separate window to monitor current telescope status.
   - NOTE: you can actually "detach" any of the views by grabbing the tab (such as the "info" tab) and dragging them to the desktop. Returning them can be a bit tricky, but you can always go to *Window* → *Reset Perspective* at the LOUI menu bar at the top of the screen to return the default tab arrangement.

3. Restart lois to ensure a clean environment:

   - If lois is running, then stop it. In the top right of the LOUI window press the red Exit LOIS

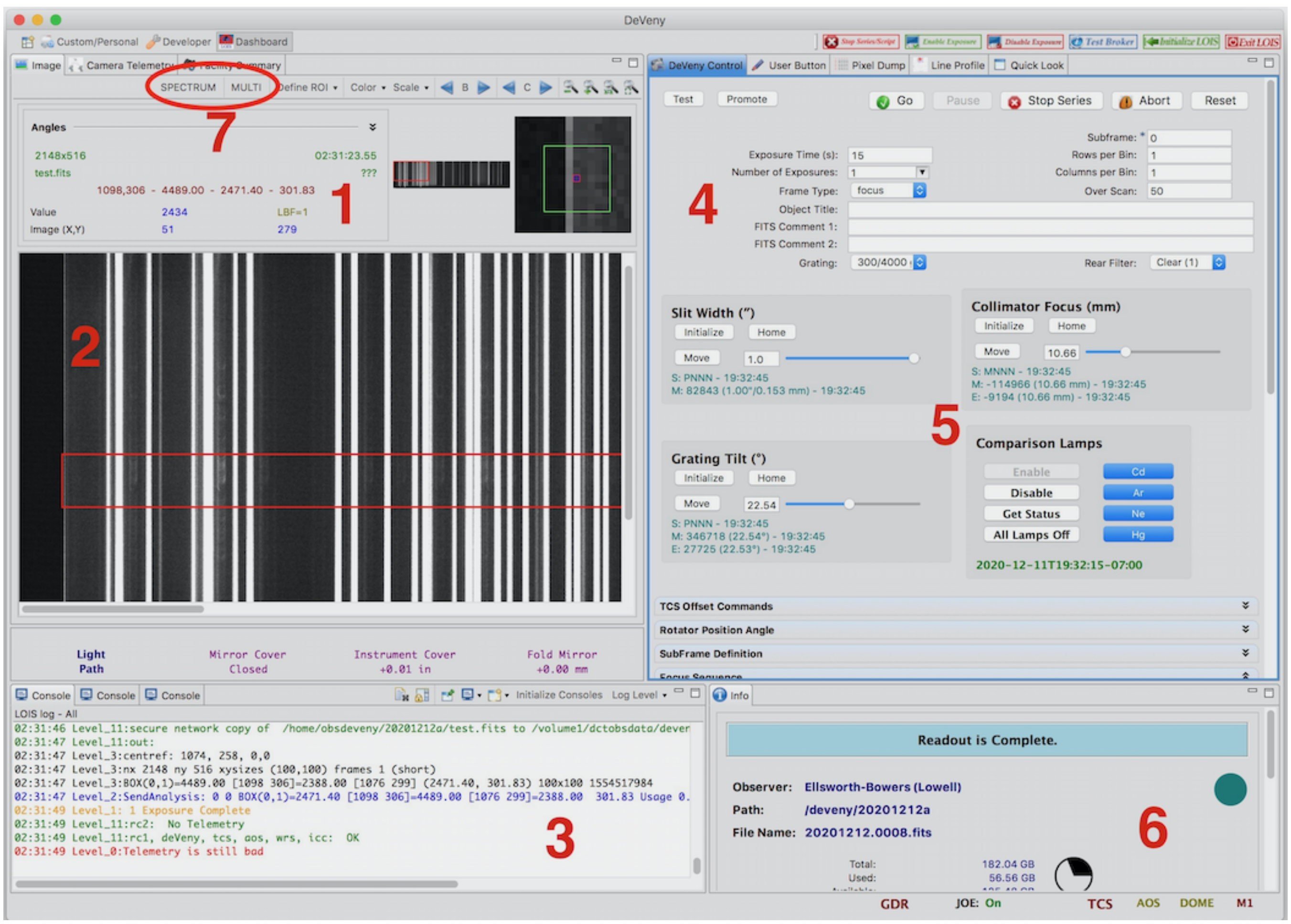


Figure 2: The layout of the DeVeny LOUI. 1: This area gives information about the currently displayed (*i.e.*, previously exposed) image. 2: Displays the spectral images, blue on the right, red on the left. 3: lois log. 4: CCD/Instrument control panel. 5: Control for spectrograph hardware and comparison lamp power. 6: Info tab, contains directory information and information about the current exposure. 7: Analysis tools.

button.
- Type `st` in the `deveny` terminal window to confirm lois is no longer running.
- Then (or if lois isn't running) type `lois &` in the `deveny` terminal window. A series of lois startup messages will be printed in both the terminal and the lois console on LOUI.
- Initialize lois by pressing the green Initialize LOIS button in the top right of the LOUI window. This will cause more log messages to appear in the lois console on LOUI.
- After this point **DO NOT** stop lois unless it is immediately restarted, as lois is responsible for the 24/7 monitoring of instrument temperatures and health.
- If both lois and temperature logging are running, there should be CCD temperature and heater readouts appearing periodically in the log.

4. Set up the data storage pathway:
   - In the Info tab (bottom right of the LOUI window) enter your name and affiliation and press Set Standard Image Path & Observer . If you are observing later in the night following another DeVeny user, also select New Rundate Directory to keep your data separate,
   - You should see your name, affiliation, and the directory structure displayed (see Fig. 3). The directory path will be `/deveny/<UTDATE>[abcd]`, where the letter appended to the UT date designates unique DeVeny observers within a given night. Selecting New Rundate Directory will increment the letter. This information will be recorded in the image FITS headers.

5. Check that JOE (Java/Joint Operations Executive) is on:
   - Either ask your TO or check the status line on the bottom of the main LOUI window.

6. Set the Grating and Rear Filter:
   - Select the installed grating (Table 4) and currently set order-blocking filter (Table 5) from the drop down menus (Fig. 2 #4). This information populates the `GRATING` and `FILTREAR` keywords,

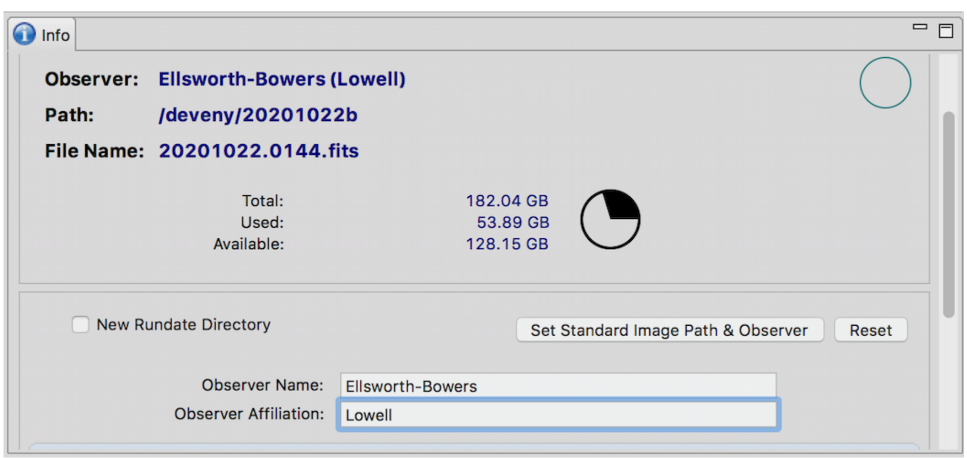


Figure 3: The "Info" tab of the DeVeny LOUI, with observer name and affiliation entered and set. Note that the directory `/deveny/20201022b` indicates that Ellsworth-Bowers is the second DeVeny user of the night 2020-10-22UT. The file sequence is continuous over the course of a night, and does not restart at 0001 for each new rundate directory.

respectively, in the image FITS headers. The act of setting these values also updates telemetry between LOUI and lois, setting all values in preparation of taking an exposure.

7. Select the binning scheme:

   For most programs, the default (1×1) binning is sufficient, but the DeVeny CCD does has the ability to be binned separately in rows and columns to fit the particular needs of a given science program. If you choose to bin your data, you may select a value other than 1 for the "Rows per Bin" and/or "Columns per Bin" fields in the DeVeny Control tab (Fig. 2 #4).

   Because the DeVeny CCD columns are very accurately aligned with the slit jaws, binning rows should have little to no effect on spectral resolution. For situations where the readnoise of the chip is the dominant contribution to signal-to-noise ratio (SNR) for your spectrum, row binning provides a means for increasing signal by combining 2 (or more) rows together before being read out. Similarly, if you are interested in only the broad spectral shape of your target and observe with a wide ($\sim 5''$) slit, column binning will likewise increase your SNR and can also make it easier to centroid your arc lines for focus and wavelength calibration.

   Carefully consider the benefits and drawbacks of on-chip binning for your particular science case. The (python) `dfocus` routine (§4.2.7) and PypeIt reduction pipeline (Appendix H) can process binned DeVeny data (currently only tested on spatially binned data).

8. Image acquisition:

   The camera software is now set up to take images. Taking a test frame now will allow you to confirm that everything is working correctly.

   NOTE: If no exposure is taken and the lois console (Fig. 2 #3) complains that telemetry is bad, simply take another test frame. This can occur if not all telescope components are fully communicating yet – this is just a warning, and will not affect the actual exposure.

   - To take an image to be saved as `test.fits`, press `Test` in the DeVeny Control tab. NOTE: Each subsequent test image overwrites `test.fits`.
   - To add an image to your numerical file sequence, press `Go` in the DeVeny Control tab.
   - If you would like to save the currently displayed test exposure into the numerical file sequence, press `Promote` in the DeVeny Control tab. The only difference between `Test` + `Promote` and `Go` is that the promoted test image will have `test.fits` in the FITS header keyword `FILENAME` rather than the sequential filename; the keyword `OBSERNO` does, however, correctly indicate the image's location in the file sequence.
   - The type of image can be set from the drop down menu. Selecting bias (or dark) will not open the shutter, and bias sets a 0 s exposure time. It is recommended that the observer select the appropriate frame type for each and every image (object / bias / flat / focus / comparison) exposed, which is recorded in the image FITS header keywords `OBSTYPE` and `IMAGETYP`.

9. Built-in spectral image analysis functions:

   In the Image perspective, there are two graphical functions (Fig 2 #7):

   - **SPECTRUM**: After clicking this tool, select a region of interest on the displayed image by clicking and dragging a rectangular region (shown in red) across the image. The spectrum (actually the average across rows in the selected region) is then plotted in the Quick Look tab,

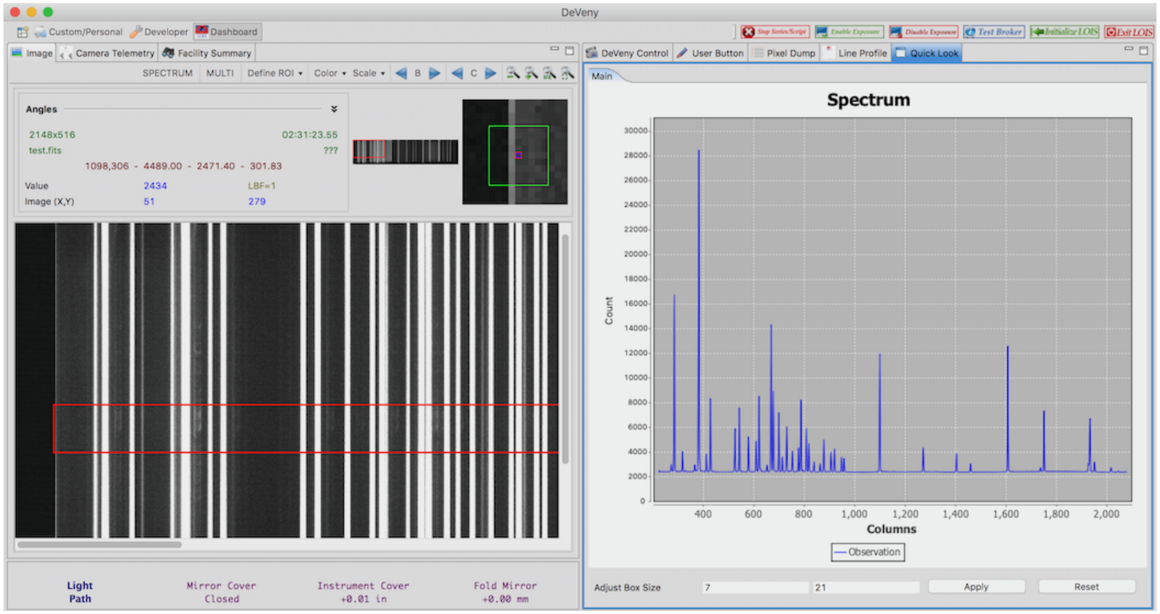


Figure 4: Use of the SPECTRUM tool. In the top portion of the DeVeny LOUI, in the left panel a region (red rectangle) has been selected via click-and-drag. In the right panel the “Quick Look” tab is selected and the mean spectrum (averaged over rows) for the selected region is displayed here.

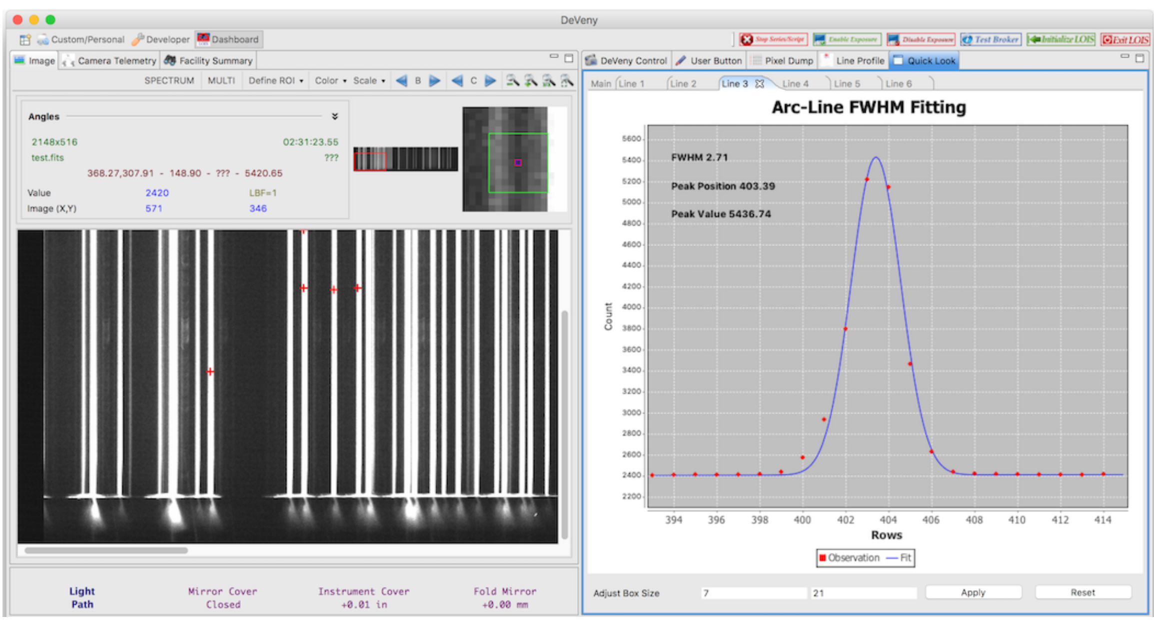


Figure 5: Use of the MULTI tool. In the top portion of the DeVeny LOUI, in the left panel several lines have been selected. In the right panel the “Quick Look” tab is selected and each line is plotted in its own tab. The tabs display the data points, a fit to the selected line and a few statistics. (NOTE: While the abscissa is labeled as “Rows”, it is actually plotting column number. This is a bug in the LOUI.)

as shown in Figure 4. (NOTE: It is sometimes helpful to "detach" the Quick Look tab and resize it, as necessary.)

- **MULTI**: After clicking this tool, select individual spectral lines of interest by clicking on them in the image window. When your selection is complete press the M key. This will open a new plot in the Quick Look tab for each line selected and perform a fit, giving the FWHM of the selected line, as shown in Figure 5. At the bottom of each Quick Look tab, there are input boxes where you can change the size of the analysis box in pixels, depending on your needs. The MULTI tool is particularly useful for confirming correct collimator focus.

See the LMI user manual (`http://www2.lowell.edu/users/massey/LMIdoc.pdf`) for more discussion of camera operations and LOUI and IRAF quick-look software, as DeVeny camera operations are very similar.

4.2 Setting Up the Spectrograph

⇒ For quick reference, each step includes the basic steps listed with arrows (like this). Below the arrows are more detailed information about the steps.

The grating tilt, slit width, collimator focus, and comparison arc lamps are controlled from the DeVeny LOUI (Fig. 2 #5). Table 1 lists the physical ranges and home positions of the motorized stages controlled by these widgets. The current positions of the three motorized stages and the status of the arc lamps are all recorded in the image FITS headers. When the LOUI is started and if JOE is running, the positions of all 3 motorized stages (grating tilt, slit width, and collimator focus) should automatically update in their respective widgets.

4.2.1 Homing the motorized stages

⇒ Initialize then Home each stage in succession using the appropriate widget (Fig. 2 #5).

Operational evidence at LDT has shown that all motorized stages should be initialized and homed at the start of an observing session to ensure the reported positions are accurate. To home any one stage, press Initialize then Home in the appropriate widget (Fig. 2 #5). The stage will move to its home position (see Table 1), then you will need to command the stage back to your desired setting. This process takes 2-4 minutes per stage. Because all three stages share the same power supply, only one stage is permitted to move at a time to prevent power supply overload.

Carefully inspect the Encoder and Motor values – if they disagree by more than the last digit of the physical units, or if any stage does not update to a real physical value (Table 1), this indicates power to the motor has cycled, and initialization and homing are required. Even with these steps taken, however, the observer is still responsible for the accuracy of their data. Wavelength solution, collimator focusing, and slit width should all be verified observationally.

Table 1. LOUI-Controlled Motorized Stages

Stage	Physical Range	Home Position	FITS Keyword	Ancillary Information
Grating Tilt	0° – 48°	0°	`GRANGLE`	Gratings used at $\gtrsim$ 20°
Slit Width	0.075 mm – 15 mm	13.1 mm	`SLITASEC`	On-sky size: 0.″5 – 98″
Collimator Focus	7.75 mm – 19 mm	12.1 mm	`COLLFOC`	Temperature-dependent

4.2.2 Setting the grating tilt

⇒ Compute the needed grating angle using the **`deveny_grangle`** tool.
⇒ Enter the grating angle (°) into the Grating Tilt widget and click Move (Fig. 2, #5).

Some commonly used grating tilt angles are given in Table 2. The desired grating tilt angle is computed using the grating equation based on groove spacing and desired central wavelength (see Appendix G.1). A graphical application is provided to do this calculation for you; an example calculation is shown in Figure 6 for the DV2 grating.

To compute the desired grating tilt angle:

1. Open a terminal window on `dct-obs1/obs2`.
2. Type **`deveny_grangle`** to launch the (python) graphical application.
3. Select your grating from the drop-down and enter the desired central wavelength.
4. Press Compute . The needed grating tilt angle and anamorphic demagnification are displayed.

Enter the computed grating tilt angle (0° – 48°) in the LOUI grating tilt widget (Fig. 2, #5) and click Move . The E ncoder and M otor values in the LOUI widget will update as the motor moves. The values in parentheses are the computed tilt angles and should be approximately the same; the grating is in position when the tilt value equals the input value. The grating position should be checked with an arc line image against the DeVeny arc line atlas (see Appendix D) to verify the spectral central wavelength and/or range.

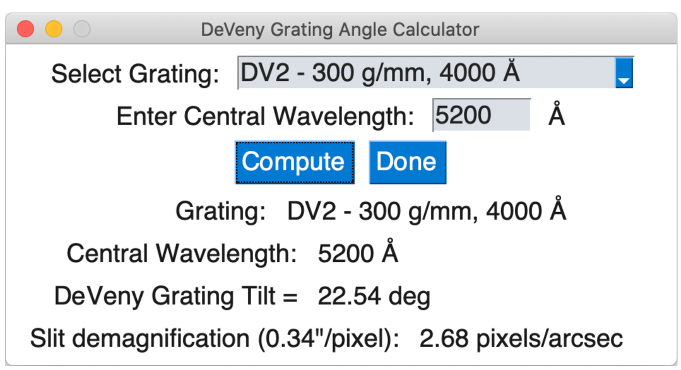


Figure 6: Grating angle calculator GUI. Select the installed grating from the drop-down, enter the desired central wavelength, and press Compute .

Table 2. Example Grating Settings

Grating[a]	Tilt (°)	λ_c (Å)	Range (Å)	Filter	Slit Demag[b] (pix/″)	Notes[c]
DV1	21.00	7200	2800 – 11,600	GG420	2.76	$m = 2$ at $\lambda > 8400$Å
DV2	22.54	5200	3000 – 7400	GG420	2.68	
DV3	24.05	6750	4500 – 9000	GG420	2.61	$m = 2$ at $\lambda > 8400$Å
DV3	25.28	8000	5800 – 10,200	OG570	2.55	
DV4	26.06	6600	4900 – 8300	GG420	2.51	
DV4	27.89	8000	5800 – 10,200	OG570	2.43	
DV5	24.62	4400	3000 – 5800	Clear	2.58	
DV5	27.24	6000	4600 – 7400	GG420	2.46	
DV5	29.04	7100	5700 – 8500	GG495	2.37	
DV6	27.04	4900	3750 – 6050	Clear	2.47	
DV7	31.19	7000	5850 – 8150	GG495	2.28	
DV8	39.51	8000	7200 – 8800	OG570	1.92	
DV9	33.20	4000	3400 – 4600	Clear	2.19	
DV9	37.27	5000	4400 – 5600	Clear	2.01	
DV9	42.30	6200	5600 – 6800	GG495	1.80	Collimator hits lower limit[d]
DV9	46.65	7200	6600 – 7800	OG570	1.62	Collimator hits lower limit[d]
DV10[†]	44.28	3700	3370 – 4030	Clear	1.72	Collimator hits lower limit[d]
DV10[†]	48.00	4170	3840 – 4500	Clear	1.56	Red tilt limit

[a]See Table 4 for line density, blaze, and free spectral range for each grating.

[b]As computed from Equation (9), or using `deveny_grangle` (Fig. 6).

[c]"$m = 2$" represents the second order spectrum, which overlaps with first order spectra at $2 \times \lambda$. The atmospheric cutoff ($\lambda \sim 3200$Å) or order-blocking filter limits the blue end of second order spectrum that will overlap onto the detector.

[d]At large grating tilt angles, the collimator runs into the lower motion limit before reaching focus. See Equation 2.

[†]The DV10 grating is not presently in service.

4.2.3 Setting the slit width

⇒ Enter the desired slit width (″) into the Slit Width widget and click Move (Fig. 2, #5).

Computing the desired slit width is a combination of science goals, detector resolution in the spectral direction, and the anamorphic demagnification of the slit as a function of grating angle. These last two, in combination, are computed for you in the `deveny_grangle` routine discussed above (and shown for example grating settings in Table 2). At large grating angles, the anamorphic demagnification factor (the *apparent* width of the slit in pixels per arcsecond of slit width) becomes significant, and the slit can be opened wider without degrading the spectral resolution (see Appendix G.2). For a more detailed discussion of the subject, see the article by Schweizer (1979).

In short, start by choosing your desired optimal linewidth on the detector. This should not be smaller than 2.5 - 3.0 pixels, else spectral features will not be adequately sampled. Larger linewidths allow for more light through the slit at the cost of spectral resolution. The desired slit width is then computed by:

$$\text{slit width} = \text{desired linewidth} \;/\; \text{slit demagnification} \tag{1}$$

In the Slit Width widget (Fig. 2, #5), enter the desired width in arcsec ($1'' = 0.153$ mm), and click Move. The Motor step values will update (the values in parentheses are the computed physical values). The slit is in position when the physical value equals the input value.

4.2.4 Enabling and turning on/off the arc lamps

⇒ Click Enable in the Comparison Lamps widget (Fig. 2 #5).
⇒ Select the lamps to turn on by clicking the appropriate button(s).
⇒ Click Get Status to force the LOUI to read back the current state of the lamps.
⇒ Click All Lamps Off as a shortcut to turn all lamps off.
⇒ After ensuring all lamps are off (Get Status), click Disable to release control.

The arc emission line spectral comparison lamps are controlled from the Comparison Lamps widget in the DeVeny LOUI (Fig. 2, #5). The characteristics and behavior of the lamps are detailed in §4.3.2. Click Enable to gain control of the lamp power. Each of the four lamps is controlled independently with one of the widget buttons. The identity and status of the individual arc lamps are recorded in the image FITS header keywords `LAMPnSRC` and `LAMPnON`, and the aggregate listing of currently energized lamps is listed in `LAMPCAL`.

Fast clicking of multiple lamp buttons may cause messages sent over the ActiveMQ broker to be discarded, so be slow and deliberate when turning on and off the emission lamps. The All Lamps Off button is a convenience for turning off the lamps after taking comparison spectra. At the end of the night, be sure to Disable control of the comparison lamps before exiting the LOUI.

Clicking Get Status will read the current lamp status and refresh button display. It is advisable to click this button before taking exposures (either comparison or science) to ensure the lamps are in the desired configuration. In particular, at the end of the night it is helpful to click Get Status after All Lamps Off and before Disable to be certain the lamps are off.

4.2.5 Changing the order-blocking and/or neutral-density filter

⇒ Communicate with your TO about which filter(s) you need – preferably ahead of time.
⇒ Update the Rear Filter dropdown in the LOUI (Fig. 2, #4).

This is a manual operation performed by your TO. The available long-pass order-blocking filters are listed in Table 5. Please let them know what filter(s) you will need when you arrive or (preferably) before your run. Be sure to update the Rear Filter dropdown in the LOUI (Fig. 2, #4) with the currently selected filter position.

4.2.6 Setting the decker NOT CURRENTLY INSTALLED

The decker limits the spatial extent of the slit. Scattered light may be an important consideration for some long slit programs. The decker will reduce the overall amount of light getting into the spectrograph.

4.2.7 Setting the collimator focus (focusing the spectrograph)

TelOp Note: This task can currently only be done from `dct-obs1` and `dct-obs2`, as the necessary NAS mounts are not currently active on `dct-to1`.

⇒ Compute the approximate focus position using Equation (2).
⇒ Set the slit width to produce an optimum linewidth of 2.5 - 3.0 pixels on the CCD.
⇒ Turn on the appropriate arc lamps (and wait for them to stabilize).
⇒ Set the number of LOUI exposures to 1.
⇒ Construct a Focus Sequence range that centers on the computed focus value; run.
⇒ Use the command-line (python) tool `dfocus` to analyze the focus frames and compute the optimum focus position.
⇒ Monitor the mount temperature for significant changes that require refocusing.

The internal optics of the instrument are focused by pistoning the collimator mirror. This is a separate task from focusing the telescope onto the spectrograph (see §4.5). For a discussion of the physics behind the collimator focus procedure (including the origin of Equation 2), see Appendix G.3. This process is controlled with the Collimator Focus widget in the DeVeny LOUI. To estimate roughly where the collimator focus ought to be, use Equation (2) to find the approximate (±0.6 mm) center point for the focus script:

$$\text{collimator focus} \approx 11.0 - 0.08\, T_{\rm m}(^\circ\text{C}) - 0.14\,(\text{tilt} - 25^\circ) + 0.7\,\delta_{\rm filter} \quad \text{mm}$$
$$\delta_{\rm filter} = \begin{cases} 0, & \text{if no order-blocking filter } (\texttt{REARFILT = Clear (C)}) \\ 1, & \text{if using an order-blocking filter } (e.g., \text{GG420}) \end{cases} \qquad (2)$$

where $T_{\rm m}$ is the mount temperature (viewable in the NightWatch window or recorded in the `MNTTEMP` FITS header keyword) and tilt is the grating tilt angle set in §4.2.2 above.

Note: The focus increases by 0.4 mm for each 5 C° decrease in the mount temperature. This has implications for when during an observing session the collimator is focused. Many nights there is a steep drop in mount temperature after sunset, often > 5 C°, as the telescope cools to equalize with the night air. For most stable nights, however, the intranight temperature range is typically < 5 C° after the mount equilibrates with the ambient air. If you focus the collimator in the afternoon for calibration frames, it is advisable to monitor $T_{\rm m}$ and refocus the collimator if necessary.

Observers should also note that the lower limit on the collimator focus motorized stage is 7.75 mm (Table 1). In warm weather and/or for large grating tilt angles, the optimal focus may lie beyond this limit. Set the collimator focus value at the lower limit and press on.

To measure and adjust focus:

1. The width of optimally focused spectral lines in pixels on the CCD is a function of slit width and the grating angle, called the "anamorphic demagnification of the slit". The best balance between Nyquist sampling the spectrum and spectral resolution means you should aim for optimum linewidths of about 2.5 - 3 pixels for the focusing sequence. (Of course, your science goals may dictate a different slit width for on-sky observing, and you will need to adjust the slit width after the focus sequence is complete.) Use Equation (1) to compute the necessary slit width for focusing.

   For example, DV2 (300 g/mm) tilted for a central wavelength of 5200Å will image the slit at a scale of 2.7 pixels/$''$ (see Fig. 6). So, the slit width can be set to 1$''$ for the focus run.

2. If an order-blocking filter is used, make sure the filter wheel has been set to the proper position. Ensure that the correct grating and blocking filters are selected from the LOUI drop-down menus, as these values populate the image FITS keywords `GRATING` and `FILTREAR`.

3. Measuring focus requires the use of arc lamp spectra, described in §4.3.2. Turn on the appropriate arc lamp(s) – see Table 3 for lamp warmup times. The focus process can be conducted with the fold mirror in the beam path or stowed, but the instrument cover should be closed. (Count rates are slightly higher if the fold mirror is stowed.) The status of these components are shown in the bottom section of the LOUI Facility Summary tab.

4. Take a test image of length 15 s, and make a line plot in the LOUI (Fig. 4) to check line brightness. The fainter mercury and cadmium lines will peak at a few hundred counts at 15 s, while argon and neon will be at thousands of counts. This is a good compromise if both Hg/Cd and Ne/Ar sets are used. If only Ne/Ar are used, then the exposure length can be reduced to $2 - 5$ s.

5. Set the number of exposures selected in the LOUI to 1 (see Fig. 2 #4), otherwise the script will take the requested number of exposures at each position. The focus analysis routine (see below) will ultimately fail while consuming lots of time.

6. In the DeVeny LOUI, click on the drop down tab labeled Focus Sequence (Fig. 7). This widget will take a series of exposures interleaved with collimator moves to scan across the approximate focus range, with a starting position, step size, and number of steps. **Construct a range that centers on the value computed from Equation (2).** Unlike the M2 focus – §4.5 – or LMI focus procedures, this script does not take the *expected* focus value, but rather one end of the range. After you press Focus Sequence, the colored text will show the progress through a sequence.

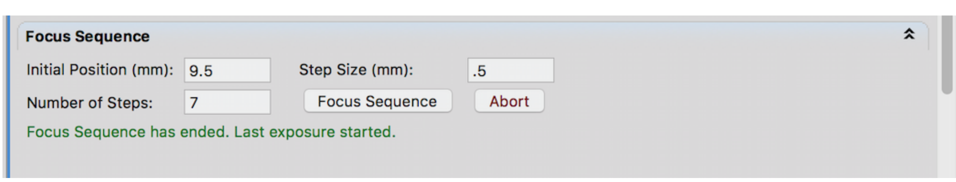


Figure 7: Focus Sequence drop down tab.

7. Once the image sequence has completed, a (python) command-line routine is available to analyze the images and determine the optimal collimator focus position. From a `dct-obs1/obs2` terminal window move to the current focus directory (`cd /deveny/<UTDATE>/focus`). Then type `ls` to check for a file of the form `deveny_focus.<UTDATE>.<UTTIME>`. The image files are stored one level above, and can be examined with `ds9`, IRAF, or other tools.

8. In this directory, type `dfocus` . The code will read in the files, compute the optimal focus position, then launch the Preview App to display the PDF document containing the plots. An example output from the program is blow, with the accompanying plots shown in Figure 8. The program `dfocus` has online help accessible with the `-h` option.

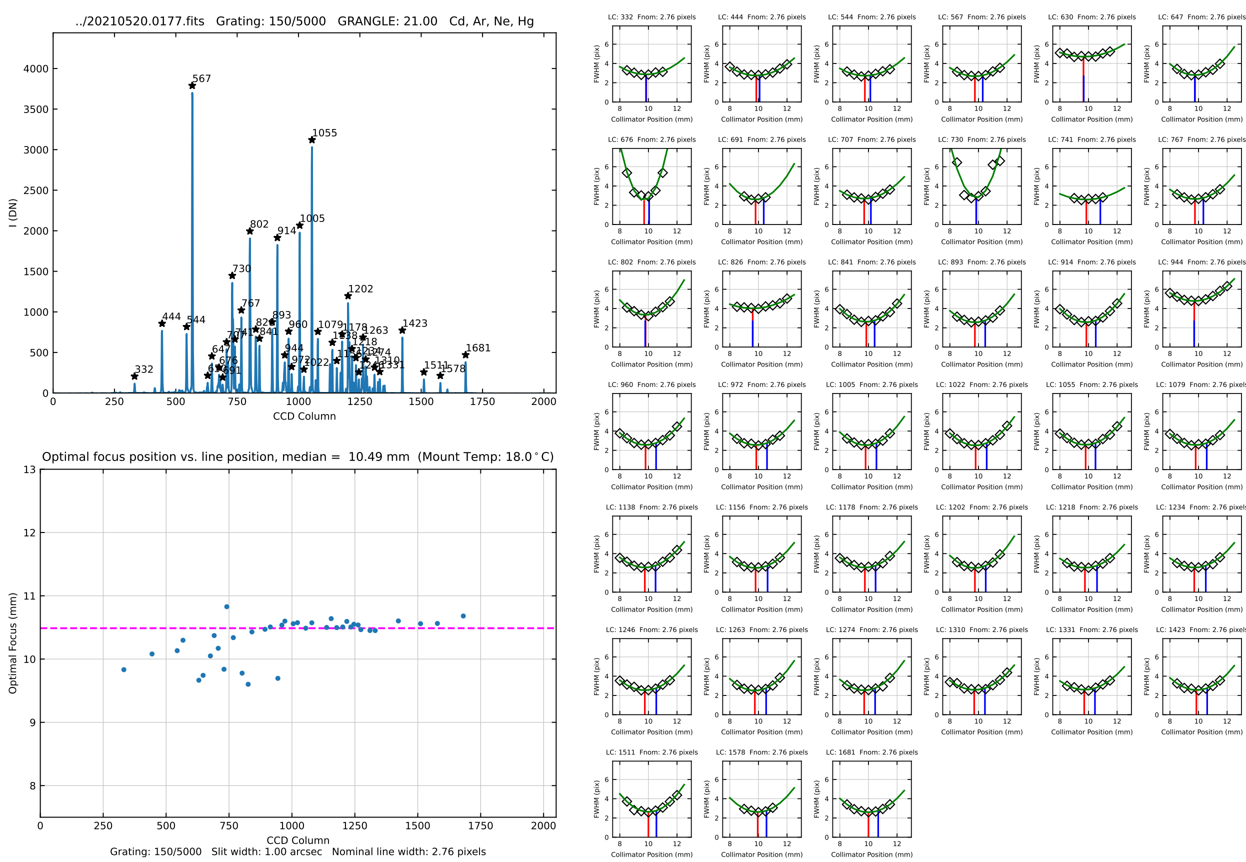


Figure 8: Example output plots from `dfocus` analysis for DV1. *Upper left*: Arc line plot. *Lower left*: Optimal focus vs. line position plot. The median value is 10.49 mm. *Right*: Individual line focus curves.

```
==============================================================================
  DeVeny Collimator Focus Calculator

 Processing center focus image ../20210520.0177.fits...
  Background level: 2351.1   Detection threshold level: 2451.1
 Number of lines: 39

 Processing arc images...
100%|████████████████████████████████████| 10/10 [00:00<00:00, 18.68frame/s]

  Median value of all linewidths: 3.03 pix
==============================================================================
*** Recommended (Median) Optimal Focus Position: 10.49 mm
*** Note: Current Mount Temperature is: 18.0ºC

  Plots have been saved to: pyfocus.20210520.040659.pdf
```

The recommended focus position and mount temperature are printed in the terminal window and included in the plots. The separate pages in the saved PDF document are:

(a) Page 1 (Fig. 8, *upper left*): A spectral arc line plot showing lines found and marked whose peak value is above a default threshold of 100 DN. This is a good threshold for spectra that includes Hg and/or Cd. For spectra of Ne and Ar that are well-distributed across the CCD image, the number of lines utilized can be reduced by increasing the threshold. Re-run the code, using the threshold parameter: *e.g.*, `dfocus --thresh 1000` .

(b) Page 2 (Fig. 8, *lower left*): Nominal collimator focus position for each analyzed emission line (blue line in each of the individual line plots) plotted vs. column number. The median value is highlighted with a purple horizontal line and is also printed in the plot title.

(c) Page 3 (Fig. 8, *right*): The full set of focus curves for the lines analyzed, including the green parabolic fit to the linewidths. The red vertical line marks the minimum of the fitted parabola, and the blue line indicates the nominal focus value for that line.

Note: The nominal focus values will *not* lie at the minima of the focus curves because of astigmatic effects in the spectrograph and camera. See Appendix G.3 for a discussion of this issue.

These plots will indicate whether the collimator position range needs to be extended or re-centered if the curve fits show only one side of a parabola (and not passing through minimum).

9. If the nominal focus position results look good, with well-fit parabolas for most emission lines and a fairly flat distribution across columns, set the collimator focus to the median value using the LOUI widget (Fig. 2 #5). Note that higher collimator focus values are common at lower column numbers (left, red side) due to optical elements in the Wynne camera (see Fig. 16).

10. Take note of the current mount temperature, particularly if the focus procedure is being done in the afternoon. If the mount cools appreciably by the start of your science observations, you may wish to revisit the collimator focus.

It is important that the image headers have valid telemetry for the slit width and collimator focus (FITS keywords `SLITASEC` and `COLLFOC`). If the analysis bugs up with “−9999” values in the focus curves, that is why. (Go back through the steps from §4.1.)

4.3 Taking Calibration Data

Before taking calibration frames, the slit needs to be set for the desired on-sky width. Use Equation (1) to choose the appropriate slit width for your science program.

4.3.1 Bias Frames

💡 Bias frames are used to remove the CCD’s fixed-pattern noise from your data to account for the electronic pre-loading of pixels necessary for proper operation. These are zero-second exposures with the shutter closed, and provide an estimate of the readout noise of the CCD.

To take bias frames in the LOUI interface, select the Camera Control tab (Fig. 2 #4), select Frame Type “bias”, set the number of exposures required, and click `Go`. The exposure time setting is ignored when Frame Type is “bias”, and all exposures are 0 s.

Figure 9 shows an example bias frame. In January 2018 a significant ground loop was broken, eliminating the formerly prominent “corduroy” noise pattern. Bias images may still contain another pickup mode: low-level (±2 DN), time-variable scalloped noise pattern as shown, which may affect low-SNR spectral extractions. This noise is likely caused by another ground loop; LDT Staff hope to address this low-level pickup noise in the future.

4.3.2 Arc Lamp Spectra

💡 Spectrographs separate incoming light into its colors for analysis. The CCD, however, records all photons whose energy exceeds the silicon bandgap (*i.e.*, $\lambda < 11,000$Å) without distinguishing color. To colorize the black-and-white spectral image, DeVeny uses atomic-emission arc lamps to translate CCD column number to wavelength.

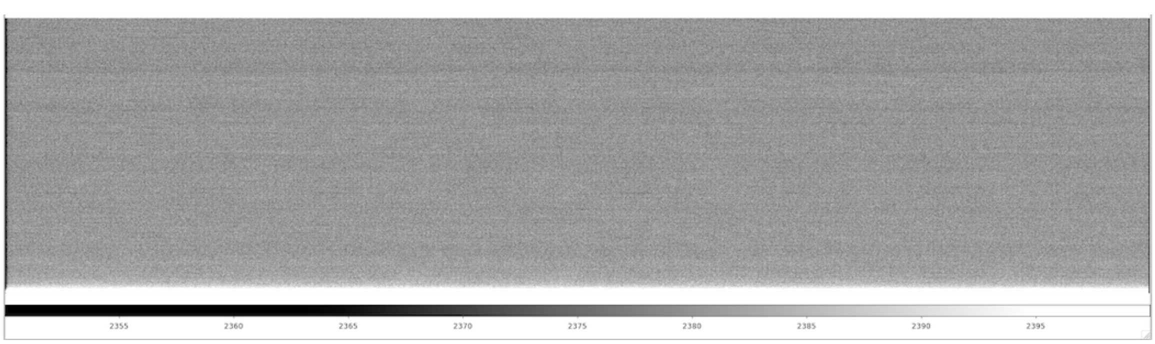


Figure 9: Example of a well-behaved bias frame (2020-12-14UT). Some bias frames will display a remaining low-level (±2 DN), time-variable noise pattern, which may affect low-SNR spectral extractions.

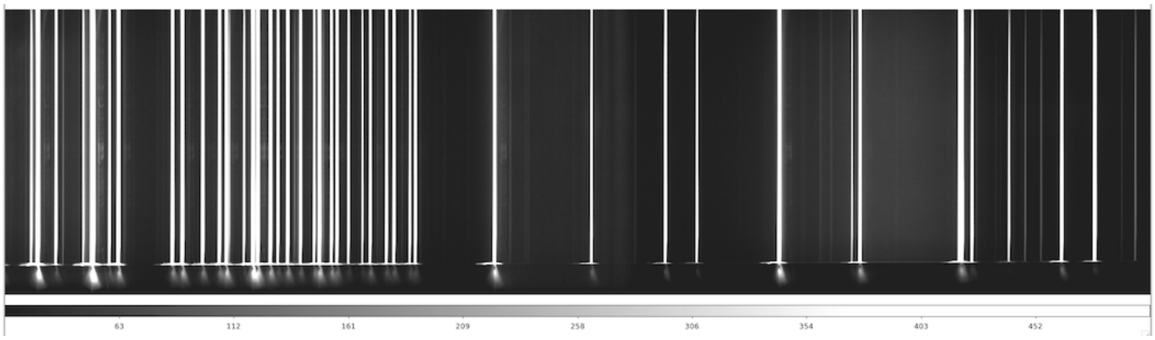


Figure 10: Example arc frame, taken with the DV2 grating at a central wavelength of 5200Å. Lines are from all four lamps (Ne, Ar, Hg, Cd). Wavelength coverage is approximately from 7350Å on the left to 3000Å on the right.

Table 3. Arc Lamp Wavelength Coverage

Arc Lamp	Primary Wavelength Coverage (Å)	Approx. Stabilization Time	Nominal Exposure Time (s)†
Cadmium (Cd)	3200 – 5500‡	3 – 6 min	15 – 20
Mercury (Hg)	3300 – 5800	2 – 3 min	15 – 20
Neon (Ne)	5800 – 8600	a few seconds	2 – 8
Argon (Ar)	6900 – 9700	$<$ 1 min	2 – 8

†For the low-dispersion gratings (DV1 - DV3) when the lamps are warm. Higher dispersion gratings and/or cold lamps may require longer exposure times.

‡Including 3 lines in the so-called "green gap" around 5000 Å.

To take arc spectra, turn on the desired lamps with the Comparison Lamps widget (Fig. 2 #5), and CLOSE the instrument cover. Arcs can be taken with the fold mirror either stowed or extended. The underside of the instrument cover is white and is used as a scattering surface for the arc lamps. Table 3 lists primary wavelength coverage, approximate stabilization time, and nominal exposure time for each emission lamp. Appendix D contains arc line identifications for the DV1, DV2, and DV4 gratings (Figs. 23–25), along with the line list tabulation (Table 7). An example arc line spectral frame for the DV2 grating is shown in Figure 10.

For a discussion of how DeVeny's spectral flexure (which changes as a function of telescope elevation and cassegrain rotator angle) affects wavelength calibration, see Appendix F.

4.3.3 Flat Field Spectra

- To remove pixel-to-pixel variations in CCD sensitivity and effects of dust on the slit, spectra are taken of an out-of-focus white screen illuminated with incandescent bulbs. Data reduction steps (whether via PypeIt – Appendix H – or otherwise) process these spectra to produce models for correcting science data to account for these effects.

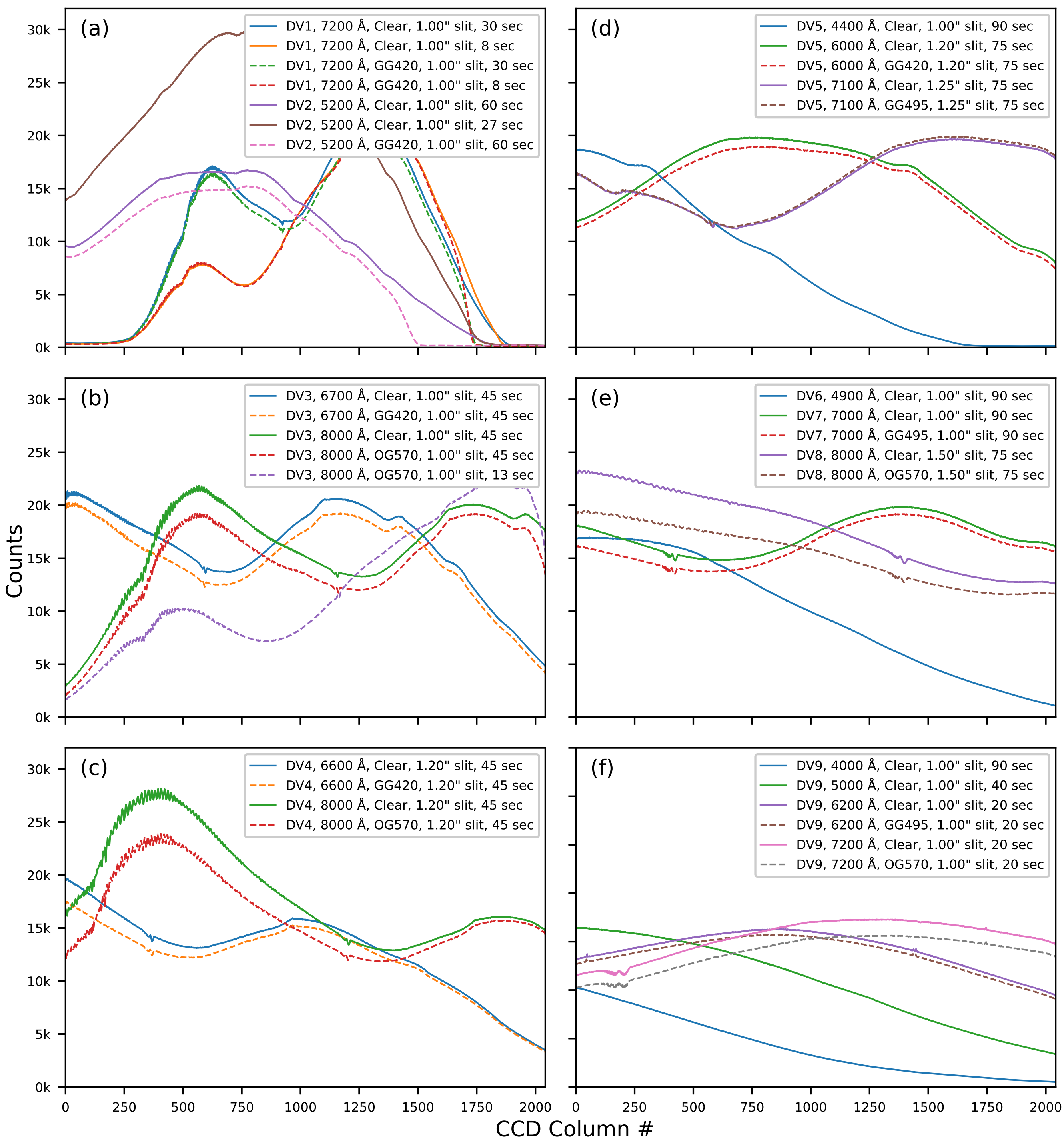


Figure 11: Flat field spectra for all example grating settings shown in Table 2 (data collected from 2020-Dec to 2021-Mar). All panels share the same axes. These spectra are bias-subtracted, but not wavelength calibrated. They are shown how they would appear on the detector with red on the left and blue on the right. The legends give the central wavelengths and exposure times (varied to give 10k - 30k counts). Fringing is seen in the red end of the spectra. Panels (a) - (e) were taken using the top-ring lamps (CLST) at a setting of 12V, and panel (f) was taken using the Photo Flood lamps (CLSD).

For dome flats, ask your TO to insert the fold mirror that feeds the spectrograph into the beam, open the instrument cover, and point the telescope at the flat field screen. For most gratings, the Top Ring Lamps are best suited for flat field exposures. The expected spectral shapes and count rates for the DeVeny gratings are shown in Figure 11 along with expected exposure times.[1] For more detail on the LDT's set of flat field lamps, see §7.5.

The CCD shows fringing redward of ~ 8200Å, with an amplitude of $\sim 1-3\%$, as seen in the flat field profiles of DV1, DV3, DV4, and DV8 in Figure 11. (This is significantly reduced from the previous thinned e2v CCD42-10, which exhibited 5% fringing at 7000 Å, rising to 20% at 8000 Å and 40% at 9000 Å.)[2]

NOTE: If fringing is seen in your flat field images where you do not expect it, check and re-home the grating tilt motor – this may be a symptom of the grating not being tilted at the desired angle.

Ask the TO to begin opening the telescope. If you are observing at the start of the night, at this point ask your TO to begin opening the telescope and perform the pointing check (if it is dark enough) while you set up the slit viewing camera software (§4.4). Once you have the software set up, wait until the TO informs you that the telescope is ready to observe before moving on to §4.5.

4.4 Setting Up and Operating the Slit Viewing Camera

NOTE: The slit viewing camera saves files in directories corresponding to that night's UT – which changes over at 5:00pm MST. The scripts used to start up the camera controller and `slitviewg` GUI utilize the UT date when the command is invoked. Therefore, to avoid issues with GoQat or `slitviewg` crashing, please wait to complete this step until after 5:00pm MST. (The earliest sunset at LDT occurs around 5:15pm MST in December, so this requirement should not cause inconvenience.)

The slit viewing camera is controlled by the computer `vishnu`, through the GoQat software package, and operated on-sky with the IDL `slitviewg` interface.

1. GoQat Camera control software start-up:

   (a) From a local terminal window on `dct-obs1/obs2`, login to the control computer:
   `ssh -Y lois@vishnu`, password: ask your TO

[1] The set of Top Ring Lamps was replaced in May 2021, and the new lamps have a slightly different spectral shape. In general, they are brighter and peak slightly bluer than the curves shown in Figure 11.

[2] Fringing is caused by long-wavelength light reflecting internally within the CCD before being absorbed, causing interference patterns. The deep depletion region of the current chip increases the fraction of long-wavelength photons absorbed on first pass, leaving fewer to cause interference fringes.

(b) In this terminal, type `goqat.start`; this script will start GoQat and set the following parameters automatically:

- Autosave "True" (`COMMAND chkFileAutoSaveCCD 1`)
- Output directory (`COMMAND flcFilderCCD /home/lois/deveny/<UTDATE>`)
- Base filename (`COMMAND txtFileCCD <UTDATE>`)
- Binning: 2×2 (`COMMAND spbCCDBin 2`)

Also, the "Expose" command will open an instance of `ds9` to display the slit viewer camera images.

Inspect the GoQat console (Fig. 12, bottom) and verify that commands are printed there announcing the above settings without errors. The `goqat.start` script opens the camera connection through a shell-script command. Even with scripted waits, sometimes execution of a command is delayed or not received by GoQat, and succeeding commands don't take.

If the console output in GoQat does not look similar to Figure 12 and the "Expose" command appears to have failed, you will need to enter the proper settings manually in GoQat's "CCD Camera" and "Files" tabs.

Follow these steps if the GoQat console does not indicate a successful exposure taken:

- Open the CCD camera connection from the "Cameras" menubar item.

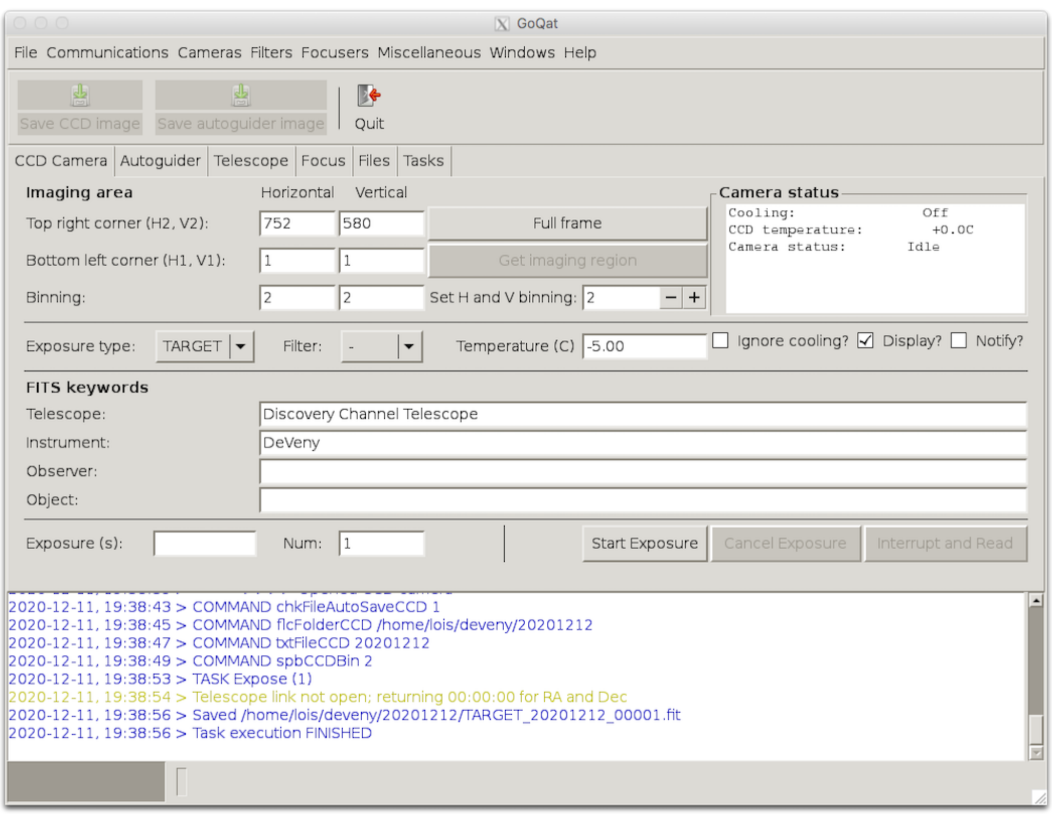


Figure 12: GoQat camera software graphical user interface, "CCD Camera" tab. The log entries shown indicate a successful startup.

- In the “Files” tab (see Fig. 13), select “Autosave each image”, set the output directory: `/home/lois/deveny/<UTDATE>`, base filename: `<UTDATE>`, and the appropriate `<SEQNUM>` starting value (1 if at the start of the night, next-in-sequence if GoQat was restarted for any reason).
- In the “CCD Camera” tab, set binning to 2×2.
- Take a 1 s test image; this will open an instance of `ds9` for image display.

NOTES:

– If you should ever need to restart GoQat, the file number needs to be set to the next in sequence when the restart happened, otherwise existing files will be overwritten. If restarting, be sure to note the current file number *before* you restart.

– The `ds9` display can be used separate from the IDL operational interface to adjust contrast and conduct other image interpretive actions.

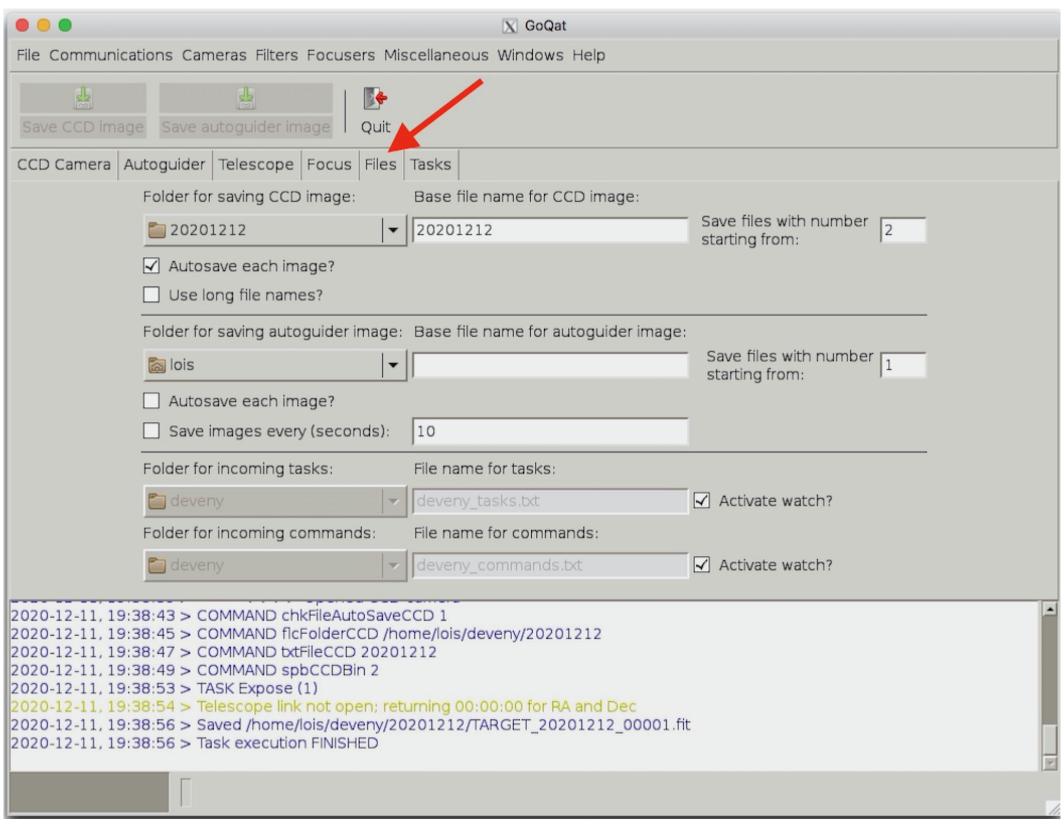


Figure 13: GoQat “Files” tab. This panel provides manual selection of the directory and base filename `<UTDATE>`, first file number, and autosave files.

2. IDL `slitviewg` application start-up:

   (a) The `goqat.start` script from above completes with an automatic start of IDL, and compilation of `slitviewg`.

   (b) At the `IDL>` prompt, type `slitviewg`. This launches the slit viewing camera top level control GUI (Figure 14).

Troubleshooting: See §A for some basic troubleshooting. If `slitviewg` continues to hang or does not return to proper functioning, the easiest way to reset it (and to ensure all terminals are in the correct directories) is to:

1. Note the current exposure number for the slitviewing camera.
2. Fully log out of `vishnu`; log back in, following the instructions in §4.4 above.
3. Set the exposure number in GoQat to the next exposure in the sequence.
4. Resume observing.

Running `slitviewg`:

NOTE: Because the DeVeny shutter lies in front of the slit (see Fig. 16), the slit viewing camera will not be able to see the sky (and therefore the target object) during the readout of the spectral CCD. Since readout is quick (~ 8 s), this should have minimal impact, but the observer should be aware of it.

Below are the key features of the `slitviewg` GUI (Fig. 14) you will need for interacting with the slitviewing camera while on-sky.

1) **Acquire Image**: Takes an image, with integration time `tacq` seconds (Figure 14A). The file name is written to the following field, with the format `TARGET_<UTDATE>_<SEQNUM>.fit`.

2) **Read File**: Loads the image file named in the field into the display. This happens automatically when a new exposure is taken, but a different file may be loaded using this function for comparison or analysis.

3) **Repeat Acquire**: Takes `Numexp` images in sequence with the specified interval in between. This function can be used to monitor tracking. All of the images are saved, so caution is advised when executing long sequences. To interrupt the sequence, regain focus in the IDL session window, and type `^C`, followed by `@recover`. To avoid buffer overflow crashes of GoQat on the server, set the interval between exposures to 5 s or longer.

4) **MARK Star**: Fits a 2-D Gaussian function to a selected star in the field of view; the center of the PSF is utilized for offsetting operations. Click the button, then select the target with the cursor and click. NOTE: The Status field will change to say `Markstar!` and the cursor will change. After the fit is calculated, a 1-D radial plot of the target intensity with the fitted curve is displayed in the upper right window, and a contour plot of the selected star and fit parameters are displayed in the middle-right window (Figure 14D). A box will be displayed around the marked star.

5) **Point REF**: The TCS-defined pointing origin for DeVeny is located approximately $5''$ above the center of the slit; this button will offset the telescope to place the target there. A verification image is

automatically taken following the offset. After pressing this button, the Status field will change to say `Markstar!` and the cursor will change. The radial fit and contour plot, along with a box around the star, follow after click-target selection.

6) **Point SLIT**: Offsets the telescope to put the target approximately at the slit center position, with the same `Markstar!` functionality. A verification image is automatically taken following the offset.

7) **IPA, Parang, and Frame**: The rotator instrument position angle (IPA), parallactic angle (Parang), and rotator frame (Frame) are fields that are automatically updated from TCS telemetry, through the GUI event loop every time an image is taken. These 3 parameters are subsequently used to configure offset coordinate frames according to the rotator mode. If you are observing in "Target" mode (*i.e.*, slit fixed with respect the sky), IPA is the slit-sky position angle. If you are observing in "Fixed" rotator mode (*i.e.*, slit fixed with respect to the horizon, and atmospheric dispersion fixed relative to the slit), IPA is the slit-zenith position angle. Set the IPA to 0º or 180º for dispersion along the slit. The N/E and AZ/EL compass roses seen in the top left corner of the image will also update with each image taken. See §5.3 for a more thorough discussion of rotator modes.

8) **ABS Offset RA/Dec (Xi/Eta (arcsec))**: Sends an absolute telescope offset in arcseconds in TPLANE Xi/Eta coordinates (*i.e.*, dRA/dDec) (Figure 14B). The offset is absolute with respect to the original TCS commanded position. The field values actively accumulate relative offsets applied through the two REL offset buttons below. An absolute offset of (0,0) should always put the target back in the original position.

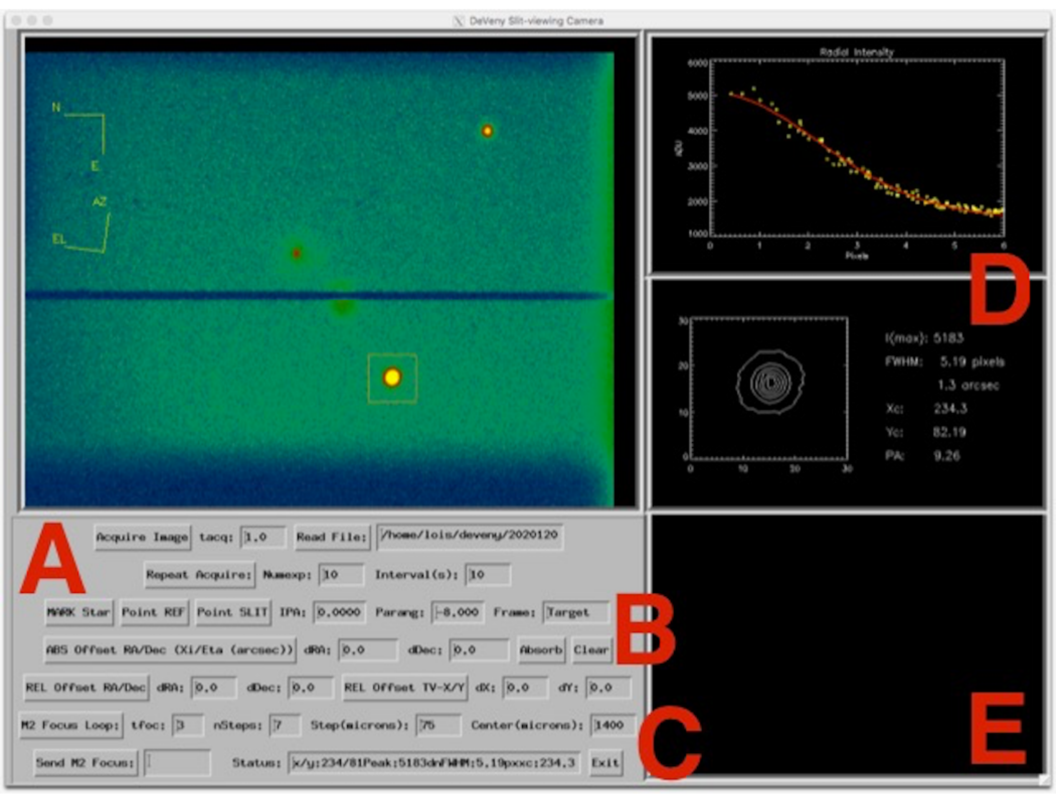


Figure 14: IDL `slitviewg` control GUI

9) **Absorb and Clear**: Click Absorb to establish a new origin after a non-zero absolute offset; the dRA and dDec fields will be set to 0, and a verification image will be taken. Any subsequent offset will be a new absolute offset from this redefined origin. Click Clear to clear any accumulated offsets and offset the telescope to the previous origin, followed by a verification image.

10) **REL Offset RA/Dec**: Sends a relative telescope offset in TPLANE coordinates of the values in the fields. These offsets are accumulated in ABS dRA/dDec, and a verification image is taken with each offset.

11) **REL Offset TV-X/Y**: Sends a relative telescope offset in the camera image X/Y coordinates, followed by a verification image. These offsets are also accumulated in ABS dRA/dDec. This function can be used to dither along the slit, as well as make fine adjustments in the object position perpendicular to the slit. See also the discussion in §5.5 on open loop vs. guided offsets, and why open loop offsets are preferred for target set up.

4.5 Focusing the Telescope

At this point all of the software should be set up and the beginning of the night calibration images collected. Once your TO has completed their start-of-night checks, you will be ready to focus the telescope before moving on to your object spectra. The telescope is focused on the DeVeny slit by pistoning the telescope's secondary mirror (M2). The most straightforward way to do this is via the slit viewing camera GUI (`slitviewg`):

1) **M2 Focus Loop**: Execute a focus loop with an imaged star on the slit plane by piston of M2 using the telescope active optics system (AOS) (Figure 14C). Pressing this button starts the loop with a reference image, after which `Markstar!` is prompted to locate the target and proceed with the following parameters:

   `tfoc` - Exposure time for the focus sequence images. [Default: 3 s]

   `nSteps` - Number of steps taken during the focus. [Default: 7]

   `Step (microns)` - Size in microns of each step. [Default: 75 μm] The step size can be modified according to seeing conditions.

   `Center` - The focus value around which the `nSteps` will be made. [Default: 1400 μm]. The value defaults to the current AOS nominal focus offset (check with your TO if this value has changed).

   The focus loop graphical output (Figure 14E) is progressive. The focus curve fills in as the loop progresses, accompanied by radial fitting and contour plotting. The loop can be interrupted for reasons such as starting too far out in focus position, bad star, mis-entering numbers in the fields, etc. To interrupt the loop, in the IDL terminal session type `^C`, followed by `@recover`.

   The focus curve data and fit are plotted in the lower right window. The M2 position finishes at loop's end, and the predicted position for minimum focus is marked for inspection and printed in the plot title, and then displayed in the `Send M2 Focus` field.

2) **Send M2 Focus**: Carefully inspect the focus loop graphical output to ensure nothing pathological happened in the curve fitting. If you are satisfied with the computed focus offset value, send it to the Active Optics System by clicking `Send M2 Focus`. The value is entered in microns, and is auto-filled after running a focus loop. If your inspection of the focus curve fitting indicates a different M2 focus offset is warranted, you may enter it directly into the `Send M2 Focus` field and press the button.

Spatial focus of a target star should be double-checked following a focus run. The LDT M2 focus offset for the DeVeny is roughly 1400 μm (confirm the default value with your TO). Use a 13^{th} magnitude star (approx.) for focusing, with `tfoc = 3 s`. The camera saturates at 65k counts, so for optimal focus the star used should have 10k to 20k counts in the peak.

5 Observing

5.1 Logs

Many observers like to take logs as a backup to the image FITS header information. If you do not already have a preferred logging method, printable log sheets for DeVeny are available both on Confluence and on the Desktop of the observer machines (`dct-obs1`/`dct-obs2`).

5.2 The Nightly Report App

To keep track of observer experience with the facility, we request that you let us know how your observing time went.

There is a night report form (called Nightly Report) on the user interface computers (`dct-obs1` / `dct-obs2`). Click the icon on the Desktop on the right side of the primary screen, among where you find the LOUI start icons. The night report form can be updated throughout the night, or filled out at the end. Many observers find it helpful to record seeing and note issues along the way rather than try to remember everything at the end of the night.

5.3 Pointing the Telescope

Now that the spectrograph and telescope are all set to observe, you need to cause the telescope to point at your desired pinprick of light. There are several ways to send the telescope to your targets of interest:

1. You may give the coordinates to your TO, who can then manually enter them into TCS.
2. You can create an Observer Target List and then send your targets directly to TCS using the GUI on the observer computer (Fig. 15).
3. For non-sidereal targets, you can supply ephemeris files or have your TO generate them (using the TCS's built-in JPL Horizons interface).

The first method is not very practical for most observing programs, but works in a pinch.

Observer Target Lists are user-prepared target catalogs consisting of plain-text files containing object names and coordinates along with other astrometric information (see Appendix B for how to construct a Target List). It is best to construct a target list directly in a basic text editor (Notepad, vi, emacs, nano, etc.) to avoid having formatting characters cause problems with the Observer Target List UI.

Copy your prepared target list to `dct-obs1/obs2` either via USB drive or over the network using secure copy (`scp`)[3]. Open the Observer Target List UI (icon on the Desktop called `observerTargetList`), and load the target list files using the "File" drop down menu (Figure 15). The Observer Target List UI also contains various catalogs of photometric and spectrophotometric standard stars. Clicking on one of the "Sky Plot" buttons (button text size indicates relative size of the resulting plot) produces an Az-El plot of the current sky locations of catalog objects.

In cases where the observer supplies object files (target lists or ephemerides) it is recommended that these be ready before your observing run starts. The Observer Target List UI requires a very specific syntax

[3] *e.g.*, `scp mytargets.tls observer@dct-obs1:~/Desktop/TargetLists/`.

(Appendix B), so users unfamiliar with this tool should be sure to try to load their catalogs well before trying to slew the telescope to their first target.

The TCS ephemeris tool is equally particular about syntax. (Having the TO generate ephemerides through the TCS interface is usually the preferred method to ensure correct syntax.) For slowly moving non-sidereal objects, it is possible to use the Observer Target List UI, and enter the proper non-sidereal motions (see Appendix B) rather than use the JPL Horizons ephemerides.

One final consideration, regardless of how your coordinates get to TCS, is the orientation of the slit on the sky. TCS supports two basic frames of reference (this is NOT the same thing as the coordinate system reference frame for RA,Dec etc.). The two options are "Target" frame and "Fixed" frame.

- "Target" frame is the most common case for imaging, and maintains a constant orientation in the RA/Dec on-sky frame of reference. The zero point of this frame has the line North-South aligned with the instrument fiducial. For an imager, the detector columns are the normal fiducial, and for spectrographs the slit is the normal fiducial. Instrument rotation angles will be measured from North through East.

- "Fixed" frame is often used for spectroscopic observations of point source objects. The zero point for this frame has the instrument fiducial aligned with the vertical direction. (Note that there can be a 180° ambiguity in this definition.) For DeVeny, setting the frame to "Fixed" and the instrument angle to 180° will align the slit vertically with respect to the horizon, which is also the parallactic angle. For guiding, the TO will need to select the guide mode for "Fixed" frame, to account for the lack of instrument rotation compensation.

You may add this information to your Observer Target Lists directly (see Appendix B), or inform your TO if using manual entry or ephemeris files.

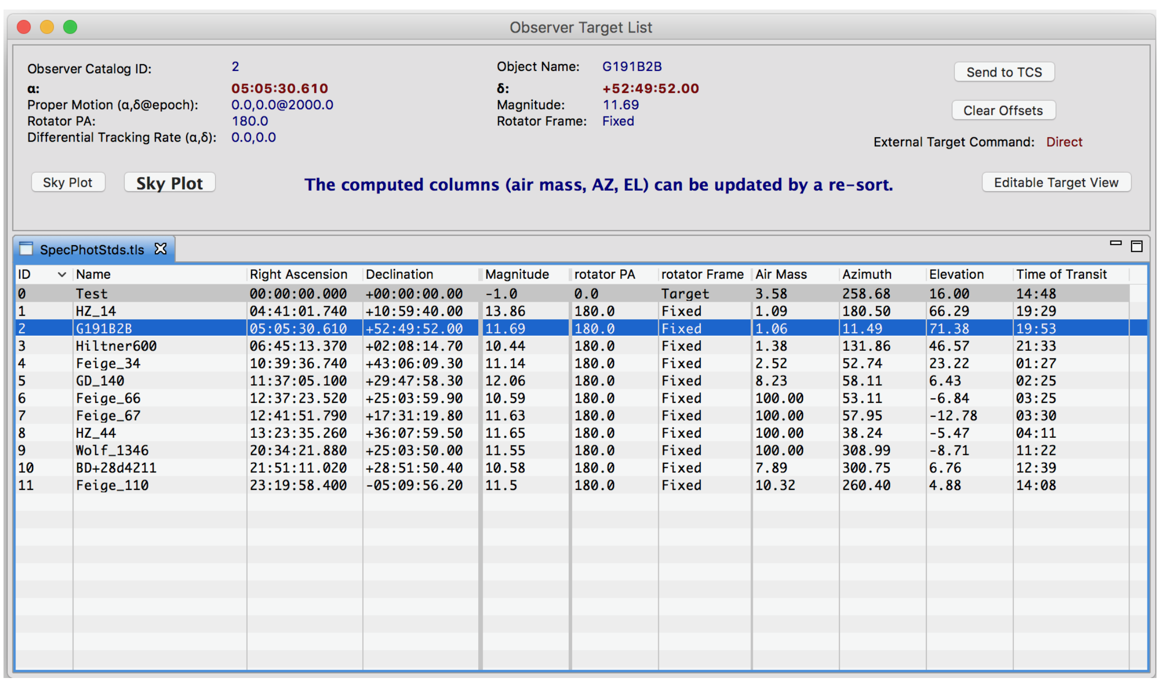


Figure 15: The Observer Target List UI. The four right-most columns are automatically generated and do not appear in the base file. The rows are editable to allow for corrections and/or sending of additional targets.

5.4 Science!

And now the moment you've been waiting for! Send the telescope to your first target and start collecting photons. After the telescope slews to a new position, it takes several seconds to settle and be ready for image acquisition. There are four status indicators at the bottom of the DeVeny LOUI that will turn green when the telescope is ready:

- TCS - Telescope Control System
- AOS - Active Optics System
- DOME - Dome shutter position
- M1 - Mirror Cover

Red indicates that the status is bad (*e.g.*, the light path is blocked, the telescope is still in motion, etc.). Yellow indicates that the status is unknown (this is usually seen at the beginning of the night before any commands have been sent or received, or if JOE is off). Green indicates that all is well.

Use the slit viewing camera to identify and offset targets onto the slit. As mentioned in §4.4, to correctly apply offsets, the IPA must be filled in correctly. If you have trouble identifying which angle you require, ask your TO for assistance.

Use the Point SLIT function in `slitviewg` to place your target near the center of the visible slit in the image display. Once the target is centered on the slit you are ready to begin exposing. If desired, your TO can set up guiding once you are happy with the pointing (see §5.5 for more information on guiding).

To take spectra of your object, in the DeVeny LOUI set Frame Type to "object", enter the exposure time, and press `Go`. If you need to abort an exposure for any reason, the image will be lost (there is no current provision in software for readout before the end of the commanded exposure time). For this reason, the LOUI will offer a warning if you enter an exposure time exceeding 10 minutes (the warning is informational only, and you may select any exposure time you desire).

5.5 Guiding

Guiding is performed by inserting a pick-off mirror into the beam off-axis, below the side-port fold mirror. Your TO will set this up, and doing so takes 30 seconds to a minute depending upon the local star field and sky conditions. When guide lock is established, the GDR indicator at the bottom of the LOUI will turn green. Like the other status indicators, it has three states: red indicates that the telescope is parked, yellow indicates that it is tracking unguided (open loop) and green indicates that the telescope is guiding (closed loop).

If telescope offsets are required to set the target object at the appropriate position on the slit, it is most efficient to do this with guiding off (GDR indicator yellow). Once you are satisfied with the location of your target on the slit, you may ask the TO to reestablish guiding. If it is necessary to issue telescope pointing offsets while maintaining guiding, do not issue such commands in rapid sequence. Since all communication between the slit viewer GUI, guider interface, and TCS flows over a message broker, it is important to avoid out-of-sequence messages. If the various systems get out of sync, your exposure can be negatively impacted.

Reestablishing guide lock after a guided offset command takes ~ 15 s, so confirm the completion of any guided offset move before issuing the next offset command.

5.6 Taking *in situ* Calibrations

The primary *in situ* calibrations are flexure related (see Appendix F for details). Arcs may be taken by closing the instrument cover; flats may be taken by rotating the dome in front of the telescope.

6 At the End of the Night

6.1 Calibration Frames

If you require end-of-night calibration images, be sure to communicate this with your TO(s) well in advance. When you are finished with on-sky observations, let your TO know so they can close the dome shutter and set up for your calibrations. See §4.3 for reference on calibration frames.

6.2 Shutting Down the Software

At the end of your observing session, it is important to cleanly close out any software used and return the observing computer (`dct-obs1/obs2`) to the state you found it in as a courtesy to following observers.

On `vishnu`:

- Click the Exit button at the bottom of the `slitviewg` window (Fig. 14C).
- Close the GoQat window and the `ds9` window.
- `exit` the IDL session and `logout` of `vishnu`.

In the DeVeny LOUI:

- In the Comparison Lamps widget, Enable the lamps to ensure control over the power. Then, click All Lamps Off to turn off the power to the arc lamps. Finally click Disable to drop the connection from the LOUI to the power strip.
- **DO NOT** Exit LOIS or kill the terminal window to `deveny`. Either of these actions would disable monitoring of the instrument temperatures.
- Exit the DeVeny LOUI with the top-level pull down menu.

On the observing computer (`dct-obs1/obs2`):

- Fill out the Observer's report using the Nightly Report application (§5.2) on the desktop. This report sends valuable feedback to the LDT staff about the quality of the night as perceived by the observers. If desired, this application can be open during your entire observing session, and you can enter data about seeing and time lost as your session progresses.
- Close the Observer Target List UI.
- If used, gracefully quit IRAF: type `logout` in the xgterm window, and close the window.
- Close any local `ds9` displays.

6.3 Taking Your Data Away With You

The easiest ways to take your data home with you are to bring a small external USB drive or USB flash drive with you to the site or to copy the files out over the network. To estimate storage capability and transfer times, consider that each (unbinned) raw image is 2.1MB. Depending on your observing plan and number of calibration frames, you may take between 100 and 300 images in a night. This translates to 200MB – 600MB for one night – almost trivial given modern USB portable drives and network transfer speeds.

- For on-site observing, you can plug a USB drive into the port on the back of `dct-obs1/obs2`, and perform a `cp /deveny/<UTDATE>` to your drive.
- For network transfer, you may use either secure file transfer protocol (`sftp`) or secure copy (`scp`) to move your data to your home institution. Please note that the LDT is connected to the world via a microwave network link with somewhat limited capacity. Do not transfer data during someone else's observing time, as it could cause connection issues for others due to link saturation.
  - `sftp` to `observer@dct-obs1/obs2`, `cd /deveny/<UTDATE>`, and `get *.fits`
  - `scp -r observer@dct-obs1:/deveny/<UTDATE> .`

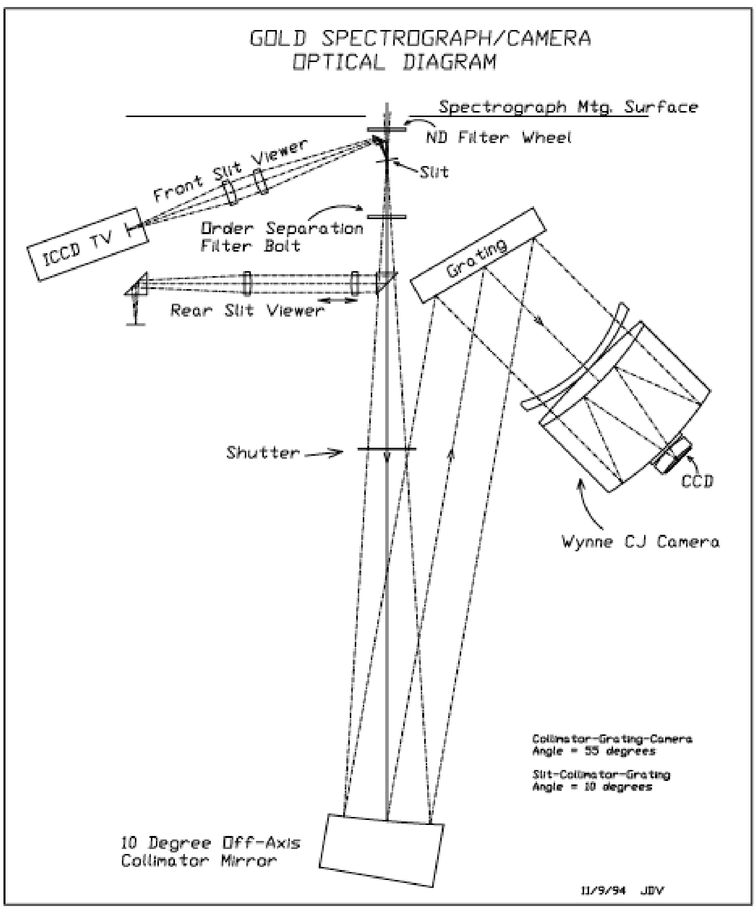
The files you see on the observing computer are actually just a copy of the original data, and the data is also backed up offsite. Thus, while we can't guarantee we can retrieve your data for you a year from now, it's not unlikely either. Still, the process of retrieving data after-the-fact is labor intensive and cumbersome, and we recommend you take responsibility for your data.

7 Quick Reference Specifications and Operating Options

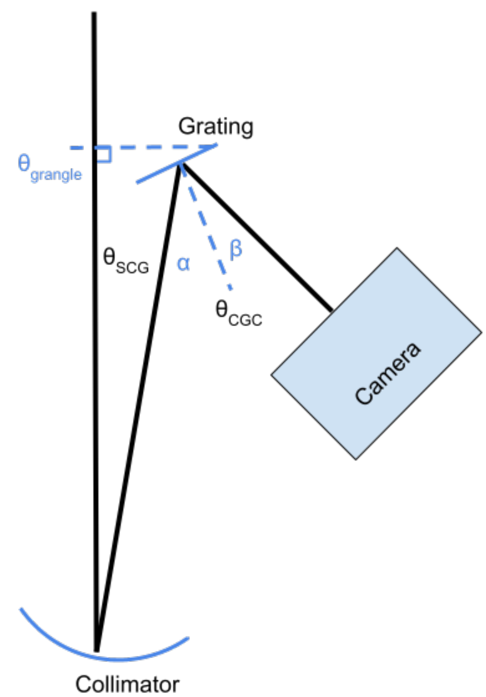
7.1 Schematic and Light Path

The DeVeny Optical Spectrograph's schematic and light path are shown in Figure 16. Features to note: as part of the conversion for use with Lowell telescopes, the shutter and 2-lens focal converter sit in front of the slit. This means that when the shutter is closed during CCD readout, the slit viewing camera cannot see the sky. Because readout takes ~ 8 s, this should be a minimal issue. The neutral density ("Front") filter wheel also sits before the slit.

Behind the shutter, decker, and slit-jaws there is a pupil-matching lens, order-blocking filters, an off-axis parabolic collimator, and a grating carriage that holds one of a set of 128×154 mm plane reflection gratings. The image is formed on the CCD by the f/1.25 Wynne (version E) camera, which has two powered reflective surfaces and a series of weak fused silica refractive correction surfaces. The secondary "mirror" (an aluminized rectangular spot on a key surface) introduces a substantial central obscuration in the camera.



(a) KPNO Gold Spectrograph



(b) Angles in DeVeny

Figure 16: Optical diagrams for the KPNO Gold Spectrograph (a) and the DeVeny Spectrograph (a.k.a. KPNO White Spectrograph, b). The two spectrographs are near cousins of each other, and share a basic optical configuration (grating sets, pertinent angles, filter configuration).

Table 4. DeVeny Gratings

Name	g/mm	Blaze Wavelength (Å)	Dispersion (Å/pix)	Free Spectral Range (Å)	R (2.5-pixel, on-blaze)	FITS keyword `GRATING`	Comments
DV1	150	5000	4.3	8800	450	`150/5000`	KPNO 201
DV2	300	4000	2.17	4440	920	`300/4000`	KPNO 09
DV3	300	6750	2.17	4440	1250	`300/6750`	KPNO 32
DV4	400	8500	1.66	3400	2850	`400/8500`	
DV5	500	5500	1.33	2720	1500	`500/5500`	KPNO 240
DV6	600	4900	1.14	2320	1400	`600/4900`	KPNO 26new
DV7	600	6750	1.14	2320	2370	`600/6750`	KPNO 35
DV8	831	8000	0.80	1630	4000	`831/8000`	KPNO 47
DV9	1200	5000	0.58	1180	3450	`1200/5000`	
DV10†	2160	5000	0.33	670	5250	`2160/5000`	4500Å red limit

†The DV10 grating is not presently in service.

Of particular note are the three angles that define the spectrograph system:

- the Slit-Collimator-Grating angle $\theta_{SCG} = 10°$,
- the Collimator-Grating-Camera angle $\theta_{CGC} = 55°$, and
- the Grating Tilt angle $\theta_{\rm grangle}$ (user selectable – §4.2.2).

In Figure 16b, the relevant angles within the spectrograph are labeled. In particular, the incoming and outgoing angles for a ray hitting the center of the camera are:

- $\alpha = \theta_{\rm grangle} + \theta_{SCG}$, and
- $\beta = \theta_{CGC} - \alpha$.

Specular ($0^{\rm th}$-order) reflection occurs when $\alpha = \beta$, or $\theta_{\rm grangle} = 17.5°$.

7.2 Gratings

All of the gratings are 128×154 mm $1^{\rm st}$-order blazed plane reflection gratings that were used with the KPNO White and Gold Spectrographs for many years. The LDT/DeVeny grating complement is shown in Table 4. A preliminary assessment of instrumental efficiency vs. wavelength for 3 gratings is shown in Figure 17. Estimated system signal-to-noise ratio and point source count rates for select gratings are shown in Appendix C.

The blaze angles are chosen such that specular reflection off the sawtooth grating lines aligns with the $m = 1$ diffraction peak for a particular wavelength of light. The sawtooth pattern can be inscribed for $1^{\rm st}$-order on either one side or the other of $m = 0$, and our gratings are blazed and mounted such that the operational grating tilt range is $20° \lesssim \theta_{\rm grangle} \leq 48°$. (For a discussion of why this is, see §G.2.)

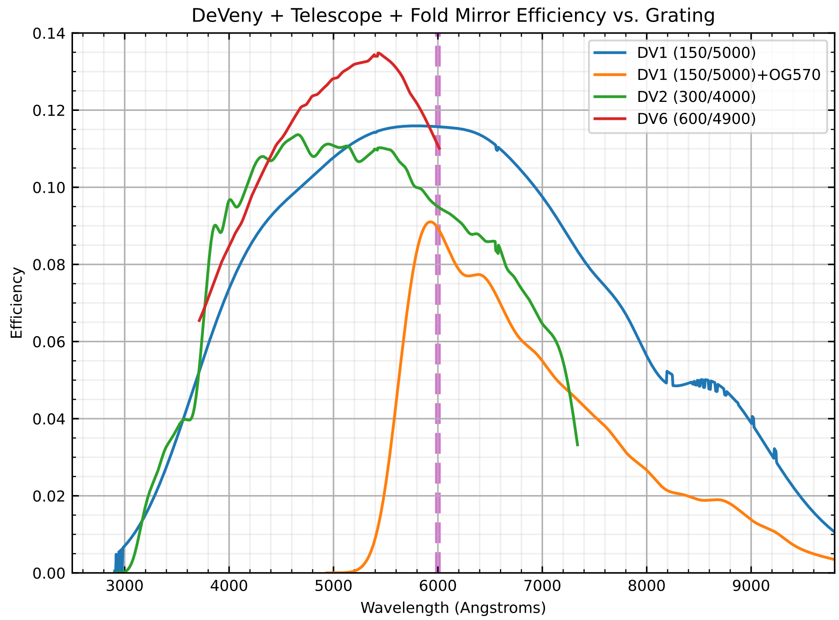


Figure 17: On-sky measured DeVeny efficiency vs. wavelength for several gratings. The vertical line at 6000Å shows where 2^{nd}-order leakage would begin for unfiltered spectra. The spectra were all taken with a 5″ wide slit. Blue: DV1, no filter, 2022-04-14, BD+33 2642. Orange: DV1, OG570, 2022-04-15, BD+33 2642. Green: DV2, no filter, 2015-05-07, Feige 66. Red: DV6, no filter, 2022-02-05, G191-B2B.

The grating tilt is controlled with a stepper motor attached to the stage drive shaft, with an encoded resolution of $< 0.001°$. The grating tilt angle is modified using a widget on the DeVeny LOUI (see Figure 2). The angles are given by the grating equation (see Appendix G.1), and should position the spectral format centered within a small number of pixels. The python GUI utility `deveny_grangle` (see §4.2.2) performs this computation for you.

While all of the gratings are mounted in identical cassettes, there is a slight variation in the exact angle of the normal vector to the surface of the grating with respect to the cassette from one grating to the next. The roll, pitch, and yaw of the grating within its cassette lead to shifts in the spatial and spectral directions, and alignment of those axes with the CCD columns/rows, respectively. The roll is seen by a vertical displacement in the the entire spectrum (including the visible slit edges) on the CCD from grating to grating – but the slit location remains fixed for a given grating. The grating pitch is degenerate with the adjustable θ_{grangle}, so is not noticeable by the observer. Lastly, the grating yaw affects alignment of the slit along columns of the spectral CCD, but this angle is not levered into a noticeable variation from grating to grating and can be ignored.

7.3 Shutter and filter wheels

The iris shutter is made by Uniblitz (model CS-45), and was installed for the LDT upgrade. Due to space constraints within the instrument, it is positioned above the slit assembly. Therefore, the slit-viewing camera will be blocked from the sky and the images will be blank when the spectral channel CCD is reading

Table 5. Filter Wheel Positions

Wheel	Position C	Position 1	Position 2	Position 3	Position 4
Front filters	Clear	2.5mag ND[a]	5mag ND[a]	7.5mag ND[a]	Empty
Rear filters	Clear	GG420	~~GG495~~[b]	OG570	Empty[c]

[a]ND = neutral density grade.

[b]The GG495 filter was removed from the instrument in April 2021 – see Confluence for updates.

[c]We plan to install a UV-blocking long-pass filter (*e.g.*, WG360 or similar) in the near future.

out.

A recent measurement of the shutter photometric accuracy was conducted using flat field images at various exposure times (2021-01-29UT). This test revealed that the fractional error in the image intensity above that expected purely from computed exposure time was larger than 3% for exposure times $\lesssim 0.5$ s, growing to over 25% for `exptime` < 0.1 s. This agrees with the manufacturer data sheet, which specifies a typical opening and closing times of 14 ms and 24 ms, respectively. The above analysis was conducted on a broad section of the CCD and represents the average photometric accuracy across the slit. An analysis of the spatial variation along the slit reveals the fractional error is greatest at the center of the slit ($> 30\%$ for `exptime` $= 0.1$ s) and lower closer to the edges of the slit ($< 20\%$ for `exptime` $= 0.1$ s). If your observing program requires these very short exposures in conjunction with photometric accuracy, carefully consider your calibration needs.

DeVeny is equipped with two filter wheels (see Table 5) for modifying the light passing through the instrument. In the wheel in front of the slit jaws are installed a collection of neutral density filters. These consist of a layer of Inconel (austenitic nickel-chromium-based superalloy) on a quartz substrate, and may be used when observing particularly bright targets. If these filters are used for absolute or relative fluxes, they should be independently calibrated using standard stars.

Long-pass order blocking filters are installed in the rear filter wheel (behind the slit). These are 1.75 in diameter $\times$ 2 mm thick circular filters. Fabricated from Schott glasses and polished to 1 wave/inch with $1'$ wedge maximum, these filters are broad-band AR coated on both sides. Both filter wheels are 5-position, and installed filters are shown in Table 5. Representative transmission curves from Schott are shown in Appendix E.

7.4 Slit and Decker

The slit width is adjustable from a widget in the DeVeny LOUI, described in §4.2.3. The slit width is controlled by a stepper-motorized micrometer made by PI (model M-229.26S), with 0.08 μm resolution and 10 μm ($0\farcs065$) backlash. If the observer is concerned about this level of precision and repeatability in the slit width, we recommend always setting the slit width in the closing direction. The installed slit-jaws are aligned end to end within a pixel.

Slit Width Drive Specifications:

- Focal plane plate scale: 0.153 mm/″
- Minimum slit width: $\sim 0.''5$ (0.075 mm)
- Maximum slit width: 98″ (15 mm)
- Slit position angle: $0 - 360°$ via the Cassegrain rotator

The maximum slit length without the decker is about $2.'5$. With the decker, the maximum slit length is $1.'9$. The decker plate is not currently installed.

7.5 Calibration Lamps

The arc calibration sources are AC-powered pencil-style atomic emission lamps, installed on the front end of the spectrograph and switched with the DeVeny PDU through a LOUI widget, described in §4.2.4. Light from the lamps backscatters from the instrument cover and fold mirror to illuminate the slit. Currently installed lamps are: mercury (Hg – Newport; lifetime 5000 hours), neon (Ne – Newport; lifetime 250 hours), argon (Ar – Newport; lifetime 500 hours), and cadmium (Cd – UVP/AnalytikJena, lifetime unknown); sample spectra are shown in Appendix D. As outlined in Table 3, the lamps each take a different amount of time to stabilize. Figure 18 illustrates the stabilization as a function of time for Ar, Hg, and Cd (Ne stabilizes within a few seconds).

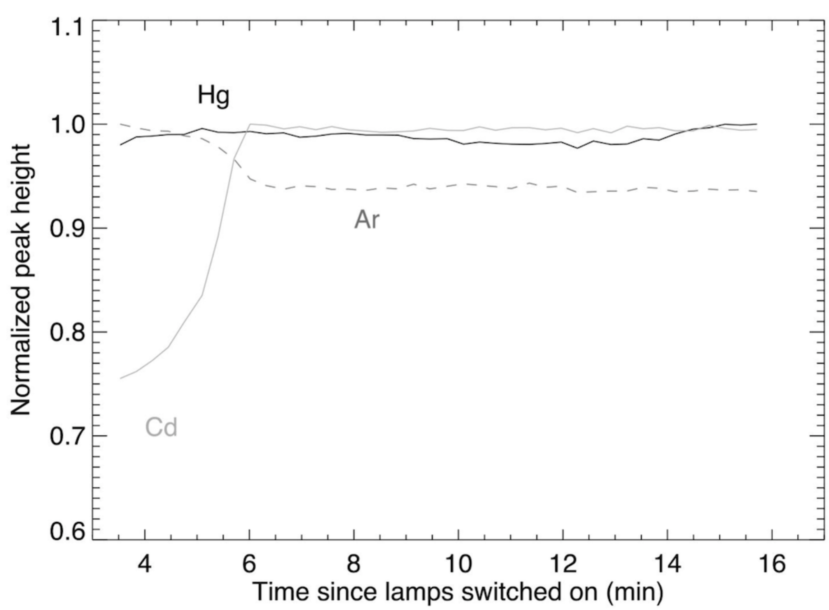


Figure 18: Arc lamp warm up curves. Ne and Ar brightnesses stabilize within a minute, Hg in 1-3 minutes, and Cd in about 6 minutes. They may well be usable before fully stabilized, but caveat emptor. (Courtesy: N. Moskovitz)

To illustrate what is meant by "stabilization" of the arc lamps, view the videos of time-lapse extracted spectra for each of the lamps on the Confluence DeVeny Gratings / Filters / Lamps page. While neon and argon (inert gases) stabilize quickly, the two metallic gas lamps take longer to reach equilibrium. The initial lines seen in both the mercury and cadmium videos are, in fact, argon lines. This is because argon is the carrier gas filling the lamp tube, and when the Hg or Cd lamp is turned on, the argon becomes ionized first and you only see lines from it. As the lamps warm up, the argon lines are replaced by the metal lines as the metal evaporates off the lamp filaments and fills the tube.

For flat fielding, there are three main lamp sets used. For most DeVeny observations, the Top Ring Lamps are appropriate. For the highest dispersion gratings, the Photo Floods may be used to obtain flat field frames in a reasonable amount of time. Samples of flat field spectra are shown for the complement of LDT/DeVeny gratings in Figure 11.

Available flat fielding lamp setups are:

- Top Ring Lamps (a.k.a. "DeVeny Lamps"): These are mounted on the secondary mirror support ring, and produce a characteristic "clover-leaf" pattern when illuminating the flat field screen due to the narrow distance between the ring and the screen. Only the "Low-intensity" bank is currently fully operational. This bank consists of 4× Solux 4700K, 35W, 36-degree, MR16 lamps (tungsten, halogen, quartz) with a cover glass (rated lifetime 4000 hours). Figure 19 shows the lamps' spectral power distribution, as published by the manufacturer. Ask the TO to set these lamps to 12V using the CLST application.
  Incidentally, although the "clover-leaf" pattern seems not at all consistent with the illumination of the night sky, the *illumination functions* (see §F.2) for the two match to within 0.5% (see bottom panel of Fig. 30).
- Photo Floods (a.k.a. "IGRINS Lamps" or "Boom Lamps"): These are mounted on the lamp boom attached to the dome, and are Ushio (#1000246) 3200K, 600W/120V, G7 halogen "Stage and Studio" photo flood bulbs. They were originally installed for use with the IGRINS near-infrared instrument.

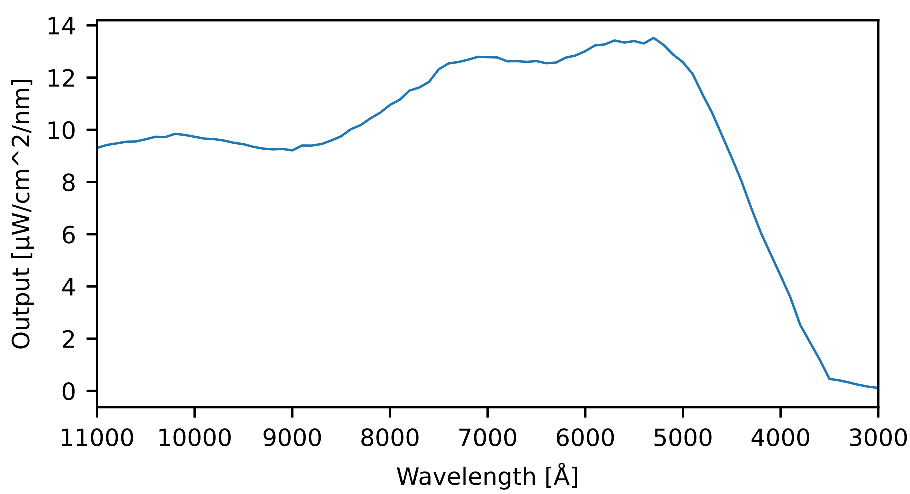


Figure 19: Manufacturer's spectral power distribution curve for the SoLux 4700K ("Top Ring") lamps. The abscissa is drawn with blue to the right to match how spectra appear on the CCD.

These lamps produce significant flux at all DeVeny wavelengths, but should only be used if the Top Ring Lamps do not provide enough flux for the bluest portions of DeVeny's spectral coverage with the higher-resolution gratings. These lamps are controlled by the TO with the CLSD application (they no longer require adjustment of the variac). NOTE: The lamp rated lifetime is quite short (75 hours) compared to the other flat field lamps, so these should be used sparingly.

- The LMI flat field lamps: These are mounted on both the dome and lamp boom to provide even illumination for LMI, and are not used for DeVeny calibrations as they yield significantly lower count rates on the DeVeny CCD than the top-ring lamps. These lamps are also controlled by the TO using the CLSD application.

See Figure 20 for a comparison of the spectral response and intensity between the Top Ring Lamps and the Photo Floods.

7.6 Slit Viewing Camera

The slit viewing camera is a Lodestar X2 made by Starlight Xpress. The detector is a Sony ICX829AL ExView2 interline CCD, with 752×580 pixels. The camera is always operated binned 2×2 (376×290 pixels). The pixels are 8.6×8.3 μm with embedded vertical antiblooming circuitry. The QE peaks at about 77% at 6200 Å, and drops to 45% at 4000 and 7700 Å. A manufacturer's relative response curve is shown in Figure 21. The read noise is less than 10 e^{-}, full well is greater than 50,000 e^{-}, and typical gain is

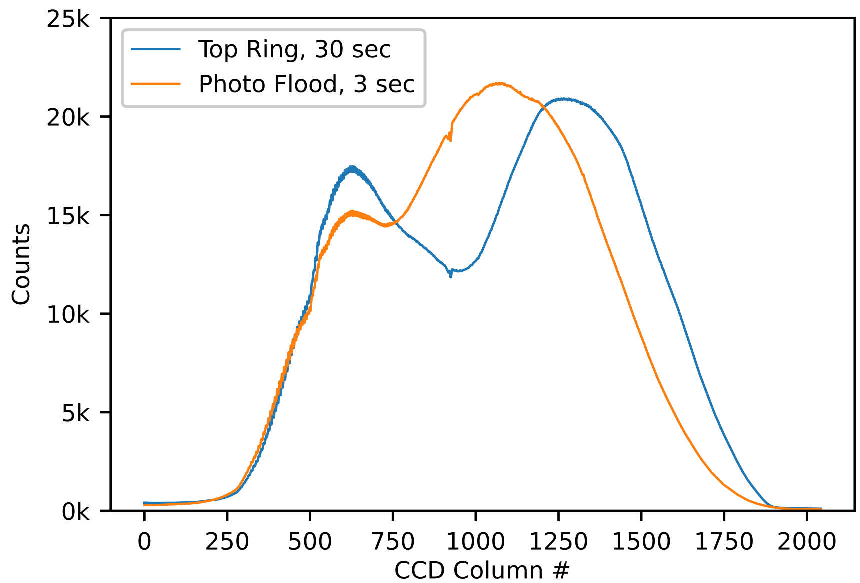


Figure 20: Comparison of Top Ring Lamps and Photo Floods. Both flat field spectra were taking using the DV1 grating with $\theta_{\rm grangle} = 21°$ ($\lambda_c = 7200$ Å). The "Top Ring" spectrum was exposed for 30 s, while the "Photo Flood" spectrum was exposed for 3 s. Note that the Photo Flood lamps are not necessarily bluer (right side of the plot) than the Top Ring lamps, but the $\sim 10\times$ peak intensity provides sufficient flux at blue wavelengths for the higher-dispersion gratings (see Fig. 11). Data collected 2021-01-29UT.

0.4 e$^-$/ADU (per the manufacturer's literature). The camera is uncooled so the hot pixel count increases with exposure time. In late 2020B, the slit viewing application `slitviewg` was updated to mask hot pixels in an attempt to minimize interference of the hot pixels with star centroiding.

The slit viewing camera is USB-based, connected by a fiber-based extender from the instrument, and run by a linux machine (`vishnu`) using the GoQat software package. Typical image download times are roughly 0.2 s via USB2. It is operated on-sky by a custom IDL GUI (see §4.4).

Slit Viewing Camera Specifications:

- Pixel Scale: $0.253''$ / binned-2×2 pixel
- Image Size: 376×290 16-bit pixels
- Field of View: $95 \times 73''$

Note that the field of view along the length of the slit is $1.'6$, whereas the full slit itself is $2.'5$ (or $1.'9$ with the decker), so there are portions of the slit that are not monitored by the slit viewing camera.

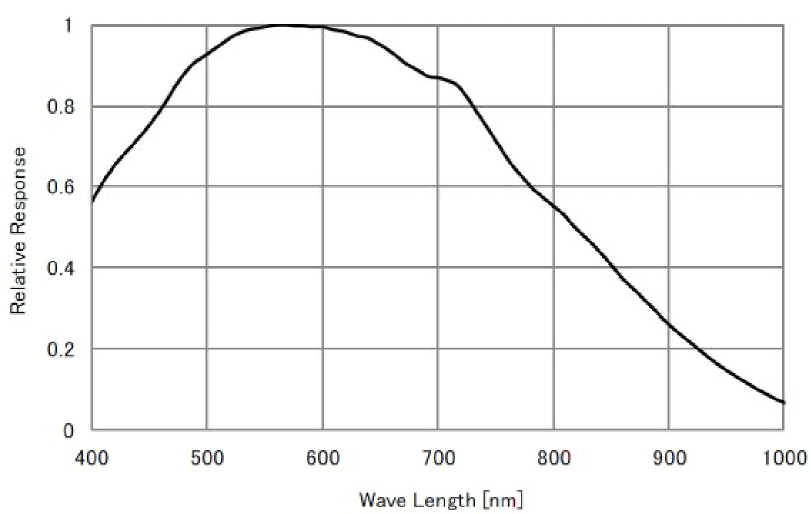


Figure 21: Typical CCD response curve for a Lodestar X2.

7.7 Spectral Channel CCD Camera

The DeVeny CCD camera was developed at Lowell, and is operated with ARC Gen-III control electronics. The CCD is an e2v CCD42-10 deep depletion device, which replaced a similar e2v standard silicon thinned CCD to reduce fringing in the red end of the spectrum. The CCD has 2048×512 13.5 μm pixels. The device is AR coated with e2v's 4-layer Astro-broadband anti-reflective coating.

CCD Camera Specifications:

- Gain: 1.52 e^-/ADU
- 16-bit ADC; Full-Well: $\sim$ 100k e^-
- Read Noise: 3.2 ADUs, about 4.9 e^-
- Typical bias level: $\sim$ 2370 ADU
- Linearity: Linear to 97% of saturation ($\sim 63,500$ ADU)
- Fringing: 1-3% fringe amplitudes, redward of 8000 Å (Figure 11)
- Operating Temp: -110°C
- Dark Current: 4.5 e^-/h = 0.0013 e^-/s
- Readout Time: 8 s
- Spatial Pixel Scale: 0.34″/pixel

A Troubleshooting Notes for Observers

A.1 If the IDL `slitviewg` widget hangs:

If images are not updated, or offsets are not being received, the application may be in an error state, which is usually evident in the IDL terminal session. To return to the main execution level, at the IDL prompt in the terminal that launched the IDL widget, type: `IDL> @recover`

A.2 If the DeVeny image pixels are uniformly stuck at a single value:

If the DeVeny images appear to be stuck at a single, high value (like 22,000 ADU), this is most likely because the analog power supply to the Leach controller has dropped out. This can occur, for example, through RF interference when operating devices on the spectrograph, such as the grating tilt drive, or switching the arc lamps.

The solution is to quit, restart, and re-initialize lois:

- In the top right of the LOUI press Exit LOIS.
- Type `st` in the `deveny` terminal window to confirm lois is no longer running.
- Then (or if lois isn't running) type `lois &` in the `deveny` terminal window. A series of lois startup messages will be printed in both the terminal and the lois console on LOUI.
- Initialize lois - in the top right of the LOUI press Initialize LOIS.

A.3 If the slit viewing camera will not open:

If logging out of `vishnu` and repeating the steps in §4.4 does not help, please ask your TO to troubleshoot the issue.

A.4 If the lois log shows Telemetry Damaged:

This is a result of the stages not having been moved (grating tilt, slit width, and collimator focus) or the telemetry not having been set (grating name or rear filter). Homing the stages and setting the grating and rear filter in LOUI will correct this issue. The telemetry will also become damaged at any time that JOE is restarted.

B The Observer Target List Tool

As mentioned in §5.3, the telescope may be controlled through the use of the Observer Target List Tool. To use this tool a Target List must be provided. These lists are provided in the form of a text file, saved with the extension `.tls`. The files must contain metadata, so that the GUI/widget can identify which columns to create and what data to expect. A number of sample files are shown below. For a full description please see the online documentation on Confluence. NOTE: The colors in the examples below are to highlight which metadata tags are set to `true`, but the entire metadata header must be present in every `.tls` file, and in the order shown, regardless of whether the options are `true` or `false`.

1. File to load a target list that contains name, RA, and Dec only. These are the minimum required fields for Target List files.

```
#title=true ra=true dec=true epoch=false muRA=false muDec=false magnitude=false
dRA=false dDec=false rotatorPA=false rotatorFrame=false comment=false
#
"187799"     12:16:38.99 +00:33:58.3
"30512"      16:03:58.72 +14:55:08.0
"3552"       10:08:05.70 +19:19:07.2
"2016_EE156" 08:45:13.69 +59:34:02.4
"248590"     11:32:16.42 +68:19:08.2
```

2. File to load a target list that contains name, RA, Dec, and differential track rates (`dRA`, `dDec`). (NOTE: Track rates must be entered in arcseconds per hour.)

```
#title=true ra=true dec=true epoch=false muRA=false muDec=false magnitude=false
dRA=true dDec=true rotatorPA=false rotatorFrame=false comment=false
#
"uranus 11UT"   01:28:50.65 +08:39:22.3  3.920  1.521
"Makemake 04UT" 12:50:49.36 +25:38:34.7 -0.261 -1.402
"Makemake 05UT" 12:50:49.34 +25:38:33.3 -0.254 -1.406
"Makemake 06UT" 12:50:49.33 +25:38:31.9 -0.245 -1.409
"Makemake 07UT" 12:50:49.31 +25:38:30.5 -0.234 -1.412
"Haumea 04UT"   14:01:41.50 +17:40:55.3 -1.075 -0.919
```

3. File to load a target list that contains name, RA, Dec, object magnitude, (fixed) Cassegrain Rotator position, and a comment. (A file of this format will set you up to observe at the parallactic angle with the sky rotating. The comment field will appear in the FITS header as a `COMMENT` line.)

```
#title=true ra=true dec=true epoch=false muRA=false muDec=false magnitude=true
dRA=false dDec=false rotatorPA=true rotatorFrame=true comment=true
#
"HD 49009"           06:48:21.72 +41:18:08.36  7.24 180 Fixed "NGC 2281 member"
"HD 49040"           06:48:22.12 +40:57:45.09  8.82 180 Fixed "NGC 2281 member"
"G191B2B SpecStd"    05:05:30.62 +52:49:51.92 11.69 180 Fixed "WD SpecStd"
"BD+75 325 SpecStd"  08:10:49.49 +74:57:57.94  9.50 180 Fixed "sdO SpecStd"
"IC 3568 PN"         12:33:06.87 +82:33:48.95 11.10 180 Fixed "Lemon Slice Nebula"
"NGC 2392 PN"        07:29:10.77 +20:54:42.48  9.68 180 Fixed "Eskimo Nebula"
```

The available metadata variables that can be set are:

- Title or Name (surrounded in double quotes) - **required**. This value will be sent to the TCS as the science target name and cannot be blank. NB: The double quotes should be ASCII character 0x22 (`"`), not the matched left and right double quote (“ and ”) that a word processor is likely to embed. It is recommended to use a simple text editor to get this right.
- Right Ascension (hh:mm:ss.sss) - **required**. The seconds can be either integer or float.
- Declination (+/-dd:mm:ss.ss) - **required**. The plus sign is optional for the degrees, and arc-seconds can be either integer or float.
- Proper Motion in RA (mas/yr). This is the angular measurement used by most catalogs: $\mu_\alpha \times \cos(\delta)$.
- Proper Motion in Dec (mas/yr). This is the angular measurement used by most catalogs: μ_δ.
- Magnitude. This item is not used by TCS, but is included for the benefit of the observer when selecting targets from the catalog.
- Differential Tracking Rate in RA (″/hour). Non-sidereal tracking rate in RA.
- Differential Tracking rate in DEC (″/hour). Non-sidereal tracking rate in Dec.
- Rotator Position Angle (degrees). This adjusts the Cassegrain rotator to place the focal plane at the specified angle with respect to either the sky (“Target” frame) or the telescope mount (“Fixed” frame). This item should always be specified alongside Rotator Frame to ensure the correct rotation of the focal plane. For “Target” frame the position angle is measured E from N, and for “Fixed” frame the position angle is measured with respect to the elevation axis.
- Rotator Frame (“Target” or “Fixed”). A literal string without the quotes specifying which mode the Cassegrain rotator should operate in. This item should always be specified alongside Rotator Position Angle to ensure the correct rotation of the focal plane.
- Comment (surrounded in double quotes). This is a convenience column for observer’s use. The value of this field ends up in a `COMMENT` line in the image FITS header (and is shown in the LOUI).

Observer Target Lists should be created in a basic editor (*e.g.*, vi or emacs), as the UI does not recognize smart characters, and will reject lines with characters outside the ASCII set. Observers new to using this tool should allow enough time to test their lists in the tool before starting to observe.

C DeVeny Signal-to-Noise and Count Rate Estimates

The following plots and table provide estimates of instrumental signal performance.

Figure 22a. The signal-to-noise ratio (SNR) of the spectrograph, telescope, and gratings expected at 5400 Å, with a 100 s exposure in 1″ seeing and 50% lunar phase, and no slit losses. To estimate SNR at other wavelengths, utilize the efficiency plots of Figure 17, and scale the SNR in this plot by the square root of the ratio of the desired grating wavelength efficiency to that printed here at 5400 Å. For example, the DV1 grating has an efficiency of 0.135 at 5400 Å, with SNR of 134 and count rate of 180 e^-/s for $m_V = 14$. At 4500 Å, the DV1 efficiency is 0.1 (Figure 17), so a SNR of 115 at 100 s, and count rate of 155 e^-/s are expected at that wavelength.

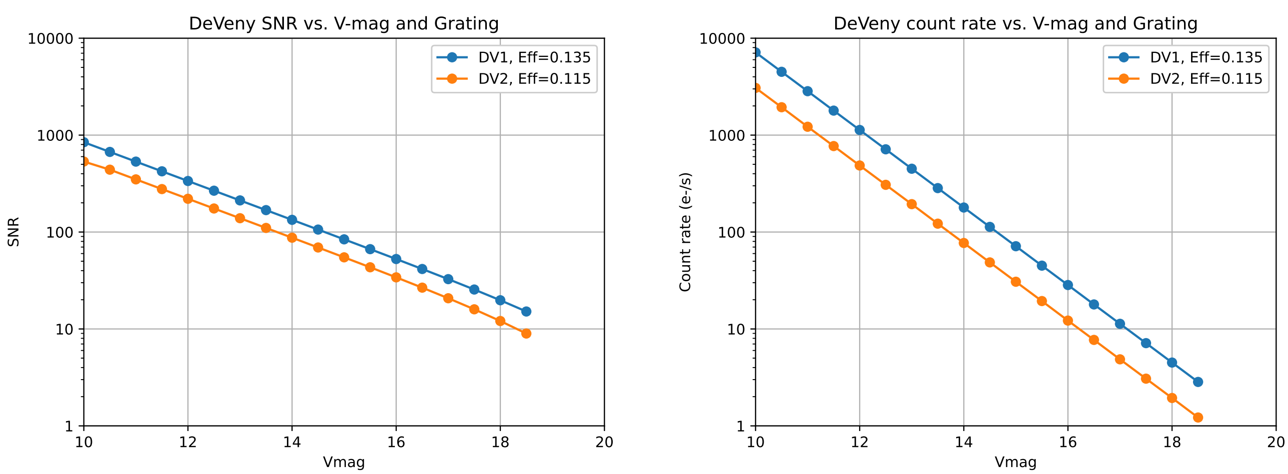
Figure 22b. The estimated count rate at 5400 Å of gratings under the same conditions; scale this plot for other wavelengths in the same fashion.

The expected count rate for a star at a particular wavelength may be computed from:

$$\text{count rate} = \eta \times A_{eff} \times d_R \times [\text{photon flux}(m_V)] \times \text{QE} \tag{3}$$

where η is the efficiency of telescope-fold mirror-spectrograph system (as measured from a spectrophotometric standard star), A_{eff} is the effective collecting area of the primary mirror, d_R is the reciprocal dispersion of the grating (Å/pix), and the photon flux as a function of visual magnitude is computed from Code (1960) is 1,030 $\gamma/s/cm^2/Å$ for a V = B = 0 star. For a $m_V = 10$ star, this value would be multiplied by 10^{-4}, or 0.103 $\gamma/s/cm^2/Å$.

Using an effective collecting area $A_{eff} = 1.285 \times 10^5$ cm^2 of the primary, $d_R = 4.3$ Å/pix and $\eta = 0.135$ for the DV1 grating (150 g/mm), and QE = 0.929 e^-/γ for the spectral channel CCD at 5400Å, we end up



(a) SNR vs. m_V and grating.

(b) Count rate (e^-/s) vs. m_V and grating.

Figure 22: *Left:* SNR vs. V-mag and grating, at 5400Å system efficiency and 100 s exposure time. *Right:* Count rate (e^-/s) vs. V-mag and grating, at 5400Å system efficiency.

Table 6. Signal-to-Noise Ratio and Count Rate Estimates

SNR at `exptime` = 100 s			SNR, peak pixel		Count rate (e^-/s)	
	Grating		Grating		Grating	
V_{mag}	DV1	DV2	DV1	DV2	DV1	DV2
10.00	844.71	533.81	270.16	177.10	7140	3070
10.50	670.96	439.88	214.58	140.66	4500	1940
11.00	532.94	349.38	170.42	111.70	2840	1220
11.50	423.30	277.48	135.35	88.69	1790	771
12.00	336.20	220.36	107.48	70.40	1130	486
12.50	267.01	174.97	85.33	55.87	714	307
13.00	212.03	138.90	67.73	44.31	450	194
13.50	168.35	110.23	53.74	35.11	284	122
14.00	133.63	87.42	42.61	27.78	179	77.1
14.50	106.03	69.28	33.75	21.93	113	48.6
15.00	84.07	54.82	26.69	17.25	71.4	30.7
15.50	66.60	43.29	21.05	13.50	45.0	19.4
16.00	52.67	34.07	16.53	10.48	28.4	12.2
16.50	41.56	26.68	12.91	8.05	17.9	7.71
17.00	32.66	20.74	9.99	6.08	11.3	4.86
17.50	25.52	15.95	7.64	4.51	7.14	3.07
18.00	19.78	12.08	5.74	3.26	4.50	1.94
18.50	15.14	8.97	4.22	2.30	2.84	1.22

with

$$\begin{aligned} \text{count rate} &= 0.135 \times \left(1.285 \times 10^5 \text{ cm}^2\right) \times \left(4.3 \text{ Å/pix}\right) \times \left(0.103\ \gamma/\text{s/cm}^2/\text{Å}\right) \times (0.929 \text{ e}^-/\gamma) \\ &= 7.14 \times 10^3 \text{ e}^-/\text{s} \end{aligned} \quad (4)$$

for a 10^{th} magnitude star. The expected count rate for any arbitrary m_V star may be found by scaling in the usual manner.

D Arc Line Identification

This appendix contains the line identifications for the four (individually controllable) lamps installed in the DeVeny (§7.5). As of v1.7.1 of this manual, all wavelengths shown herein are the *vacuum wavelengths* for these arc lines, to correspond with the standard adopted for PypeIt (Appendix H). NOTE: Earlier versions of this manual listed *air wavelengths* for all lines. The conversion back and forth is straightforward and is included in the Astropy-coordinated package `specutils`.[4]

The list of reliably identified lines for each of the four lamps is given in Tables 7 and 8, with the former listing all lines by species and the latter listing lines in order of wavelength for all but the neon lamp to correspond with the following line identification plots.

Reference arc spectra for manual identification are shown in Figures 23 - 27. Figure 23 shows the overview of lines from the Hg, Cd, and Ar lamps (as seen by the 300 g/mm gratings) across the functional wavelength range of the spectrograph. Next, Figures 24 - 26 show zoomed-in sections of the full spectrum for these same 3 lamps (as seen by the 600 g/mm gratings) on a log scale to emphasize weaker lines. Because neon has a veritable forest of lines for $\lambda \gtrsim 6000$Å, its identification plot is shown separately in Figure 27. Please refer to Tables 7 and 8 when line identifications are printed over top each other

[4] https://specutils.readthedocs.io/en/stable/index.html

Table 7.   Arc Line Identification by Species

Species	Wavelength (Å)	Species	Wavelength (Å)	Species	Wavelength (Å)	Species	Wavelength (Å)	Species	Wavelength (Å)
Ar	4159.76	Ar	8105.92	Cd	5156.10	Ne	5883.53	Ne	7537.85
Ar	4201.86	Ar	8117.54	Cd	6440.25	Ne	5946.48	Ne	7945.37
Ar	5441.50	Ar	8266.79	—	—	Ne	5977.19	Ne	8084.68
Ar	6026.82	Ar	8410.52	Hg	2968.15	Ne	6031.67	Ne	8138.64
Ar	6033.80	Ar	8426.96	Hg	3022.38	Ne	6076.02	Ne	8302.61
Ar	6679.13	Ar	8523.78	Hg	3342.45	Ne	6097.85	Ne	8379.91
Ar	6754.70	Ar	8670.33	Hg	3651.20	Ne	6130.15	Ne	8420.74
Ar	6873.19	Ar	9125.47	Hg	3664.33	Ne	6144.76	Ne	8497.69
Ar	6953.40	Ar	9197.16	Hg	4047.71	Ne	6165.30	Ne	8593.62
Ar	6967.35	Ar	9227.03	Hg	4078.99	Ne	6219.00	Ne	8637.02
Ar	7032.19	Ar	9294.08	Hg	4340.44	Ne	6268.23	Ne	8649.42
Ar	7069.17	Ar	9356.79	Hg	4348.72	Ne	6306.53	Ne	8656.76
Ar	7149.01	Ar	9660.44	Hg	4359.56	Ne	6336.18	Ne	8856.30
Ar	7274.94	Ar	9787.19	Hg	4917.44	Ne	6384.76	Ne	8921.95
Ar	7355.32	Ar	10472.92	Hg	5462.27	Ne	6404.02	Ne	8991.02
Ar	7374.15	—	—	Hg	5771.21	Ne	6508.33	Ne	9151.18
Ar	7386.01	Cd	3134.07	Hg	5792.28	Ne	6534.69	Ne	9204.28
Ar	7437.42	Cd	3262.00	Hg	6909.37	Ne	6600.78	Ne	9329.07
Ar	7473.22	Cd	3404.63	—	—	Ne	6680.12	Ne	9375.88
Ar	7486.39	Cd	3467.19	Ne	5039.16	Ne	6718.90	Ne	9427.97
Ar	7505.94	Cd	3611.54	Ne	5332.26	Ne	6931.38	Ne	9461.81
Ar	7516.72	Cd	4414.23	Ne	5342.58	Ne	7034.35	Ne	9489.28
Ar	7637.21	Cd	4663.66	Ne	5402.06	Ne	7175.92	Ne	9536.78
Ar	7726.33	Cd	4679.46	Ne	5564.31	Ne	7247.16	Ne	9550.02
Ar	8008.36	Cd	4801.25	Ne	5658.23	Ne	7440.95	Ne	9668.07
Ar	8016.99	Cd	5087.24	Ne	5854.11	Ne	7490.93		

Table 8.   Arc Line Identification by Wavelength (Hg, Cd, Ar only)†

Species	Wavelength (Å)	Species	Wavelength (Å)	Species	Wavelength (Å)	Species	Wavelength (Å)
Hg	2968.15	Cd	4414.23	Hg	6909.37	Ar	8008.36
Hg	3022.38	Cd	4663.66	Ar	6953.40	Ar	8016.99
Cd	3134.07	Cd	4679.46	Ar	6967.35	Ar	8105.92
Cd	3262.00	Cd	4801.25	Ar	7032.19	Ar	8117.54
Hg	3342.45	Hg	4917.44	Ar	7069.17	Ar	8266.79
Cd	3404.63	Cd	5087.24	Ar	7149.01	Ar	8410.52
Cd	3467.19	Cd	5156.10	Ar	7274.94	Ar	8426.96
Cd	3611.54	Ar	5441.50	Ar	7355.32	Ar	8523.78
Hg	3651.20	Hg	5462.27	Ar	7374.15	Ar	8670.33
Hg	3664.33	Hg	5771.21	Ar	7386.01	Ar	9125.47
Hg	4047.71	Hg	5792.28	Ar	7437.42	Ar	9197.16
Hg	4078.99	Ar	6026.82	Ar	7473.22	Ar	9227.03
Ar	4159.76	Ar	6033.80	Ar	7486.39	Ar	9294.08
Ar	4201.86	Cd	6440.25	Ar	7505.94	Ar	9356.79
Hg	4340.44	Ar	6679.13	Ar	7516.72	Ar	9660.44
Hg	4348.72	Ar	6754.70	Ar	7637.21	Ar	9787.19
Hg	4359.56	Ar	6873.19	Ar	7726.33	Ar	10472.92

†This table reflects the lines shown in the identification plots of Figures 23 - 26.

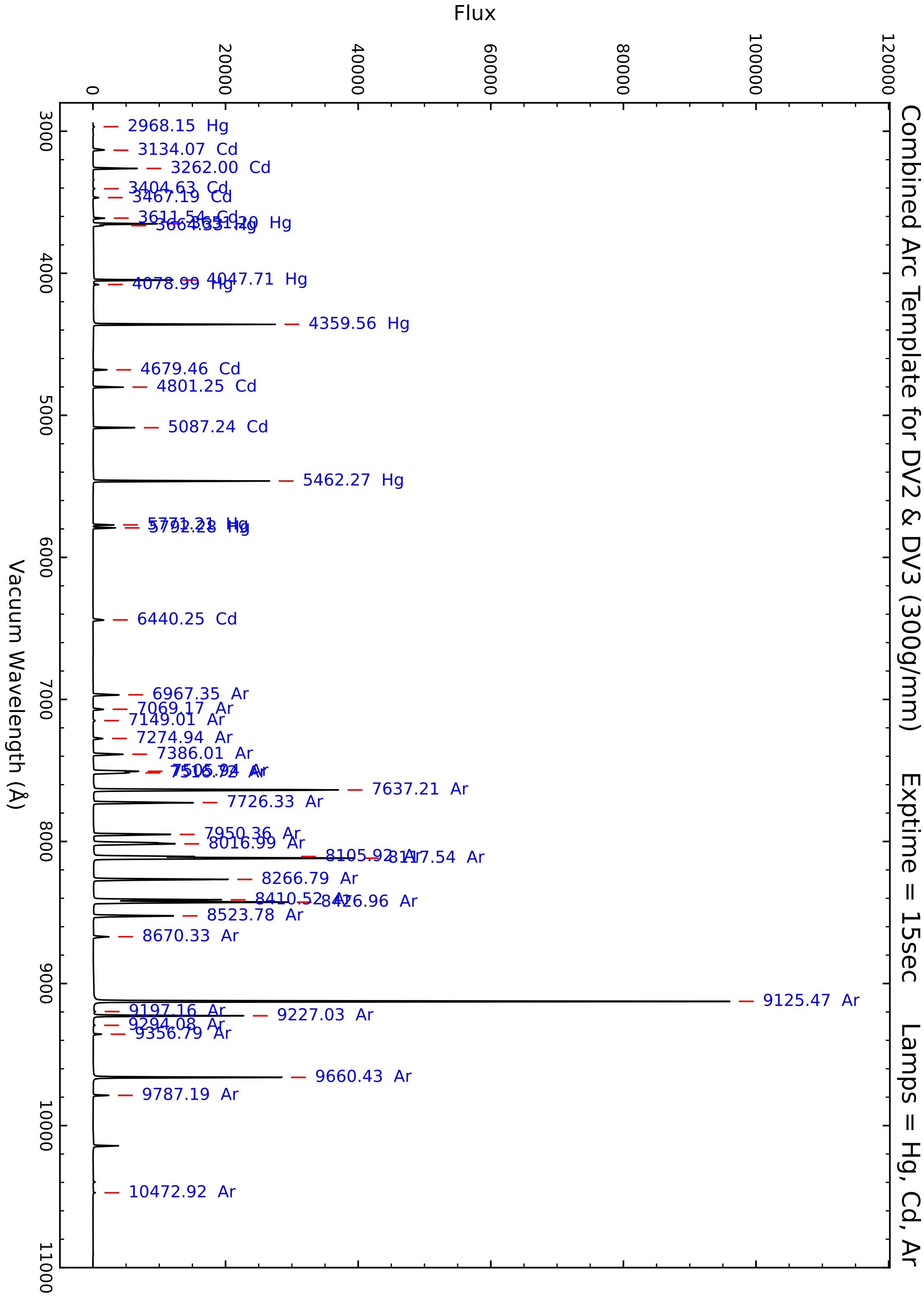


Figure 23: Line identification overview plot covering the wavelength range 2900 Å – 11,000 Å (taken with the DV2 & DV3 gratings). Enabled lamps: Argon, Mercury, and Cadmium. The OG570 blocking filter was used for the DV3 ($\lambda > 6000$ Å) portion of this template.

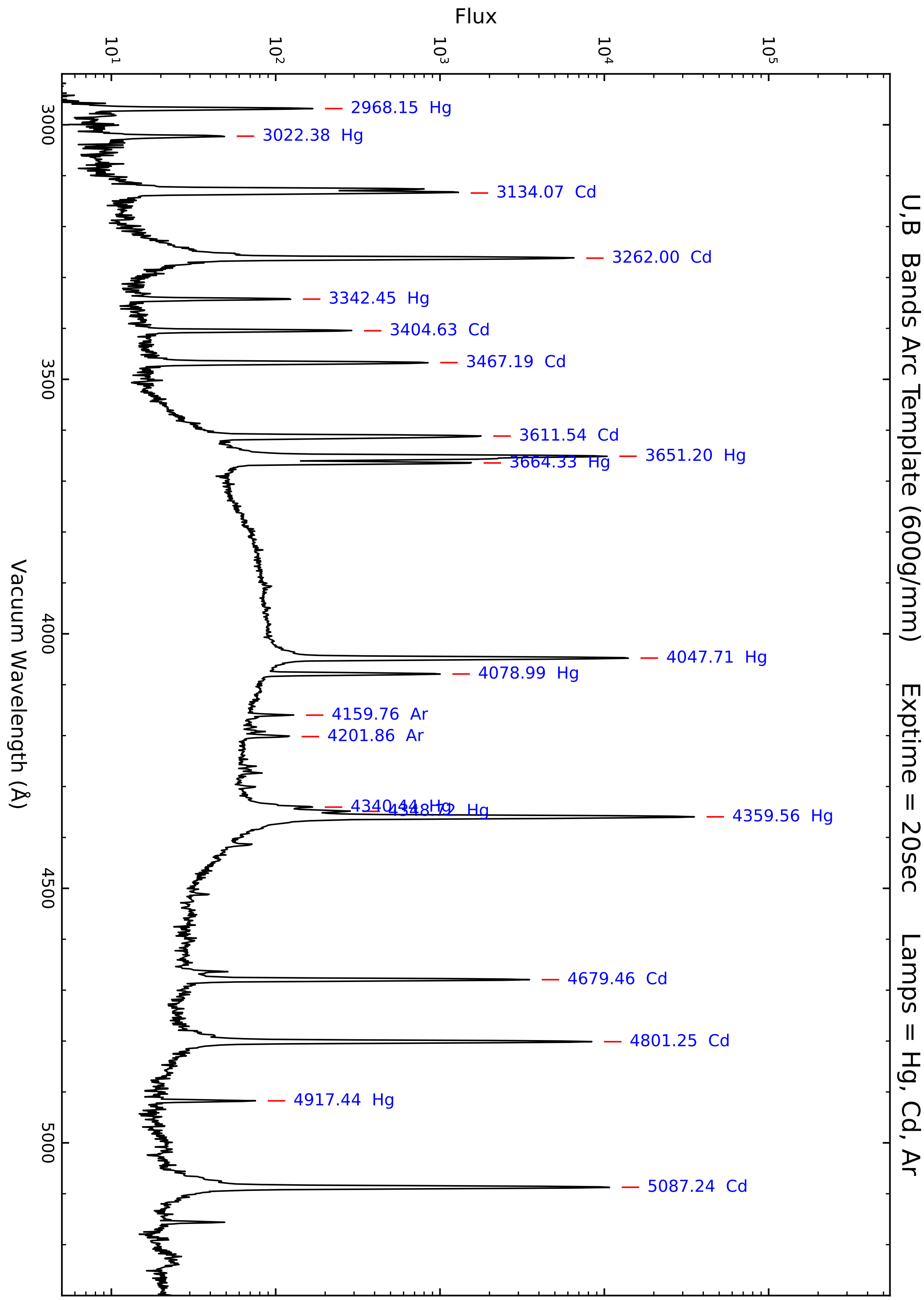


Figure 24: Line identification plot covering the wavelength range 2900 Å − 5300 Å (taken with the DV6 grating), shown on a log scale to emphasize weak lines. Enabled lamps: Argon, Mercury, and Cadmium. No blocking filter is in use.

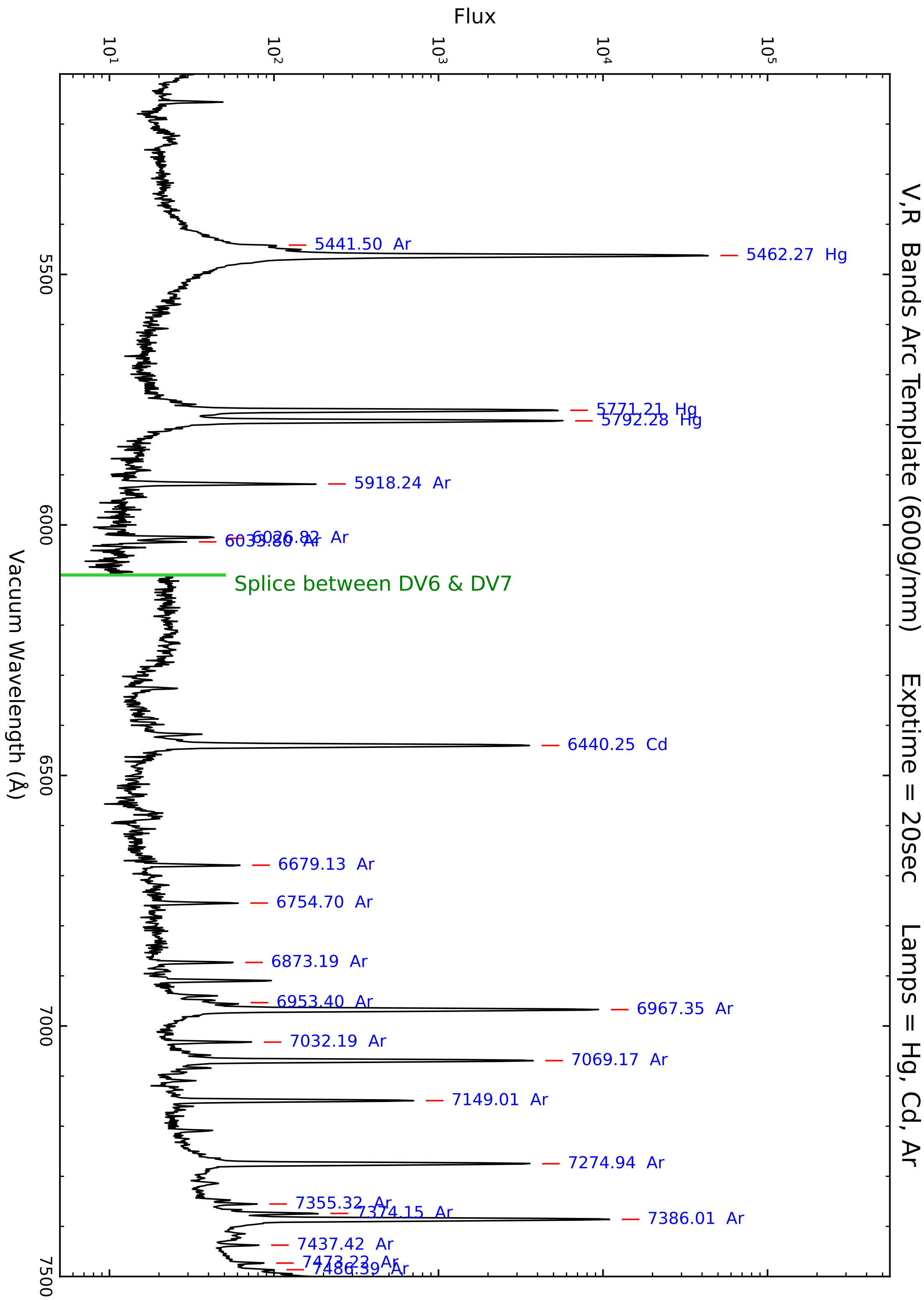


Figure 25: Line identification plot covering the wavelength range 5100 Å − 7500 Å (taken with the DV6 & DV7 gratings), shown on a log scale to emphasize weak lines. Enabled lamps: Argon, Mercury, and Cadmium. The OG570 blocking filter is in use for $\lambda > 6100$Å to limit lines to first-order spectra only.

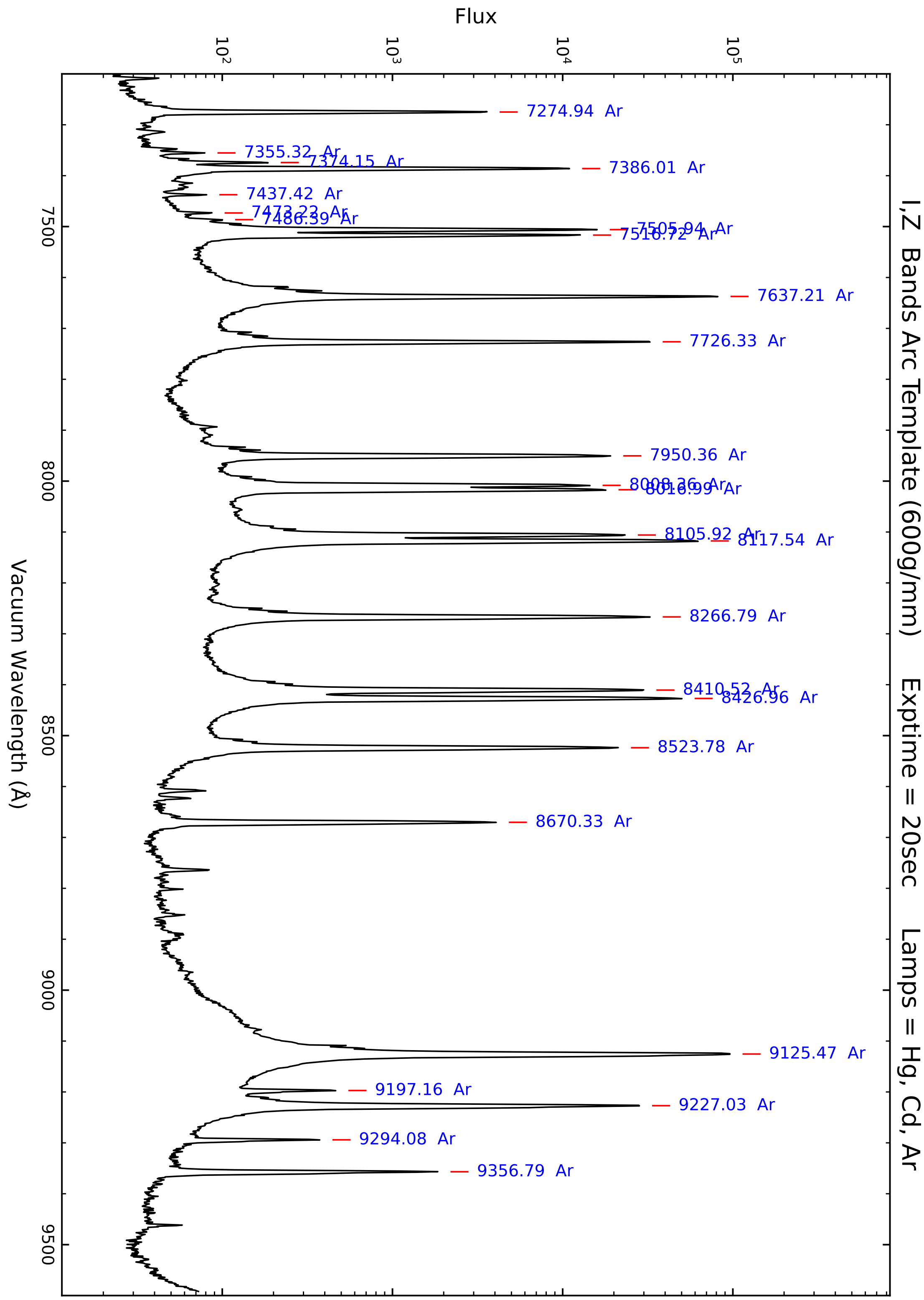


Figure 26: Line identification plot covering the wavelength range 7200 Å − 9600 Å (taken with the DV7 grating), shown on a log scale to emphasize weak lines. Enabled lamps: Argon, Mercury, and Cadmium. The OG570 blocking filter is in use to limit lines to first-order spectra only.

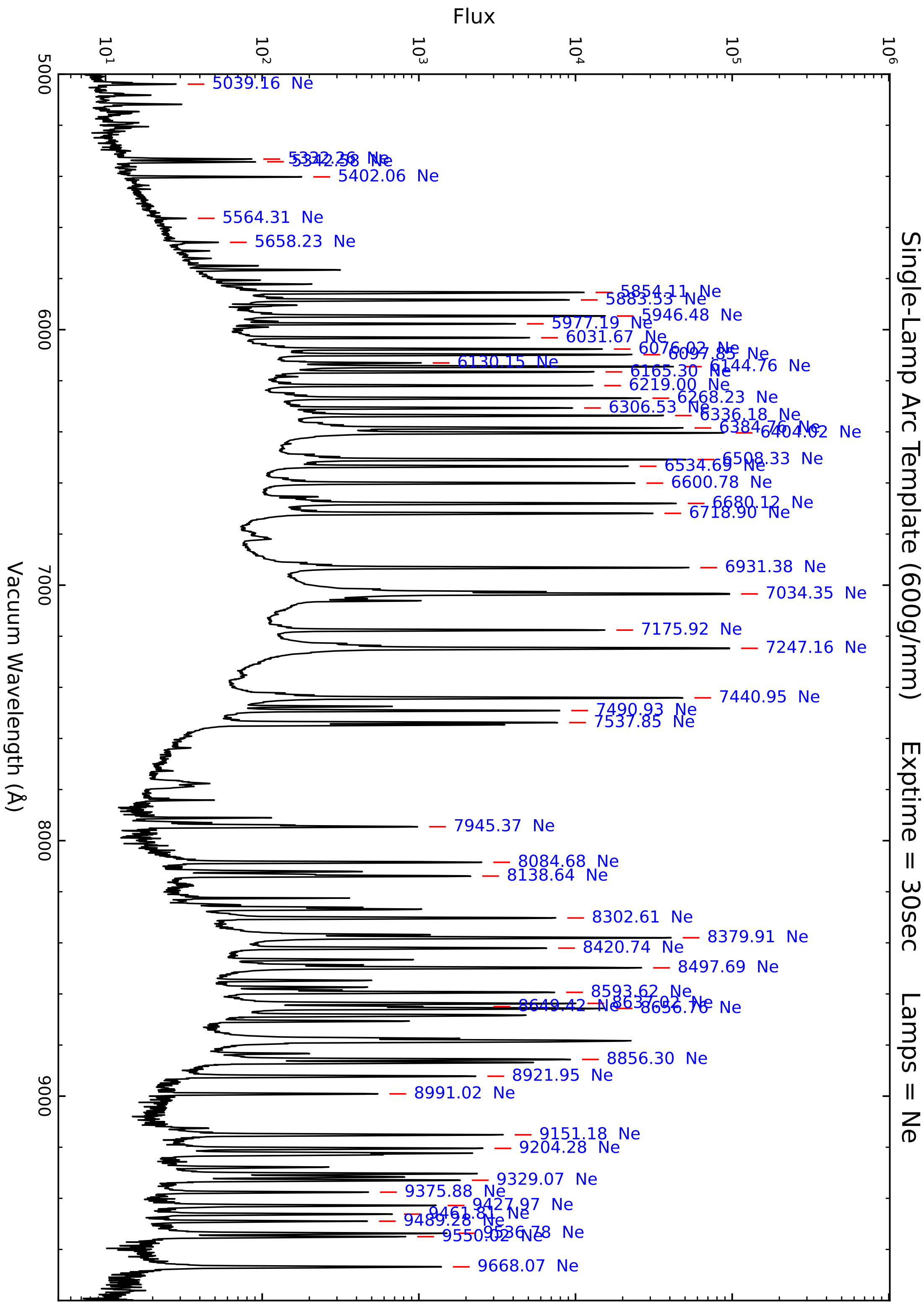
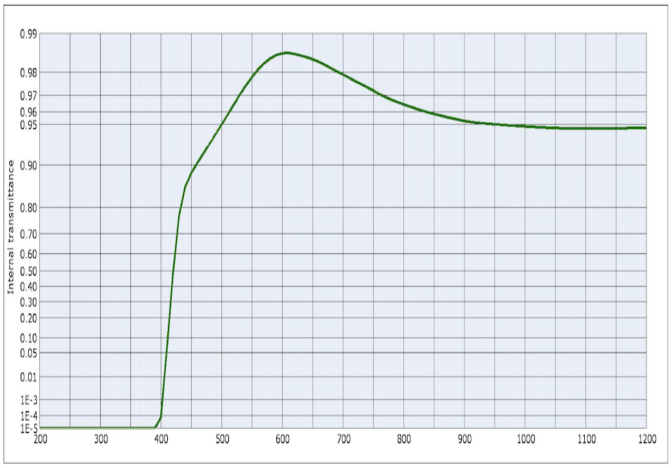


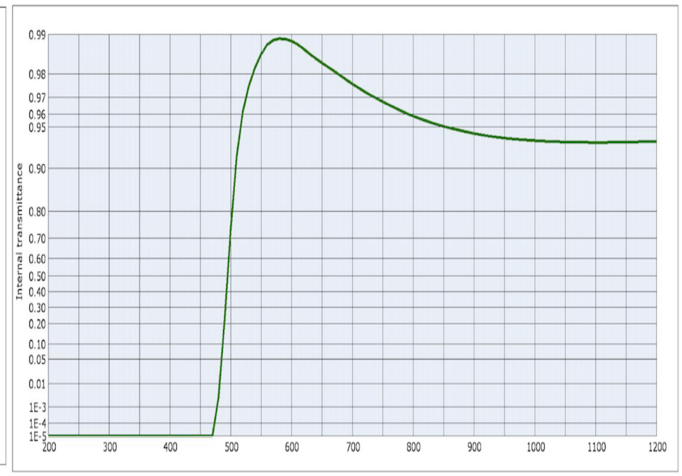
Figure 27: Neon-only line identification plot covering the wavelength range 5000 Å − 9800 Å (taken with the DV6 & DV7 gratings), shown on a log scale to emphasize weak lines. The GG420 (5900Å $< \lambda <$ 7850Å) and OG570 ($\lambda >$ 7850Å) blocking filters are in use to limit lines to first-order spectra only.

E Nominal Blocking Filter Data Sheets

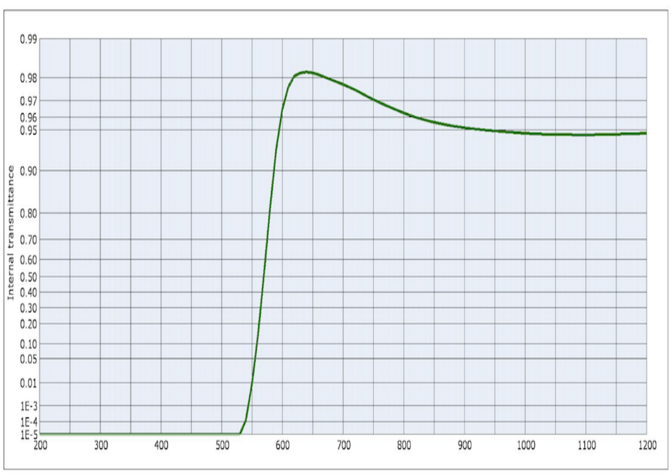
The data sheets in Figures 28a - 28d are from Schott to give a sense of the typical transmission curves for the blocking filters mounted in the rear filter wheel of the DeVeny spectrograph. We have not directly measured transmission of the actual filters in the spectrograph itself.



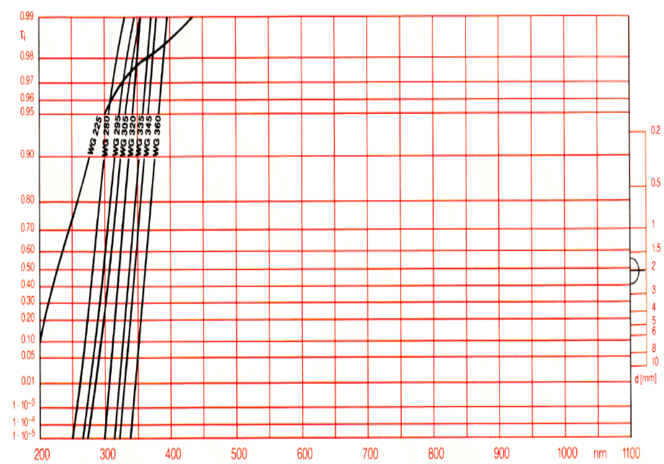
(a) GG420 filter transmission curve (from Schott).



(b) GG495 filter transmission curve (from Schott).



(c) OG570 filter transmission curve (from Schott).



(d) WG360 filter transmission curve (from KPNO).

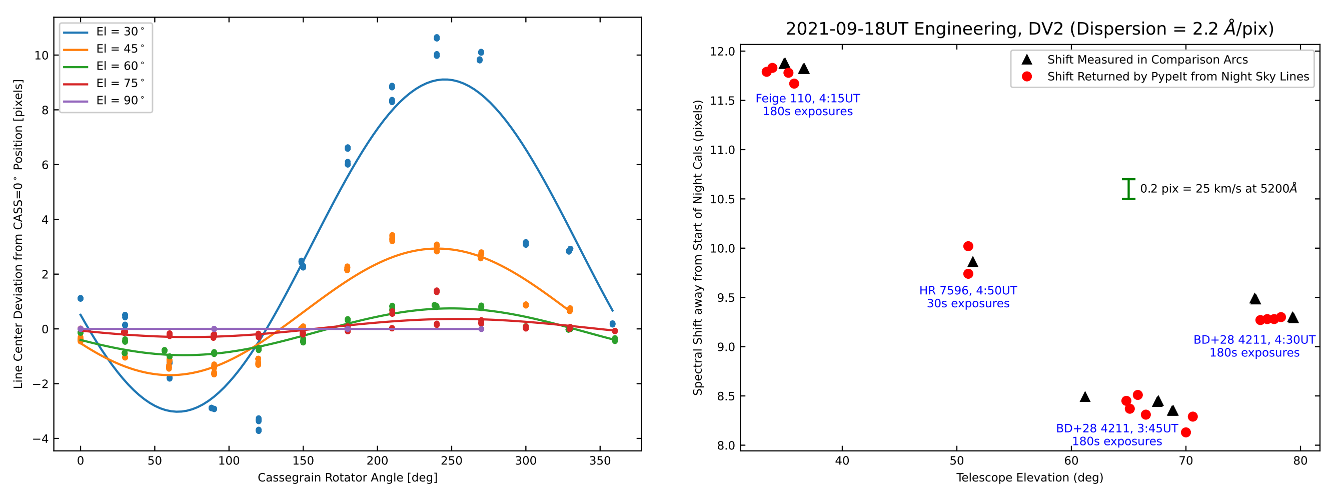
Figure 28: Transmission curves for order-blocking filters. Abscissa measured in nm.

F Compensating for Flexure in DeVeny's Camera

The current configuration of the DeVeny CCD camera causes relative motion between the spectral image and the CCD chip itself as the instrument's orientation changes with respect to gravity. Because DeVeny is mounted on one of the side ports of the LDT instrument cube, it has a fairly complex relationship with the gravity vector as the mount and rotator move. The specific cause of this motion is not fully understood, but it is indistinguishable from physical flexure of the instrument. The motion of the image on the CCD occurs in both the spectral and spatial directions, but is more pronounced (and is more problematic) in the former. Because the spectral image is oriented with the spectroscope slit along CCD columns, we can discuss the effects of the two motion directions independently.

F.1 Movement in the Spectral Direction

There is evidence of that the spectrum can shift position on the CCD by greater than ten pixels for different combinations of zenith distance and cassegrain rotator angle, as seen in Figure 29a. This can have significant impacts on the wavelength calibration of spectra if science data are only compared against the start-of-night, zenith-pointing arc frames. There are several methods to deal with this flexure:



(a) Spectral shift of arc lines as a function of telescope elevation and cassegrain rotator angle

(b) Comparison of directly measured and PypeIt-derived spectral line shifts away from zenith-pointing comparison arcs

Figure 29: (*a*) Example of arc line shifts in the spectral direction using the DV1 grating as a function of cassegrain rotator position angle. Points represent the measured average spectral offset of lines in a frame compared to their location in a frame when the cassegrain rotator is at 0°. Colored lines are a sinusoidal fit to the data, representing different elevation angles of the telescope; there is significantly more flexure at lower elevation (higher zenith distance). (*b*) Comparison of the shift in the spectral direction at various telescope angles from a direct measure of arc lines (black triangles) and the PypeIt-derived shift from night sky lines (red circles). Each cluster represents a set of science exposures where the telescope tracked a single object, and the time indicated is the rough midpoint of the observation set. For the entire collection of data, the telescope was used with a Fixed rotator at 180°, so shifts in the spectral position between observations are due entirely to flexure as a function of telescope elevation. Note that there appears to be some hysteresis as a function of elevation.

- ➢ If wavelength calibration to better than 10 pixels ($\sim$ 41Å for DV1, $\sim$ 11Å for DV6/DV7) is not required, no additional correction is needed.
- ➢ Arc frames may be taken at the sky location of science spectra (ask the TO to close the instrument cover), and these are correlated with the appropriate science frame during data reduction and analysis. For *in situ* comparison arc frames, keep in mind lamp stabilization times (Table 3, Fig. 18).
- ➢ If present, night sky lines may be used to either provide a full wavelength calibration, or at a minimum provide a shift to be applied to align the wavelength calibration and the science spectrum. (See §H.4.1 for a discussion of how this process works.)

For the second method, it is important to keep on top of comparison frames. If your observations hop from object to object across the sky, an *in situ* arc for each object is recommended. For objects very near each other (*e.g.*, members of a star or galaxy cluster), it may be possible to spread out comparison arcs, depending on the requirements of your science program.

The PypeIt spectroscopic data reduction package (see Appendix H) utilizes this last method for correcting spectral flexure in science frames with respect to either start-of-night arc frames (standard reduction) or *in situ* frames (advanced usage, §H.6). A comparison of direct measurement of spectral line positions with the PypeIt-derived shift (against the start-of-night frames) is shown in Figure 29b. In short, the two methods agree to within a few tenths of a pixel ($<$ 1Å for any grating), with better agreement for longer science exposures (stronger night sky lines). The advantage of this method is the time saved in not taking comparison arc frames (including lamp warm-up). Before committing fully to this method, however, understand your project's science requirements and inspect your science frames as you take them to ensure the presence and usability of night sky lines.

F.2 Movement in the Spatial Direction

In addition to the spectral-direction flexure, the slit image moves several pixels in the spatial (along-the-slit) direction as a function of telescope position. Where this motion will cause problems is in correcting for the illumination function along the slit for accurate flux calibration.

While designed to be so, the slit jaws are not perfectly smooth and dust-free. A slit width of 1″ means the jaw are separated by only 0.153 mm = 153 μm. A particulate grain that occludes just 3 μm of the slit will block 2% of the light at that location – a small but noticeable amount. To illustrate this issue, the top panel of Figure 30 shows the *illumination function* of the slit as seen with the DV3 grating on 2021-10-31UT. An illumination function is generated by flattening the spectrum along the spectral axis, removing variations as a function of color. As seen in the figure, there are variations of up to $\sim$ 2% within the central rows of the slit.

Fortunately, flatfielding takes care of the illumination function. The catch is that, like a wavelength calibration, a dome flat frame from the start of the night will not necessarily have the telescope in the same orientation as the science object of interest. The illumination function can shift several pixels away from its position when the telescope is pointed at the dome flat screen.

This whole discussion is connected to flux calibrating spectra – the process of converting the counts in your image into physical units by comparing science frames with same-night spectra of spectrophotometric standard stars taken at similar airmass. If your program requires accurate (better than 2%) flux calibration, you may decide to measure the illumination function at the position of your science target. Ask your TO to rotate the dome in front of the telescope and turn on the top-ring lamps. The light reflected from the inside of the dome structure will not be as bright as off the dome flat screen, but will be enough to measure the spatial flexure at that location.

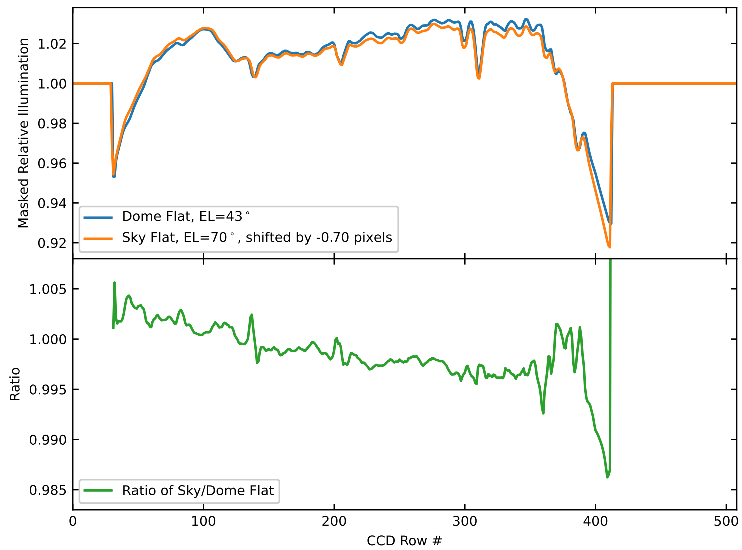


Figure 30: Slit illuminations functions for dome and sky flats for the DV3 grating. Data taken 2021-10-31UT. In the top panel, the sky flat (orange) was shifted by -0.7 pixels to align the features in the illumination functions. The bottom panel shows the ratio of sky:dome flat illumination functions to gauge the differences between sky illumination (identical to science frames) and that cast by the cloverleaf pattern of the top-ring lamps. Answer: they generally match to within 0.5%.

G Grating and Collimator Physics

G.1 The Grating Equation

The angles at which the diffracted light reflects off the grating are given by the grating equation:

$$m\lambda = d(\sin\theta_i - \sin\theta_m) \ , \tag{5}$$

where d is the spacing between adjacent grooves on the grating, θ_i is in the incident angle $\alpha = \theta_{\rm grangle} + \theta_{SCG}$, and θ_m is the outgoing angle $\beta = \theta_{CGC} - \alpha$ for light with wavelength λ diffracting into order m (see Fig. 16 and §7.1 for a description of these angles). The DeVeny gratings are typically operated in $1^{\rm st}$ order ($m = 1$), although use of $m = 2$ is possible with the proper short-pass order-blocking filters to remove $1^{\rm st}$-order light.

The graphical routine `deveny_grangle` (§4.2.2) computes the necessary tilt $\theta_{\rm grangle}$ from Equation (6) numerically for a given grating. The computation uses the groove density (g/mm) in place of d, and finds $\theta_{\rm grangle}$ for a specified $1^{\rm st}$-order central wavelength (λ_c) in Angstroms on the spectral CCD.

$$\lambda_c = \frac{\sin(\theta_{\rm grangle} + 10^\circ) - \sin(45^\circ - \theta_{\rm grangle})}{\rm g/mm} \times 10^7 \tag{6}$$

G.2 Anamorphic Demagnification

The rays hitting the grating in the plane of α and β diffract to the camera in such a way that the beam width changes as a function of α and β, whereas rays incident on the grating in the perpendicular plane have the same beam width upon incidence and reflection (see Fig. 31). Because there is a difference between the beam widths for the two planes, there will be different magnification levels (Schweizer, 1979). Whenever perpendicular planes have different magnifications, this is called "anamorphic" (de)magnification. Schweizer (1979), however, thinks the term "anamorphic magnification" is somewhat inaccurate, and prefers "grating magnification". Historically, the DeVeny manuals and associated code (*e.g.*, `deveny_grangle`) use "anamorphic", so we continue that there. The resulting magnification in the direction of dispersion due to the grating, r, arising from differentiation of the grating equation (5), is:

$$r \equiv \frac{d\beta}{d\alpha} = \frac{\cos\alpha}{\cos\beta} \tag{7}$$

(Schweizer, 1979). Practical spectrograph design aligns the slit perpendicular to the dispersion direction, and so the change in magnification is in the direction of the slit width, hence our quoted "anamorphic demagnification of slit width".

Delving a little deeper into the angles involved in the spectrograph, we can define an intrinsic tilt $t \equiv \theta_{\rm grangle} - 17\overset{\circ}{.}5$ that defines how the grating is tilted with respect to specular ($m = 0$) reflection (see §7.1). In terms of this intrinsic tilt, therefore, the incident and reflected ray angles become

$$\begin{aligned} \alpha &= \theta_{\rm CGC}/2 + t \\ \beta &= \theta_{\rm CGC}/2 - t \ , \end{aligned} \tag{8}$$

and the grating magnification may be written as

$$r = \frac{\cos(27\overset{\circ}{.}5 + t)}{\cos(27\overset{\circ}{.}5 - t)} \ . \tag{9}$$

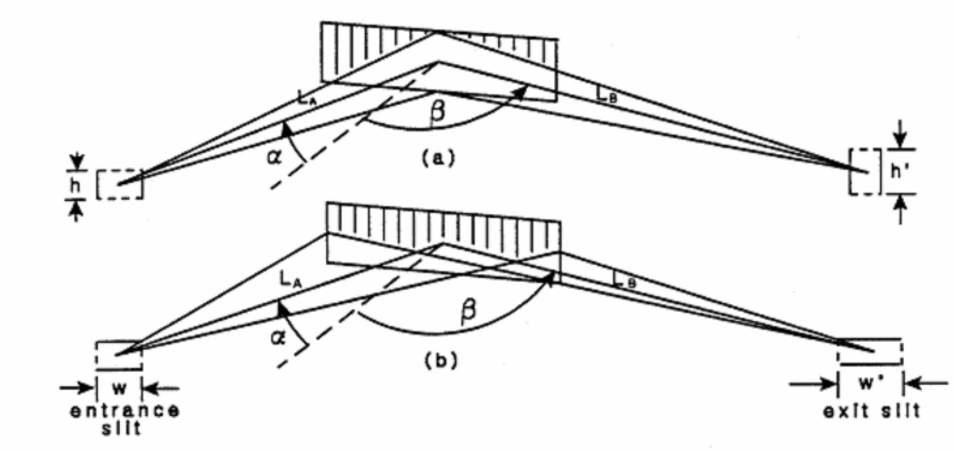


Figure 31: Anamorphic demagnification (Learner & Thevenon, 1988).

It is readily apparent from Equation (9) that the sense of the grating tilt away from specular reflection yields either a magnification or demagnification, with a positive tilt resulting in $r < 1$.

Operationally, how does this inform observation planning? To maximize spectral resolution, the slit should be as narrow as possible, but still wide enough to accurately sample the spectrum with the pixels of the detector. The narrowest a fully sampled monochromatic image of the slit should be is 2.5 - 3.0 pixels, which is why this value is used for the collimator focus procedure (§4.2.7). Nominally, the plate scale at the spectral channel CCD is $0.34''$/pixel, or 2.94 pixels/$''$. If the spectrograph were operated at $t = 0$, a $1''$-wide slit would subtend 2.94 pixels on the detector. As seen in Table 2, however, the DeVeny spectrograph is designed to operate with $20^\circ \lesssim \theta_{\rm grangle} \leq 48^\circ$, or $t > 0$.

As an example, let us consider the use of the DV8 grating (831 g/mm) at a central wavelength of 8000Å. According to Equation (6) or Table 2, this requires $\theta_{\rm grangle} = 39\overset{\circ}{.}51$. From Equation (9), we find $r = 0.65$, which means that a $1''$ slit will appear only $0\overset{''}{.}65$ (1.91 pixels) across. In order to fully sample the slit, it may be opened to $1\overset{''}{.}5$ and not lose spectral resolution on the CCD. The upshot is that the observer may collect 1.5× as much light without sacrificing spectral resolution, as compared to not considering the anamorphic demagnification. As noted by Schweizer (1979), "Of course, this increased throughput of light at a given resolution is one of the main reasons why spectrographs are designed for use with positive grating tilts."

For convenience, the python GUI application `deveny_grangle` (Fig. 6) computes the demagnified inverse plate scale (pixels/$''$) for you to aid in choosing a slit width for fully sampled spectra.

G.3 Details on Collimator Focus

There are two points to discuss here about the collimator focus on DeVeny. The first empirical, the second an explanation of optical principles.

The first is an explanation of the empirical fit used to construct Equation (2) for estimating the center of the collimator focus script. Collimator focus is a function of grating tilt (the optical path length for the ray striking the center of the detector changes with tilt angle), temperature (thermal expansion of the spectrograph body), and the presence of an order-blocking filter (change in optical path length due to refraction). To predict appropriate values, an analysis of DeVeny focus settings versus these three variables

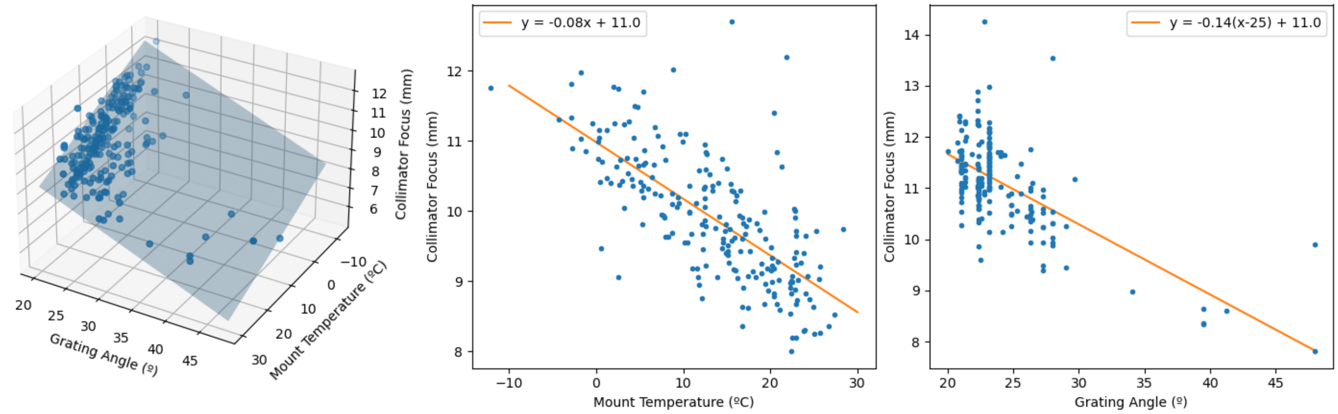


Figure 32: Collimator focus fitting. *Left:* Scatter plot of all 212 focus values from 2017 − 2020 used for this analysis, shown at each's grating angle and mount temperature. The shaded surface shows the planar fit to the data enshrined in Equation (2). *Center:* Linear fit of collimator focus versus mount temperature, with the grating angle component already fit out. *Right:* Linear fit of collimator focus versus grating tilt angle, with the mount temperature component already fit out. (As a side note, this plot indicates the relative popularity of DeVeny's low-dispersion gratings, operated at $\theta_{\rm grangle}$ between 20° and 28° – see Table 2.)

for all data from 2017 − 2020 was completed. The data were fit with a linear trend in each of temperature and grating angle, plus a Kronecker delta for filter presence, to produce an approximate center point for the focus script (Eqn 2).

While there is appreciable scatter in these data about the fit (the standard deviation of the residuals is 0.65 mm), a focus sweep of 7 − 11 0.5-mm steps centered on the computed focus from Equation (2) will span 3 − 5 mm and should easily encompass the true focus. The focus data shown in the left panel of Figure 32 were taken from archival data representing many different programs and observers over several years, and only the applied collimator focus value was used. A refit of the individual focus sequence data was not attempted.

Of note is the strong relationship between mount temperature and collimator focus – observers should be cognizant of changes in temperature between initial collimator focus and on-sky observing.

The second point to be discussed relates to the fact that spectrographs are inherently astigmatic systems, and the location of optimal focus is not the minimum of the focus curve.

The very existence of an anamorphic magnification caused by diffraction off the grating means that rays from the (perpendicular) spectral and spatial planes will come to a focus at different places. This is the very definition of astigmatism. In the illustration of Figure 33, our spectral dimension would be the blue "Tangential Focus", and the spatial dimension would be the green "Sagittal Focus". In such situations, it is common to find the "least bad" focus as a compromise between getting sharp tangential focus (with smeared out sagittal information) and sharp sagittal focus (with smeared out tangential information). We lose a little of both to balance out.

The question then arises, "To which side of spectral best focus is the optimum?" Testing with a pinhole mask over wide-open slit jaws showed that focus in the spatial direction occurs at larger collimator focus values than the spectral direction. The python routine `dfocus` (§4.2.7) therefore, marks (in blue) the collimator focus value where the spectral line FWHM is equal to the optimum value on the *larger side* of the minimum of the fitted parabola (marked in red; see Fig. 8).

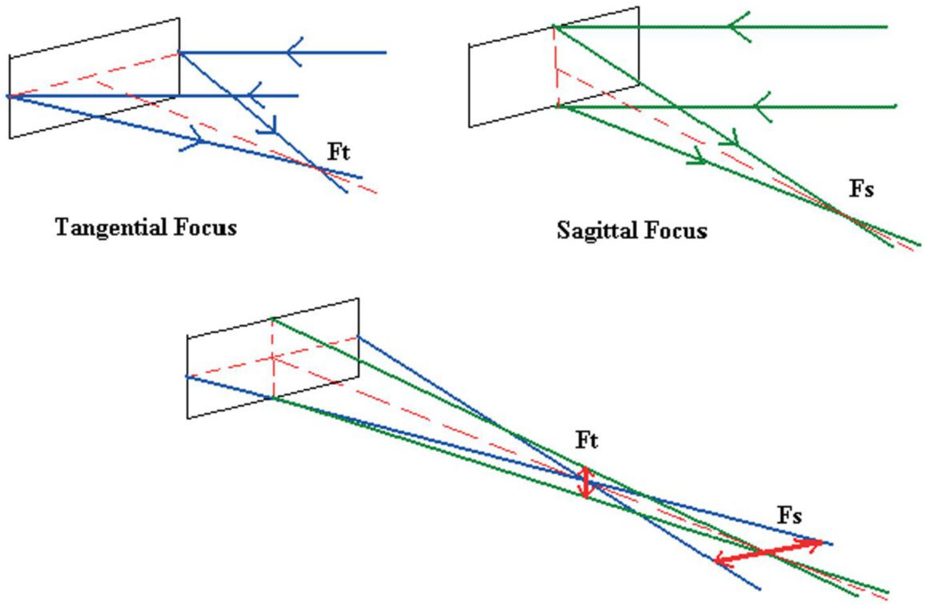


Figure 33: Astigmatism (Learner & Thevenon, 1988).

This is, it should be noted, a one-size-fits-all approach – the needs of individual observing programs may differ. For instance, there could be some situations where one would want sharp spectral focus at the expense of spatial resolution (brighter stars, for instance), some situations where spatial focus is more important than spectral resolution (galaxies maybe, or faint solar system objects), and situations where the default compromise is best (fainter objects, for which photons should not be smeared out too much spatially, but spectral resolution is also important). A future upgrade to the decker plate and slit jaws will include pinhole apertures to test optimum spatial and spectral foci and may be used by observers to configure the instrument for the specific needs of their science program.

References

Learner, J., & Thevenon, A. 1988, Jobin-Yvon Optical Systems/Instrumentss SA, 48, 1198

Schweizer, F. 1979, PASP, 91, 149

H Using PypeIt: A Python Spectroscopic Data Reduction Pipeline

H.1 Brief Introduction to PypeIt

PypeIt[5] is a Python package for semi-automated reduction of astronomical spectroscopic data, built on decades-long development of previous data reduction pipelines by its developers. It is highly configurable and designed to be applied to any standard slit-imaging spectrograph, and the configuration parameters of the DeVeny Optical Spectrograph have been contributed to the code base by LDT staff. The reduction procedures for use with DeVeny data are provided by this Appendix.

PypeIt is a set of commands designed to perform spectroscopic data reduction without any additional coding. It is designed to be used by both advanced spectroscopists with prior data reduction expertise and astronomers with no prior experience of data reduction. If you use this tool to process your data, the developers request you cite the relevant publications specified on the PypeIt documentation home page.

For interactive troubleshooting, there is an active PypeIt Users Slack (get access code here), including a `#ldt-deveny` channel.

H.2 Installing PypeIt for Reducing DeVeny Data

The `LDT_DeVeny` configuration parameters described herein are included with PypeIt v1.9.0 and later,[6] and the released package may be installed via your favorite method. Complete instructions are available in the PypeIt documentation, but brief outlines are provided here. The three main ways to install PypeIt are:

1. **`conda`**: Download the PypeIt environment file: `environment.yml`, then use `conda` to create and activate a virtual environment called `pypeit` that contains `pypeit` and all of the required dependencies:

   ```
   conda env create -f environment.yml
   conda activate pypeit
   ```

   Verify that the new environment was installed correctly and contains `pypeit`:

   ```
   conda env list
   ```

2. **`pip`**: First create a virtual environment to contain PypeIt and its dependencies:

   ```
   virtualenv pypeit source pypeit/bin/activate
   ```

   Then, install the latest release of PypeIt and its required dependencies:

   ```
   pip install "pypeit[pyqt5,bottleneck]"
   ```

3. **`git`**: Create a `virtualenv` as above, then clone the GitHub source code repository and follow the instructions in the PypeIt documentation.

Once you have installed the package, test to be sure the main driver script `run_pypeit` runs. Go to a directory outside of the PypeIt directory (*e.g.*, your home directory) and run the main executable:

```
cd
run_pypeit -h
```

This should fail if any of the required dependencies are not satisfied. See the online documentation for troubleshooting.

[5] https://pypeit.readthedocs.io/en/latest/

[6] The original `LDT_DeVeny` configuration was introduced in v1.4.2. It was updated with added features in v1.8.0, and with more complete wavelength calibrations in v1.9.0.

H.3 Using PypeIt

This section details how to use PypeIt with DeVeny data. It is paraphrased from the PypeIt documentation. See `https://pypeit.readthedocs.io/en/latest/cookbook.html` for complete and detailed instructions.

NOTE: Before you get too far, it is important to understand that PypeIt reorients all 2D image data (from any spectrograph) so that the spectral axis is vertical with increasing wavelength corresponding to increasing pixel number. In the case of DeVeny data, this amounts to a 90° CW rotation of the images with respect to the original files. Don't Panic!

⇒ There is a "cheat sheet" of common DeVeny PypeIt workflows listed in §H.7.

H.3.1 Planning Your Observations for Reduction with PypeIt

Because PypeIt is an automated data reduction pipeline with minimal opportunity to interact with the reduction in progress, pre-telescope planning is required to obtain the proper calibration frames. While most observing programs will already collect all of the frames necessary for smooth operation of the pipeline, several items bear pointing out:

- Bias frames are used to remove fixed-pattern noise in the data, and also used to generate the default bad pixel mask for reductions.[7]
- Dome flats are used for the dual purposes of removing pixel-to-pixel variations in sensitivity, and tracing the edges of the slit (which can vary from grating to grating, and will be more apparent following the future installation of the decker – §4.2.6).
- Twilight sky flats may be used to correct for the illumination function along the slit if your science program involves extended objects where accurate flux calibration along the slit is required. (NOTE: PypeIt will create an illumination function from dome flats, and these closely match the illumination pattern of the top-ring lamps – §F.2. Note, however, that spatial flexure movements are not currently compensated for.)
- Wavelength calibration is the piece most likely to cause headaches for any spectroscopy program. The user needs to decide which combination of lamps (§4.3.2) will provide suitable calibration for their program. PypeIt performs a simple combination of specified arc frames into a single `MasterArc`. While it is sometimes possible to combine frames taken with individual lamps (*e.g.*, Hg frames and Ar frames), the results are not as clean as simply turning on all desired lamps together.

  The selected slit width also plays into how well PypeIt matches the `MasterArc` spectrum with the corresponding line lists. While it is sometimes possible to attempt calibration on arc frames taken with a wide slit opening ($\gtrsim 2''$), for best results use arc spectra taken with an optimal slit width (§4.2.3) to ensure matching by the automated algorithms.

  Additionally, because of the spectral-direction flexure of the DeVeny camera (Appendix F), **do not attempt** to combine comparison arc frames from different telescope positions. The shift in line positions will create a hot-mess `MasterArc` frame and the wavelength calibration will fail. PypeIt's flexure-correction algorithm (see §H.4.1) uses night-sky lines to adjust the wavelength calibration for

[7] PypeIt does have a (somewhat cumbersome) mechanism for accepting pre-existing bad-pixel masks, but the DeVeny CCD is very clean and the BPM procedure is fast.

individual science frames, so the use of *in situ* arcs may not be necessary. It is, however, possible to correlate individual science frames with individual arc images, and this is discussed under Advanced Usage (§H.6.1) – if you go this route, we suggest you also compare it with the single-pointing arcs and PypeIt's flexure correction and let LDT staff know how well they do.

As of v1.9.0, complete wavelength templates using the Hg, Cd, and Ar lamps are available for the 150g/mm (DV1), 300g/mm (DV2, DV3), 600g/mm (DV6, DV7), and 1200g/mm (DV9) gratings. PypeIt will automatically match `MasterArc` spectra from these gratings against the appropriate template using the `full_template` method. It is possible that the other gratings (namely DV4, DV5, and DV8) can match one of these templates using the `reidenitfy` method, but that has not been tested at this time.

- At present, only the gratings DV1, DV2, DV5, DV6, and DV8 have been tested with PypeIt – suitable data sets from the other gratings were not available for test. It is quite likely PypeIt will work smoothly with the other gratings, but be sure to very carefully examine the results of your reduction to ensure expected results. Also, please contact LDT staff to share your test calibration data with the wider user base.
- To ensure your calibrations will work with PypeIt, test the pipeline on a preexisting data set whose calibration frames were taken in the same way you expect to take them. If this testing is done ahead of time, it will save much frustration later. It is also possible to run the pipeline on your observing night to ensure you have collected a workable calibration set.

H.3.2 Organize the Data to be Reduced

Download a single night's data from `dct-obs1` / `dct-obs2` to your reduction machine, as described in §6.3. The easiest method is using secure copy (`scp`), but feel free to use whatever method you prefer.[8]

Be sure your data directory includes bias, flat field, and arc lamp comparison frames taken using the same grating, tilt, and rear filter settings as your science data. Delete frames from focus runs, as these have already served their purpose (the `dfocus` task, §4.2.7) and may adversely affect your wavelength solutions. What should remain are:

- Bias frames (to remove fixed-pattern noise from the data)
- Dome Flat frames (to remove pixel-to-pixel sensitivity variations)
- Comparison Arc frames (for wavelength calibration) – All taken at the same telescope position!
- Science frames (the whole point)

Optionally, depending on the science requirements of your program, you may also include:

- Sky Flat frames (to correct for variations in illumination along the slit)
- Standard Star frames (for flux calibration)

This folder will be referred to henceforth as `RAWDIR`, and the reduced data are contained in subdirectories.

[8] *e.g.*, https://tools.ietf.org/html/rfc1149

H.3.3 Setup

NOTE: All PypeIt command-line scripts (*e.g.*, `pypeit_setup`) have online help available using the `-h` option.

Running PypeIt on a set of data is controlled by a PypeIt Reduction File that details what the software should do to each file along the way to producing reduced and calibrated data. The package provides a script `pypeit_setup` that reads through the FITS headers in `RAWDIR` to generate the reduction file based on what it finds. PypeIt defines unique instrument configurations, and sorts data in preparation for the data reduction.

For DeVeny data, instrument configurations are defined by unique combinations of the grating (FITS keyword `GRATING`), central wavelength defined by the grating tilt angle (`GRANGLE`), rear order-blocking filter (`FILTREAR`), and CCD binning (`CCDSUM`). PypeIt maps the various DeVeny FITS keywords onto a set of internal metadata keys for processing. The relevant PypeIt metadata keys for DeVeny configurations (which you will see in your reduction files) are:

```
Metadata Key   FITS Header
------------   -----------
    dispname       GRATING
     cenwave       GRANGLE
     filter1      FILTREAR
     binning        CCDSUM
```

`pypeit_setup` The script `pypeit_setup` will automatically associate your data files with specific Frame Types (used internally for different calibration steps) and collect groups of images by unique instrument configurations. The step-by-step procedure for using `pypeit_setup` is:

0. **Prepare**

   Change your working directory to the one where you wish the reduced data subdirectories to appear (henceforth `WORKDIR`). Because you can specify the location of `RAWDIR` to `pypeit_setup`, you may place your reduced data in the location of your choosing.

1. **First Execution**

   You will run the script twice. The first run will produce the skeleton files that should be inspected to ensure the code has properly divvied up the FITS files into the proper configuration(s). For most DeVeny programs (*i.e.*, a single grating tilt and rear filter used with the installed grating), `pypeit_setup` should find a single instrument configuration.

   Run the script the first time thuswise:

   ```
   pypeit_setup -s ldt_deveny -r <path_to_your_raw_data>
   ```

   where the command-line options are:

   `-s`: Sets the spectrograph configuration parameters (required).

   `-r`: Sets the full path to the raw data. (Only required if `WORKDIR` is not `RAWDIR`.)[9]

[9] The command-line arguments may use absolute or relative paths as well as shell shorthand (*e.g.*, `~/mydata`).

This execution of `pypeit_setup` searches for all `*.fits` files within `RAWDIR`.[10]

2. **Inspect the Outputs**

   The call above creates three files in the `WORKDIR/setup_files/` subdirectory:

   `ldt_deveny_{date}.pypeit`: Dummy file – can be ignored.

   `ldt_deveny_{date}.obslog`: Observing log, generated from the FITS headers.

   `ldt_deveny_{date}.sorted`: Shows unique configurations and associated image frames.

   where `{date}` is the local date `pypeit_setup` was run and the file created (this is meant for the user's housekeeping).

   `.obslog` file:

   This file should somewhat resemble your own time-ordered observing log for this set of data, with the relevant FITS keywords mapped to their PypeIt metadata keys. This is a good time to ensure that all the files you expect to see are in fact present.

   Any remaining collimator focus frames (identified with FITS header keyword `IMAGETYP = FOCUS`, see Fig. 2 #4) will have a `frametype` listed as `None` in this file. If you have already removed your *bona fide* focus files from `RAWDIR`, and there are frames listed here with `frametype None`, this indicates the FITS keyword `IMAGETYP` was not correctly set. You may either modify the affected FITS headers using your preferred method, or simply note the affected frames and later edit the relevant PypeIt Reduction File(s) (§H.3.4) with the correct frame type. If you modify any FITS headers directly, re-run step #1 above, and reexamine the output `.obslog` file.

   `.sorted` file:

   The `.sorted` file is divided into sections enumerating the unique instrument configurations and the list of frames associated therewith. Each unique configuration is given a capital letter identifier (*e.g.*, A, B, C, D...).

   Below are example headers from a `.sorted` file for LDT/DeVeny data taken with two different order-blocking filters on the same night:

```
##########################################################
Setup A
     dispname: DV1 (150/5000)
      cenwave: 7220.0
      filter1: Clear
      binning: 1,1
```

[10]You may specify a file extension other than `.fits` by using the `-e EXTENSION` argument to `pypeit_setup`.

```
###########################################################
Setup B
     dispname: DV1 (150/5000)
      cenwave: 7220.0
      filter1: OG570
      binning: 1,1
```

This `.sorted` file contains two configurations, `A` and `B`, and the "setup blocks" (shown above) describe the instrument configurations based on the relevant metadata. Each "setup block" is followed by a table listing the files and relevant metadata for all files matched to that instrument configuration (not shown – very wide table).

PypeIt does not use the `.sorted` file to guide reductions, but it is provided as a means for the user to assess the automated setup identification and file sorting. You may recognize that you are missing calibrations or you may be surprised to see more configurations than you were expecting. If, at the start of your observing session, you did not select the grating or rear filter in the LOUI before taking exposures (§4.1.6), those frames will have `UNKNOWN` listed in the associated header field. In this case, you will likely have spurious instrument configurations – go back and edit the FITS headers with the proper values and rerun step #1 above.

Importantly, you should use the `.sorted` file to decide which configuration(s) you wish to reduce. Any changes made to this file, however, are not recognized by Pypeit. All user-level edits to the frame-typing, association of frames with given configurations, etc., must be done via the PypeIt Reduction File (§H.3.4).

3. **Second execution**

   Provided you are happy with the `.sorted` file, you are ready to write the `.pypeit` file for one or more setups. Executing the `pypeit_setup` script a second time with the `-c` option will generate one or more sub-folders and populate each with a PypeIt Reduction File. Some example uses of the `-c` option are:

   `-c A`: This will generate one folder/file for configuration `A`

   `-c A,C`: This will generate a folder/file for each of two configurations (`A` and `C`)

   `-c all`: This will generate folders/files for all identified configurations in the `.sorted` file

   An example execution that only produces the PypeIt Reduction File for the `A` configuration is:

   ```
   pypeit_setup -s ldt_deveny -r <path_to_your_raw_data> -c A
   ```

   This will generate a subfolder `WORKDIR/ldt_deveny_A/` containing the base PypeIt Reduction File `ldt_deveny_A.pypeit`.

H.3.4 Edit Your PypeIt File

The PypeIt Reduction File dictates how the pipeline is executed for the files in `RAWDIR`. It is expected to end with `.pypeit` and has a very specific format (discussed below). While the file is automatically generated by the `pypeit_setup` script, it can (and should) be edited by the user to ensure the reduction happens as expected.

Each unique instrument configuration will have its own PypeIt Reduction File. In the case of DeVeny, this means different rear filters, grating tilt angles, binning schemes, or even different gratings used on different nights. This section describes the file format and the edits a user may wish to make.

File Format Here is an example edited PypeIt reduction file:

```
# Auto-generated PypeIt file using PypeIt version: 1.9.0
# 2022-05-02

# User-defined execution parameters
[rdx]
  spectrograph = ldt_deveny
[reduce]
  [[findobj]]
    sig_thresh = 3.0

# Setup
setup read
    Setup A:
        dispname: DV2 (300/4000)
         cenwave: 5195.0
         filter1: CLEAR
         binning: 1,1
setup end

# Read in the data
data read
 path /home/observer/data/20210522a
|          filename |       frametype |       ra |     dec |      target |        mjd | airmass | exptime | cenwave | filter1 | slitwid | lampstat01 |
| 20210522.0057.fits |        arc,tilt | 235.9294 | 36.8143 | HgCdAr Arcs | 59356.1319 |    1.49 |    20.0 |  5195.0 |   Clear |     1.1 | Cd, Ar, Hg |
| 20210522.0058.fits |        arc,tilt | 236.0507 | 36.8141 | HgCdAr Arcs | 59356.1323 |    1.49 |    20.0 |  5195.0 |   Clear |     1.1 | Cd, Ar, Hg |
| 20210522.0001.fits |            bias | 149.0346 | 34.9193 |        Bias | 59356.0856 |     1.0 |     0.0 |  5195.0 |   Clear |     1.1 |        off |
| 20210522.0002.fits |            bias | 149.0346 | 34.9193 |        Bias | 59356.0857 |     1.0 |     0.0 |  5195.0 |   Clear |     1.1 |        off |
| 20210522.0003.fits |            bias | 149.0346 | 34.9193 |        Bias | 59356.0858 |     1.0 |     0.0 |  5195.0 |   Clear |     1.1 |        off |
| 20210522.0004.fits |            bias | 149.0346 | 34.9193 |        Bias | 59356.0859 |     1.0 |     0.0 |  5195.0 |   Clear |     1.1 |        off |
| 20210522.0005.fits |            bias | 149.0346 | 34.9193 |        Bias | 59356.0860 |     1.0 |     0.0 |  5195.0 |   Clear |     1.1 |        off |
| 20210522.0032.fits |       illumflat | 144.8190 | 61.4406 |    Sky Flat | 59356.1068 |    1.15 |     8.0 |  5195.0 |   Clear |     1.1 |        off |
| 20210522.0033.fits |       illumflat | 144.8861 | 61.4407 |    Sky Flat | 59356.1070 |    1.15 |     8.0 |  5195.0 |   Clear |     1.1 |        off |
| 20210522.0034.fits |       illumflat | 144.9531 | 61.4408 |    Sky Flat | 59356.1072 |    1.15 |     8.0 |  5195.0 |   Clear |     1.1 |        off |
| 20210522.0035.fits |       illumflat | 145.0202 | 61.4409 |    Sky Flat | 59356.1074 |    1.15 |     8.0 |  5195.0 |   Clear |     1.1 |        off |
| 20210522.0036.fits |       illumflat | 145.0872 | 61.4410 |    Sky Flat | 59356.1076 |    1.15 |     8.0 |  5195.0 |   Clear |     1.1 |        off |
| 20210522.0022.fits | pixelflat,trace | 223.4301 | 36.8472 |   Dome Flat | 59356.0973 |    1.49 |    20.0 |  5195.0 |   Clear |     1.1 |        off |
| 20210522.0023.fits | pixelflat,trace | 223.6225 | 36.8470 |   Dome Flat | 59356.0978 |    1.49 |    20.0 |  5195.0 |   Clear |     1.1 |        off |
| 20210522.0024.fits | pixelflat,trace | 223.7397 | 36.8468 |   Dome Flat | 59356.0982 |    1.49 |    20.0 |  5195.0 |   Clear |     1.1 |        off |
| 20210522.0025.fits | pixelflat,trace | 223.8651 | 36.8467 |   Dome Flat | 59356.0985 |    1.49 |    20.0 |  5195.0 |   Clear |     1.1 |        off |
| 20210522.0026.fits | pixelflat,trace | 223.9822 | 36.8465 |   Dome Flat | 59356.0988 |    1.49 |    20.0 |  5195.0 |   Clear |     1.1 |        off |
| 20210522.0078.fits |         science | 210.8212 | 28.6579 | PG 1401+289 | 59356.2039 |    1.01 |   300.0 |  5195.0 |   Clear |     1.1 |        off |
| 20210522.0079.fits |         science | 211.4163 | 28.5237 |    FSBHB 30 | 59356.2106 |    1.01 |   300.0 |  5195.0 |   Clear |     1.1 |        off |
| 20210522.0080.fits |         science | 211.3735 | 28.5426 |    FSBHB 71 | 59356.2150 |    1.01 |   300.0 |  5195.0 |   Clear |     1.1 |        off |
| 20210522.0081.fits |         science | 242.9356 | 12.0714 |  IC 4593 PN | 59356.2222 |    1.28 |   300.0 |  5195.0 |   Clear |     1.1 |        off |
| 20210522.0082.fits |         science | 242.9356 | 12.0714 |  IC 4593 PN | 59356.2266 |    1.26 |    60.0 |  5195.0 |   Clear |     1.1 |        off |
| 20210522.0083.fits |science,standard | 237.9995 | 32.9484 |  BD+33 2642 | 59356.2366 |    1.07 |   300.0 |  5195.0 |   Clear |     1.1 |        off |
data end
```

NOTE: Several columns (`decker`, `dispname`, `binning`, and `dispangle`) have been removed from the actual `.pypeit` file and coordinates have been rounded for clarity of printing the file here.

There are three sections to the file that tell PypeIt how to reduce the data.

Parameter Block At the top of the file is the parameter block which allows the user to customize the data reduction process. Parameter categories are surrounded by square braces, and the parameters themselves are set with equal signs. Indenting is not required by PypeIt, but is included here for visual ease. When editing your own PypeIt Reduction Files, feel free to indent or not as you desire. For the example `.pypeit` file above, the first two lines shown:

```
[rdx]
  spectrograph = ldt_deveny
```

are automatically generated by `pypeit_setup`. The `spectrograph` parameter is the only one required, and tells PypeIt which spectrograph configuration parameters to use.

The next lines in the parameter block override PypeIt and instrument-specific default configurations. The DeVeny-specific modifications to default PypeIt parameters needed here are already included in the `LDTDeVenySpectrograph()` class added to PypeIt by LDT staff (listed here) – it is not necessary to reproduce them in the parameter block of your `.pypeit` file. What do go here are changes away from the DeVeny default configuration you wish to use for reducing a particular data set. For instance, the next three lines in the example file above:

```
[reduce]
  [[findobj]]
    sig_thresh = 3.0
```

specify that PypeIt should use a signal-to-noise threshold of 3 for identifying objects in the 2D spectrum rather than the 5σ specified in the DeVeny default configuration.

A discussion of typical parameter changes that may apply to DeVeny data is given in §H.5, and an exhaustive discussion of all parameters may be found in the PypeIt Documentation: PypeIt Parameters.

Setup Block The next block, beginning with the line `setup read`, describes the instrument configuration. There should only be one setup shown (*e.g.*, `Setup A`), and the parameters provided show the salient metadata for that instrument configuration. You should not edit any of this; it is informational and required.

Data Block The largest section of the PypeIt Reduction File is the data block. Beginning with the line `data read`, this section includes the path to the raw data files and a table describing those files associated with this setup. The data block is a fixed-format table as written by the underlying `astropy.table.Table` object used by `pypeit_setup`. The "`|`" symbols need not align but the number per row must be equal. Users should always generate the PypeIt reduction file using the `pypeit_setup` script to ensure all data is present as expected, but edits will often be necessary to deal with edge cases or other situations unanticipated by the automated routine.

The PypeIt Reduction File is the ultimate authority in terms of how the data are reduced. As such, you should understand how edits to this file work because these edits will override anything derived from the FITS headers! It is common to edit this table in the manners described below.

- **Add/Remove a File**: You may add or remove files from the data block to process the desired files. To add a file, the only safe move is to copy in a line from the `.sorted` file generated by `pypeit_setup` (§H.3.3). It needs to be formatted just like the others. To remove a file, you may delete the line or comment it out by pre-pending a `#`.

  Here is yet another reminder to not include bad calibration frames in the reduction (*i.e.*, frames that you do not want to use, frames with incorrectly identified types, or frames that could not be automatically classified and have a `None` type). Check them now and remove them if they are bad.

  A major reason to add files to the Data Block is the presence of two different setups for a given data set (*i.e.*, two different grating angles), but all of the bias frames ended up in one of the setups (*i.e.*, based on the `GRANGLE` keyword). Since the grating angle has no bearing on the bias level of the CCD, these files are appropriate calibrators for both setups. Simply copy the bias lines from one file to the other, in this instance, so that both setups have access to the bias frames. The ordering of table rows in the PypeIt Reduction File does not matter, so don't worry about adding lines in the "proper" location.

Care must be exercised in including arc frames for wavelength calibration. Given the large shifts along the spectral axis of the DeVeny CCD caused by flexure ($\sim \pm 10$ pixels), observers who rely upon precise wavelength calibrations typically take arcs at the location of each object to ensure the accuracy of the wavelength calibration. This is not strictly necessary for a PypeIt reduction (see Appendix F and §H.4.1 for a discussion of flexure corrections). The ensemble of *in situ* arcs should definitely not be used for PypeIt wavelength calibration, as the software defaults to combining all arc frames together to produce a `MasterArc`. PypeIt does so without regard to flexure-induced shifts between frames, and can produce an unusable mess of multiple, shifted lines. The safe move here is to include in the PypeIt Reduction File only arcs taken at a single mount position (*e.g.*, zenith at the start of the night). It is, however, possible to associate particular arcs with particular science frames; the technique for doing so is discussed in §H.6.1 under Advanced Usage.

- **Check `frametype`**: The most common edit for a given data file is its Frame Type(s). For DeVeny reduction, you need at least one file with each of the following Frame Types (see also §H.3.2):

  - `bias`: Bias frames (for removing fixed-pattern noise)
  - `pixelflat`: Flat fielding (for removing pixel-to-pixel sensitivity variations)
  - `arc`: Wavelength calibration (for colorizing the black-and-white spectrum)
  - `science`: Science exposure (for answering the grand questions of the universe)

  Remove all images with a `frametype` of `None` images, or change the `frametype` to the correct value. PypeIt will NOT run if any of the frames have `None` under `frametype`.

  As shown in the example PypeIt reduction file, a given image can have multiple frame types – enter the types as a comma-separated list without spaces.

  NOTE: Specifying an observation as a (spectrophotometric) `standard` should only be done after fully reading the Fluxing Documentation and ensuring your standard star is in the PypeIt database. Currently, PypeIt will not automatically classify DeVeny data as `standard` (a future update of lois is required); labeling an observation as such must be done manually.

- **Check `target` Names**: Because PypeIt uses the `target` name (encoded in the `OBJNAME` FITS keyword, entered in the DeVeny LOUI) as part of the reduced data filename, this column must include only legal characters for your filesystem. In general, forward slash (`/`) is always disallowed (sorry, comet observers), but others may be a concern on your particular filesystem. Additionally, parentheses or other characters in `target` names may cause issues if such characters are not escaped in shell environments.

  In general, `target` names should only include alphanumeric characters, spaces, dashes, plus signs, underscores, and periods. Editing the `target` name in the PypeIt Reduction File (and not in the actual FITS file itself) is sufficient for the limitations mentioned here.

H.3.5 Run the Reduction

PypeIt is designed (and currently only able) to do end-to-end reductions, resulting in 1D spectra for each *science* and *standard star* frames. Once you have completed the setup steps above, you are just about ready to run the pipeline.

In the directory containing your edited PypeIt Reduction File, check for folders left over from previous runs of the pipeline (if applicable). In particular, be sure to remove any calibration files from the `Masters/` folder that are stale or old versions.

`run_pypeit` The main script to execute the PypeIt reduction is `run_pypeit`. A typical run of PypeIt is initiated with a command like:

```
run_pypeit ldt_deveny_A.pypeit -o
```

The code launches, reads the PypeIt Reduction File, initiates a few internals, and then proceeds to generate a logorrheic stream of messages in the terminal window. For the most part, it is safe to ignore the flood of messages – much of what is there remains from the initial construction and debugging of PypeIt. If the code should crash before completing the reduction, the last several lines of output can yield insight into what happened.

There are two standard options that you should consider using:

- `-o` or `--overwrite`: Using this flag will over-write any existing reduced data in the `Science/` directory. It is recommended that this flag be used in most cases. In the event that you only want to re-reduce a few particular science frames (and not everything else), remove those particular output files from the `Science/` directory and `run_pypeit` without the `-o` option.
- `-c` or `--calib_only`: This flag tells PypeIt to only run on the calibration files, producing the `Masters/` directory and associated quality assurance (`QA/`) files. When first running PypeIt or preparing to reduce a large data set, this option will allow you to inspect the various calibration files (and in particular the wavelength solution) before sinking a lot of time into reducing your science frames.

The next two sections describe the outputs produced by `run_pypeit`.

H.3.6 Examine the Calibration Files

As PypeIt begins churning through your reduction, it will create and write to disk calibration frames in the `Masters/` subfolder of wherever you execute `run_pypeit`. Additional Quality Assurance files will be written to the `QA/` subfolder for some types of Master frames. It is important to take the time to inspect these calibration outputs as they are generated – preferably by using the `-c` option to `run_pypeit`, or alternatively while waiting for your science frames to reduce.

The naming convention for Master Frames is a bit cumbersome, but follows a regular pattern. For example:

```
MasterBias_A_1_DET01.fits
```

This is a bias Master from setup `A`, calibration group `1`, detector `01`. The setup is that from the Setup Block of the PypeIt Reduction File. Unless you are doing advanced calibration grouping (§H.6.1), the group should always be `1`. As DeVeny has but one detector, the masters will always end with `DET01`.

Here is a brief description of the Master Frames produced (in the order in which they tend to be created):

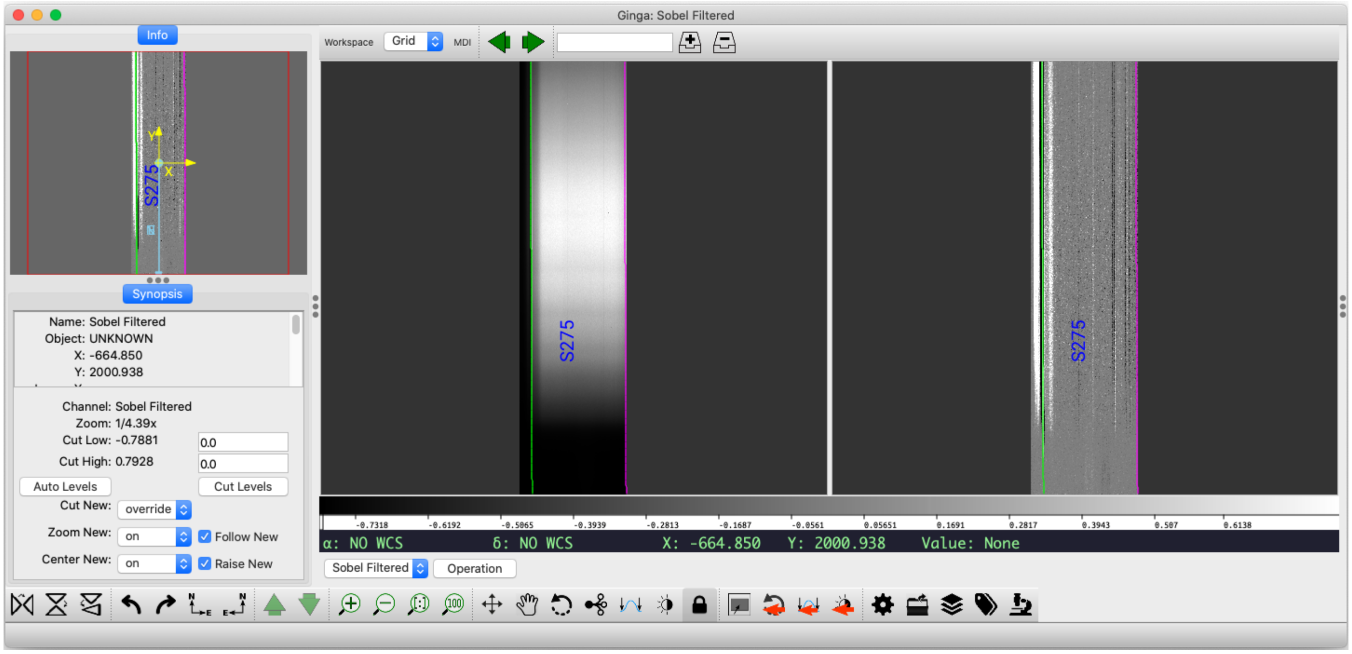


Figure 34: Example of output from the `pypeit_chk_edges` script for data taken with the DV2 grating. The magenta and green lines in the center panels mark the left and right edges of the detected slit. The CCD is about 2.′9 wide, so at least one edge of the 2.′5 slit should be visible.

- <u>**Master Bias**</u> image (*e.g.*, `MasterBias_A_1_DET01.fits`) – Processed combined bias frame used to remove fixed-pattern noise from all other images. The result is not unlike Figure 9.

- <u>**Master Edges**</u> file (*e.g.*, `MasterEdges_A_1_DET01.fits.gz`) – Collection of images and FITS bintables describing the slit traces. While this file is primarily of interest for multislit or echelle spectrographs (DeVeny has but one slit and no cross-disperser, after all), it is instructive to quickly peek at this file to ensure the code correctly identified the slit (and not some artifact at the edge of the CCD):

  ```
  $ pypeit_chk_edges Masters/MasterEdges_A_1_DET01.fits.gz
  ```

  This command will launch a GUI viewer to display the combined trace image along with a sobel-filtered version used to identify illumination discontinuities in the spatial direction (see Fig. 34). For DeVeny data, it should identify a single, wide slit with a `SpatID` (spatial ID) approximately half the spatial extent of the CCD image (mid-200s for spatially unbinned data). The exact number will vary from grating to grating due to differing small roll angles about the dispersion axis when the gratings were installed in their cells.

- <u>**Master Slits**</u> file (*e.g.*, `MasterSlits_A_1_DET01.fits.gz`) – This file contains the distilled internal information on the traced slit edges, derived from the `MasterEdges` file and organized in FITS bintables. The best way to assess these data is in the `pypeit_chk_edges` GUI.

- <u>**Master Arc**</u> image (*e.g.*, `MasterArc_A_1_DET01.fits`) – Processed combined arc spectral image, where the frames are combined using a weighted mean algorithm. The result will look like Figure 10, except rotated as noted previously. Note: If you used different combinations of the 4 arc lamps at different points during your observing session, this image may or may not make much sense. Closely examine this image in a tool like `ds9` to ensure it will be suitable for generating a wavelength solution. If not, try editing the PypeIt Reduction File to include only arc frames with the same combination of discharge lamps and rerunning `run_pypeit`.

- **Master Tilt** image (*e.g.*, `MasterTiltimg_A_1_DET01.fits`) – Image used to trace the tilting of spectral lines across the slit traces to produce an accurate 2D wavelength solution for the detector. For the case of DeVeny (single slit trace on the sole detector), this is identical to the `MasterArc` image.

- **Master WaveCalib** output (*e.g.*, `MasterWaveCalib_A_1_DET01.fits`) – Contains the 1D wavelength solution for this setup. Inspect the wavelength solution using the `pypeit_chk_wavecalib` script. This is an example output from the data described in the PypeIt Reduction File of §H.3.4 (DV2 grating, $\theta_{\mathrm{grangle}} = 22.54°$, $\lambda_c = 5195$Å):

```
$ pypeit_chk_wavecalib Masters/MasterWaveCalib_A_1_DET01.fits

 N. SpatID minWave Wave_cen maxWave dWave Nlin  RMS
--- ------ ------- -------- ------- ----- ---- -----
  0    276  2927.1   5151.3  7385.7 2.173   18 0.107
```

  The central wavelength and wavelength range should be close to what you set (see Table 2 for examples), and the dispersion (`dWave`) should be close to the value listed in Table 4. Note that the `SpatID` listed here should match that from `pypeit_chk_edges`.

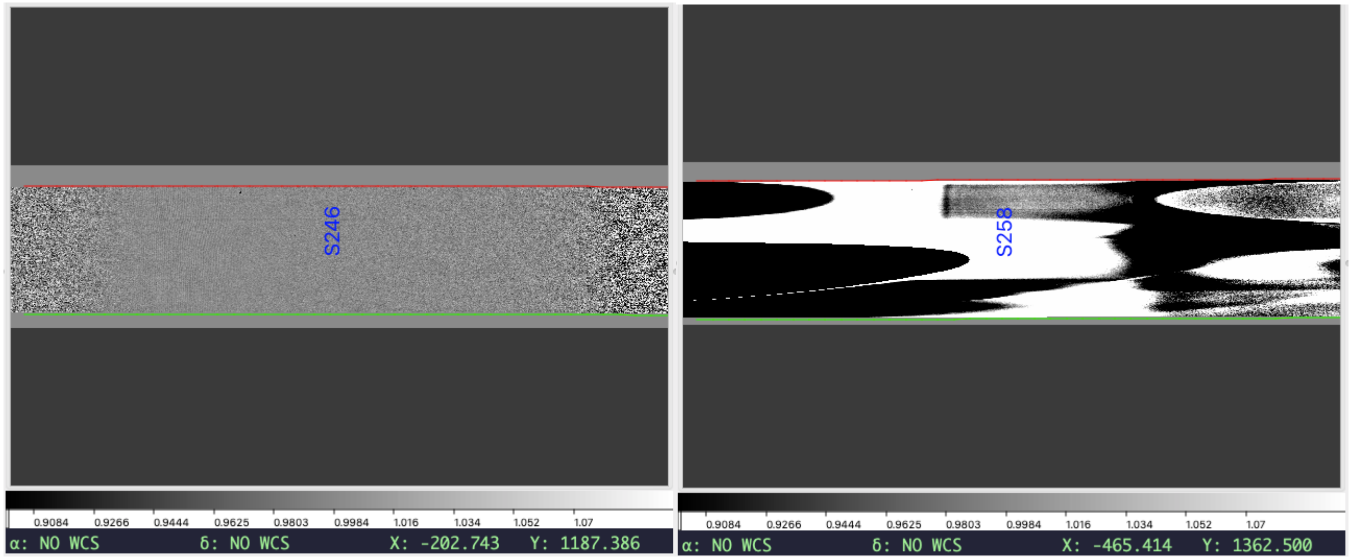
- **Master Tilts** output (*e.g.*, `MasterTilts_A_1_DET01.fits`) – Contains the 2D mapping of the slit to lines of constant wavelength. The quality of this step is shown in the images of the `QA/PNGs` directory (see Fig. 39), and should rarely need much scrutiny for DeVeny data if you have strong arc lines and a good wavelength solution.

- **Master Flat** images (*e.g.*, `MasterFlat_A_1_DET01.fits`) – Processed combined dome flat fields for removing pixel-to-pixel sensitivity variations. PypeIt fits a basis spline (`bspline`) to the spectral direction to remove the structure in the flat lamp spectra, and should yield a normalized image with all values close to 1. Examine the normalized flat field frame using the utility `pypeit_chk_flats` and compare with examples from Figure 35.

  The example normalized `pixelflat` shown in Figure 35a from the DV1 grating illustrates a successful reduction of this frame. The fact that the "salt and pepper" random variations increase at the red (left) and blue ends of the spectrum is simply the result of very low count rates at the extreme ends of the DeVeny's spectral range.

  The not-so-good example in Figure 35b is from a set of DV6 data ($\lambda_c = 4000$Å) where the flux from the usual top-ring (CLST) lamps dropped to zero near the middle of the CCD, and PypeIt had a difficult time properly fitting a function to the spectrum. This may be an example of when to use the Photo Flood lamps (see §7.5) for flat fielding to produce sufficient flux across the detector.

  The GUI launched with `pypeit_chk_flats` also shows the 2D wavelength solution derived from `MasterTilts` when you mouse over the various images. This is a good guide for determining whether artifacts seen in the flats are caused by low signal at extreme wavelengths.



(a) Good pixelflat from DV1 grating, values ~ 1.

(b) Bad pixelflat from DV6 grating, many values pegged at 0.5 (black) and 2.0 (white).

Figure 35: Examples of good (*left*) and not-so-good (*right*) normalized flatfields, as seen in the tool `pypeit_chk_flats`. If your normalized flat field looks like (b), you should examine whether you have enough flux across the CCD.

H.3.7 Examine the Science Spectra

As PypeIt runs (unless the `-c` flag is invoked), it will begin generating 2D and 1D spectra outputs in the `Science/` folder for each *science* and *standard* frame in the PypeIt Reduction File. Feel free to examine the files as they are created, even while the code continues to process the other raw frames.

- **Examine the 2D spectral images**: During the data-reduction process, PypeIt will create a reduced 2D spectral image product for each *science* and *standard* frame prior to the extraction of 1D spectra. These products are stored in multi-extension FITS files with names like:

  `spec2d_20210522.0083-BD+332642_DeVeny_20210522T054038.220.fits`

  where the filename model is:

  `prefix_frame-objname_camera_timestamp.fits`

  You may examine this image product in a tool like `ds9`, but PypeIt also provides a command-line script `pypeit_show_2dspec` for viewing the sky-subtracted 2D image (with overlays of the slit and any objects extracted) in a `ginga` RC (remote-control) viewer.[11] It should be called from the working directory (*i.e.*, the directory you were in when you called `run_pypeit`). For instance:

```
$ pypeit_show_2dspec Science/spec2d_20210522.0083-BD+332642_DeVeny_20210522T054038.220.fits
```

[11]The viewer `ginga` is installed as part of the PypeIt virtual environment (§H.2), and should launch automatically when needed. If not, in a terminal type `ginga --modules=RC,SlitWavelength &` to manually launch the viewer.

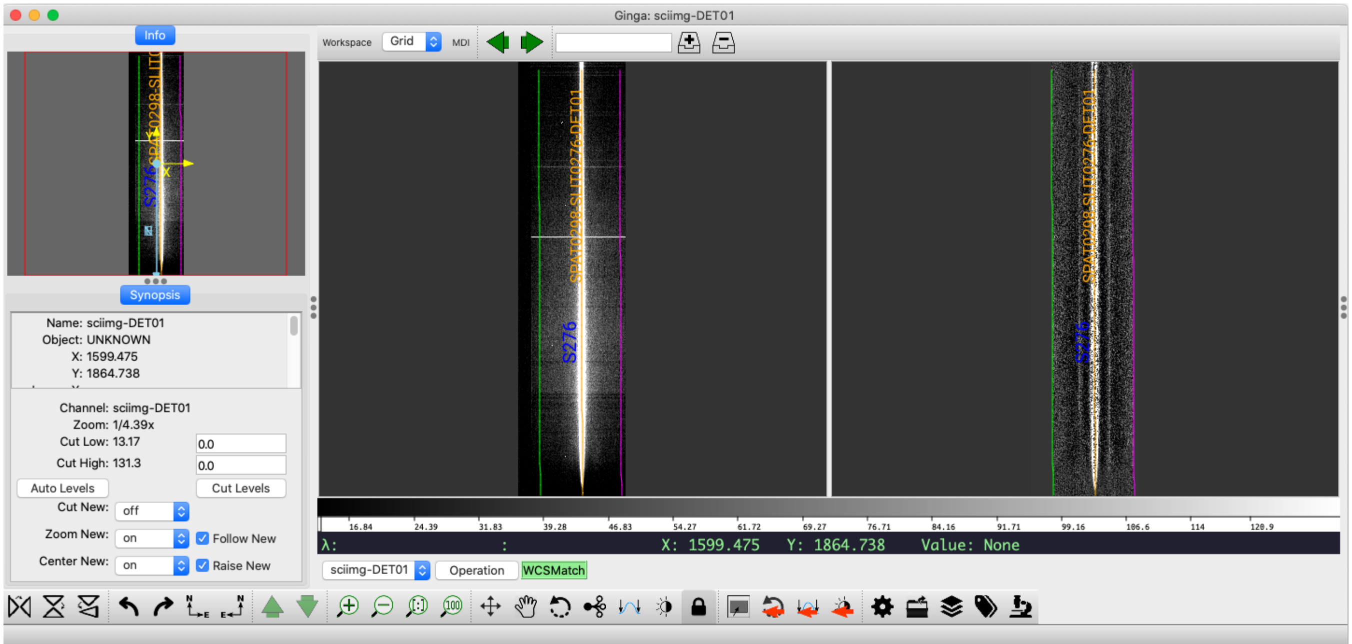


Figure 36: Example of the PypeIt reduced 2D spectrum for the object mentioned in the text displayed in the `ginga` viewer launched from `pypeit_show_2dspec`. The image on the left is the calibrated science image, while the spectrum on the right has been sky-subtracted and masked to the identified slit (magenta and green lines). The other two frames normally present have been omitted from this figure for clarity. Note that a single object has been identified (orange trace and label). Further note that these data were taken on a night when the moon phase was 86%, where the high sky brightness toward the blue can be seen in the science image (left).

This opens 4 tabs in the `ginga` display (see Fig. 36), one for each of the following:

– Procesed image (`sciimg`)
– Sky subtracted image (`skysub`)
– Sky residual image (`sky_resid`)
– Full residual image which removes the object also (`resid`)

Magenta/green lines indicate slit edges, as in Figure 34. Orange and light blue lines (if present) indicate traces for automatically detected objects and manually extracted objects, respectively. As you mouse around, the green coordinates shown at the bottom indicate the pixel number and the wavelength.

Each extracted object is named by its spatial position on the reduced image [`SPAT`], slit position on the reduced image [`SLIT`] and the detector number [`DET`]. For instance, the object shown in Figure 36 has the label `SPAT0298-SLIT0276-DET01`. Because DeVeny has a single long slit, if multiple objects are extracted from a given image, their names will differ only in the `SPAT` code.

- **Examine the extracted 1D spectra**: If one or more objects have been automatically or manually identified in the reduced 2D spectral image, a 1D data product will be produced. These 1D products are the fundamental outputs of PypeIt, and may be described by a series of 1-dimensional arrays: vacuum wavelength, extracted flux (from one or more methods), and associated error arrays. These arrays are packaged into a multi-extension FITS file, and are accompanied by a `.txt` file with Extraction Information (*read*: table of contents) for each extracted 1D spectrum.

The 1D spectra files have names like:

```
spec1d_20210522.0083-BD+332642_DeVeny_20210522T054038.220.fits
```

where the filename model is identical to the 2D version above.

To view the 1D extracted spectra, use the built-in script `pypeit_show_1dspec`, which loads the data and launches a GUI. Like the 2D version above, it should be called from the reduction directory:

```
$ pypeit_show_1dspec Science/spec1d_20210522.0083-BD+332642_deveny_20210522T054038.220.fits
```

This should launch an XSpecGUI on your screen (see example in Fig. 37). If you wish to view the flux-corrected spectrum (after you have completed that step – see §H.3.8), use the option `--flux` to the call above.

The accompanying `.txt` file contains information about the extracted objects, including FWHM of the optimal extraction (in arcsec), the SNR of the extracted spectrum, and the RMS (in pixels) of the wavelength solution:

```
| slit |                  name | spat_pixpos | spat_fracpos | box_width | opt_fwhm |    s2n | wv_rms |
|  276 | SPAT0298-SLIT0276-DET01 |       298.3 |        0.522 |      3.00 |    1.858 | 236.00 |  0.107 |
```

By default, `pypeit_show_1dspec` loads the first (lowest spatial pixel number) object extracted from the 2D spectrum. Examination of the spectral image with `pypeit_show_2dspec` or simply looking for the object in the `.txt` file with the largest SNR will help you identify which extracted object

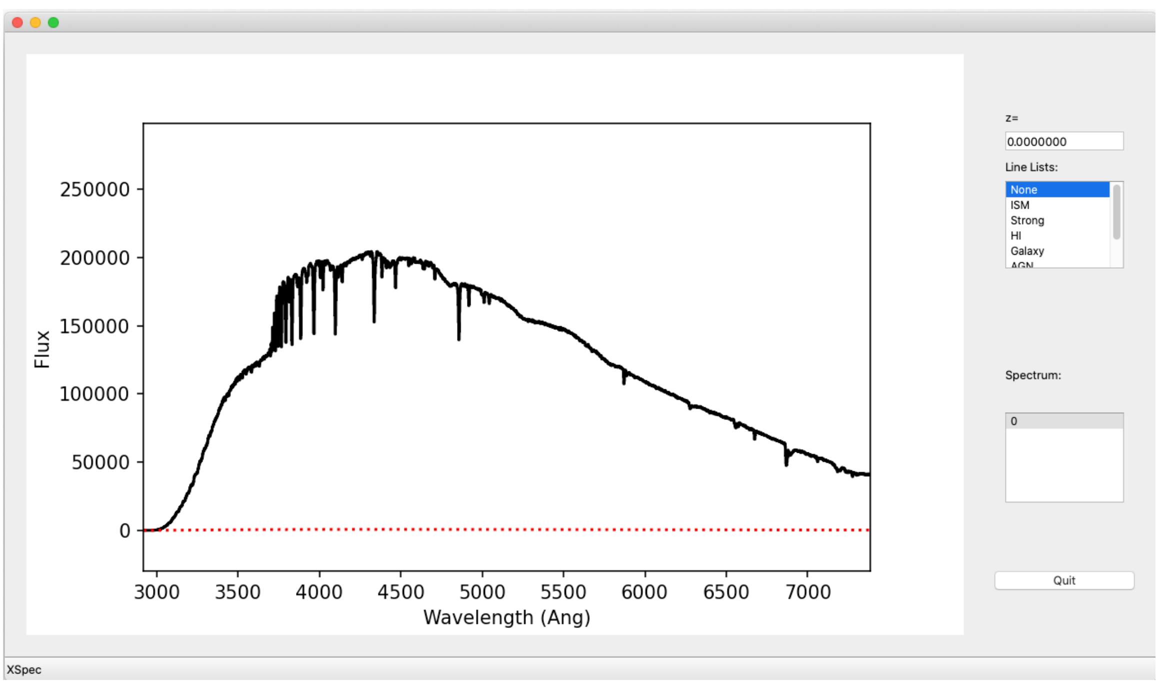


Figure 37: Example of the PypeIt reduced and extracted 1D spectrum for the object mentioned in the text (BD+33 2642) displayed in the XSpecGUI launched from `pypeit_show_1dspec`. This is a spectral type B2IV spectrophotometric standard star.

corresponds to your desired target. You may load a particular extracted object into the XSpecGUI by using the `--obj` option:

```
$ pypeit_show_1dspec --obj SPAT0298-SLIT0276-DET01 Science/spec1d_[long filename].fits
```

or by specifying a particular FITS extension (1-indexed, corresponding to the order of objects listed in the `.txt` file) via the `--exten` option:

```
$ pypeit_show_1dspec --exten 1 Science/spec1d_[long filename].fits
```

By default, PypeIt performs both a boxcar (top-hat) extraction around the trace and a Horne[12] optimal extraction using the fitted spatial profile. Unless the boxcar-extracted spectrum is specified by use of the `--extract BOX` option, the spectrum displayed by `pypeit_show_1dspec` is that of the optimal extraction.

- **Missing 1D spectra**: If you are missing 1D spectra, this means that PypeIt did not find any objects in the corresponding frame. Examine the 2D spectrum to verify this is the case using the `pypeit_show_2dspec` script. You have two options for attempting an extraction of such missing objects:
  - You may modify some of the parameters in your PypeIt Reduction File (see §H.5.2), remove this `spec2d_[long filename].fits` file, and rerun `run_pypeit`.
  - Manually identify and extract the object following the Manual Extraction instructions.

H.3.8 "After-burner" Processing Steps

Fluxing The main body of PypeIt returns extracted 1D spectra, measured in instrumental units. For some science programs, this is sufficient, and further processing is unnecessary prior to analysis (skip ahead to §H.3.9). Other programs require converting the instrumental intensity into physical flux units before the spectra can be analyzed. PypeIt provides routines for Fluxing your spectra that are run separately from and after the main run.

If you plan to flux-calibrate your spectra, it is imperative to include one or more spectrophotometric standard stars in your observing program. Exactly which stars and when to observe them depend on the specific requirements of your science program. You will want to identify such stars as `standard` in your PypeIt Reduction File.

The process of flux-calibrating your spectra happens in two stages: (1) generate a sensitivity function, and (2) apply it to your science program objects. The PypeIt docs on this topic provide a clear overview of the steps needed to carry out this processing.

Coadding For one reason or another, you may find yourself taking more than one spectrum of an object that you wish to combine. PypeIt includes the script `pypeit_coadd_1dspec` for coadding these individual exposures. In general, you will need to flux-calibrate your 1D spectra prior to coadding them. If you wish to perform this step, please read the documentation on this topic.

[12] Horne, K. 1986, PASP, 98, 609

H.3.9 Loading PypeIt 1D Spectra into specutils

PypeIt is a package for reducing spectroscopic data from raw frames collected at the telescope to 1D spectra, ready for analysis. To do the actual analysis in service of your particular science program, you will need to employ other tools. One possible tool is the Astropy-coordinated package `specutils`.[13]

There is a custom loader for importing PypeIt 1D spectra into the `specutils` `Spectrum1D` class *(in development)* for analysis.[14] Because PypeIt may find more than one object in a given 2D spectrum, we must take care when loading PypeIt files into the `Spectrum1D` class. The process looks something like:

```
from specutils import Spectrum1D, SpectrumList
try:
    spec = Spectrum1D.read("path/to/data")
except:
    spec = SpectrumList.read("path/to/data")
```

where `specutils` will automatically recognize PypeIt data from the FITS headers and properly parse the data into either a single `Spectrum1D` class instance or a list of such instances.

What you do with the `Spectrum1D` object will be defined by the requirements of your science program and is beyond the scope of this manual.

H.4 Special Considerations and Troubleshooting

The above instructions should be sufficient to produce usable 1D spectra using PypeIt. The remainder of this Appendix is devoted to special considerations, troubleshooting, parameter modifications for specific cases, and advanced usage.

H.4.1 Flexure in DeVeny and How PypeIt Handles It

Appendix F outlines the flexure that occurs in the DeVeny camera and general methods of correcting for it. The present standard method for flexure correction is to apply a flexure shift based on the extracted sky spectrum. This method will be applied automatically using the current `LDT_DeVeny` parameters, and you should use only single-pointing arcs for wavelength calibration (*e.g.*, taken at zenith or the position of the flatfield screen).

This default method of flexure correction computes a cross-correlation between the extracted sky spectrum and an archived spectrum. The correlation is used to shift the wavelength solution in pixel space to align with the night sky lines extracted from the 2D image via simple linear interpolation. If you wish to not have any flexure correction applied, you may add the following to the Parameter Block of your PypeIt Reduction File:

```
[flexure]
  spec_method = None
```

[13] `https://specutils.readthedocs.io/en/stable/index.html`
[14] For now, download the custom loader and place it in your `~/.specutils` directory for use.

If your science requirements indicate the taking of *in situ* arcs for wavelength calibration, see §H.6.1 for a description of this advanced usage.

H.4.2 Troubleshooting: Crash raises `ValueError` on `None`

If your PypeIt run crashes out very early (*i.e.*, just after reading in the frame metadata), and you get output to your screen similar to:

```
[INFO]    :: metadata.py 1233 get_frame_types() - Typing files
[INFO]    :: metadata.py 1240 get_frame_types() - Using user-provided frame types.
Traceback (most recent call last):
...
    raise ValueError('The following bit names are not recognized: {0}'.format(
ValueError: The following bit names are not recognized: None
```

the issue is the inclusion of files with a `frametype` of None in your PypeIt Reduction File. Go back to §H.3.4 and verify all files listed in your PypeIt Reduction File meet the criteria described therein.

H.4.3 Troubleshooting: When Wavelength Calibration Fails

The trickiest piece with spectroscopic data reduction is the production of a valid wavelength calibration. PypeIt produces Quality Assurance plots of this step for inspection, and you may use the `pypeit_chk_wavecalib` script (§H.3.6) to determine the accuracy of the calibration. Figure 38 shows `QA` examples of both accurate and poor wavelength calibrations.

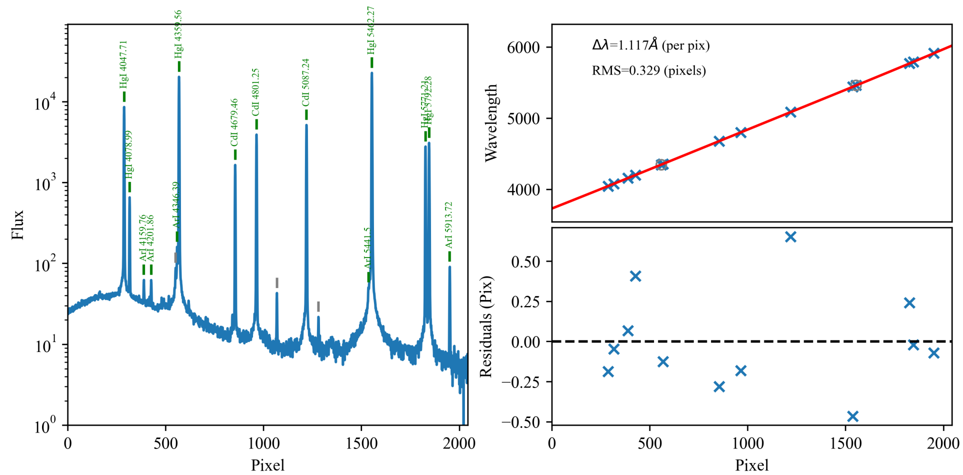
As of v1.9.0, PypeIt contains full wavelength templates for the 150g/mm (DV1), 300g/mm (DV2, DV3), 600g/mm (DV6, DV7), and 1200g/mm (DV9) gratings. The code uses the `full_template` method to match your arc spectrum against the template using a cross-correlation to establish the wavelength baseline for identifying and fitting individual lines. These templates were created using the Hg, Cd, and Ar lamps – if your particular data sets do not match this lamp set, the cross correlation may not work as nicely, and you could end up with a situation such as Figure 38b. For gratings DV4 and DV8, we do not yet have good template spectra yet, and so these gratings rely upon the `holy-grail` method, which is based on pattern matching the detected lines with that expected from the lamps observed. The DV5 grating has a limited template spectrum for the $\lambda_c = 6000$Å grating angle.

When running `run_pypeit -c` and examining the `QA` outputs, you find either a wavelength calibration akin to Figure 38b or no wavelength calibration at all, you will need to manually identify the lines using the `pypeit_identify` utility and the spectra in Appendix D. New in PypeIt v1.9.0 is the ability to cache and directly use the output of `pypeit_identify` without resorting to filesystem shenanigans. When you save and quit the GUI, the script will print to the terminal instructions for using the wavelength solution you just created, namely adding the following to the parameter block of your PypeIt Reduction File:

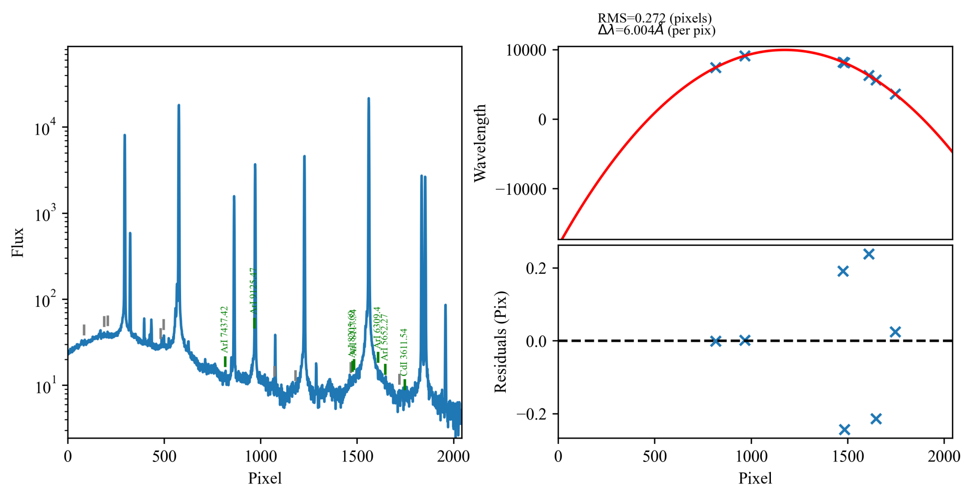
```
[calibrations]
  [[wavelengths]]
    reid_arxiv = wvarxiv_ldt_deveny_<YYYYMMDD>T<HHMM>.fits
    method = full_template
```

where the date and time in the filename are those of the file's creation. Simply add the block and **run_pypeit**.

If you need to do this for your data, please also send your `wvarxiv.fits`, `wvcalib.fits`, and DeVeny setup information to LDT Staff so that it may be added to the standard PypeIt configuration in a future release.



(a) Good wavelength calibration for DV6 grating.



(b) Bad wavelength calibration for DV6 grating.

Figure 38: Examples of good (*top*) and not-so-good (*bottom*) wavelength calibrations for the same setup using DV6 on different nights. For the top plots, PypeIt found the bright lines, correctly associated them with the line lists (see Appendix D), and produced a roughly linear wavelength as a function of pixel number. In the bottom plots, the **holy-grail** method was not able to correctly identify the lines, latching onto noise in the continuum, and produced a nonsensical wavelength solution.

H.4.4 Troubleshooting: Other edge cases or weird crashes

[This section will be filled in as other cases present themselves.]

H.5 PypeIt Parameter Modifications for Specific Cases

There are various situations in which you will need to modify the Parameter Block of your PypeIt Reduction File (see §H.3.4). The default DeVeny parameters were chosen to cover the major use cases for the spectrograph, but the instrument's high configurability and varied uses means there will still be many instances where these default parameters must be modified. The principal categories of modifiable parameters are grouped below, but the complete list is given at PypeIt Parameters.

NOTE: Think of parameter modifications as part of an outline, where each level represents a unique thought. Therefore, if you need to modify both the arc lamps and the FWHM of the arc lines under wavelength calibrations, you would include something like:

```
[calibrations]
  [[wavelengths]]
    lamps = HgI, CdI, ArI
    fwhm = 7.0
```

rather than two individual `[calibrations]` blocks. In short, each parameter group in brackets should appear only once in your Parameter Block. Also, indentation is not necessary, but may help in visually organizing the outline.

H.5.1 Wavelength Calibration Parameters

Wavelength Solution Order Once the lines have been identified, PypeIt iteratively fits a function of Legendre polynomials between pixel and wavelength space. For DeVeny, the polynomial order of the initial guess and final solution at the wavelength calibration are grating-dependent, given the varying wavelength coverages of DeVeny's grating complement (see Table 4). Shown in Table 9 are the values for these orders for each grating. If you are unsatisfied with the RMS of the wavelength solution, adjusting the solution order may improve the situation. These values may be changed by modifying the parameters:

```
[calibrations]
  [[wavelengths]]
    n_first = <initial guess>
    n_final = <final solution>
```

Arc Lamps PypeIt is able to read the identification of the arc lamps energized directly from the FITS header, and the user is no longer required to specify which line lists should be used in the wavelength calibration process. If, for whatever reason, the line lists gathered in this fashion cause failure of the wavelength solution, the user may directly specify which line lists PypeIt should use. For instance, if you used the Hg, Ar, and Cd lamps, but wish PypeIt to only use the two metal lamp line lists, you would add to your Parameter Block:

Table 9. PypeIt Wavelength Calibration Legendre Polynomial Orders

Grating	`n_first`	n_final	Grating	`n_first`	n_final	Grating	`n_first`	n_final
DV1	3	5	DV4	3	5	DV7	2	5
DV2	3	5	DV5	2	5	DV8	2	4
DV3	3	5	DV6	2	5	DV9	2	4

```
[calibrations]
  [[wavelengths]]
    lamps = HgI, CdI
```

NOTE: The order of the lamps specified here is inconsequential, as the code sorts the list internally. The names of the lamps (*e.g.*, `HgI`) are connected to the ion line lists included with the PypeIt distribution (*e.g.*, neutral mercury). Furthermore, there are several faint lines of Cd and Hg that have been identified in DV9 arc spectra, but are not particularly useful for other gratings. These lines are included in DeVeny-specific line lists (that are a superset of the usual line lists), and can be utilized in your reduction by replacing `CdI` and `HgI` with `Cd_DeVeny1200` and `Hg_DeVeny1200`, respectively.

Line Width for Arc Frames For wavelength calibration, PypeIt assumes that your spectral line FWHM are around 4.0 pixels, but also measures the FWHM directly from the `MasterArc` file. If you are using arcs taken with a slit width that produces FWHM significantly different from this value, you may need to specify the expected value in your PypeIt Reduction File based on a manual inspection of the arcs. (See §G.2 for a discussion about optimal slitwidth.) For instance, if you set the slit width to have arc lines with a FWHM of ~ 9 pixels (say, a $3''$ slit with DV1), you would specify:

```
[calibrations]
  [[wavelengths]]
    fwhm = 9.0
    fwhm_fromlines = False
```

Specifying `fwhm_fromlines = False` forces the code to use the supplied FWHM and may result in a more successful wavelength calibration.

Night Sky Lines for Calibration Use of night sky lines for wavelength calibration is the basis of DeVeny's flexure correction (§H.4.1). You will need to take at least one arc spectrum at some point in the night (*e.g.*, during start-of-night calibrations) to establish a wavelength reference across the CCD. PypeIt extracts the night sky spectrum from the background of your science frames, and computes an approximate wavelength calibration by cross-correlating it with an archived sky spectrum. No additional arcs are needed to make this link, and PypeIt will compute a pixel shift in the wavelength calibration to match your science frame with your `MasterArc`. No changes to the Parameter Block of your PypeIt Reduction File are required, as this is the default behavior for DeVeny data.

PypeIt does support night-sky wavelength calibration for near-infrared instruments using the copious OH lines in this portion of the spectrum, but DeVeny does not reach far enough into IR for this method to apply.

H.5.2 Object Finding and Extraction

The parameters related to object finding and extraction are generally modified *after* you have done an initial pass through `run_pypeit`, and wish to improve the ability of the code to work with your data.

General Object Finding Refer to Object Finding for full details on the algorithms. Object finding is governed by the `findobj` set of parameters, and is carried out on the spectrally-smashed image (a 1D array that represents the spatial profile of the exposure). The most commonly modified parameter is `sig_thresh`, which limits the search to sources with peak flux in excess of `sig_thresh` times the RMS of the smashed image. The default is (a signal-to-noise of) 5 and you may wish to reduce this parameter. Add the following to the Parameter Block:

```
[reduce]
  [[findobj]]
    sig_thresh = 3.
```

This will search for any source with peak flux 3-sigma above the estimated RMS in the integrated slit profile.

On the flip side, if you observed fairly bright objects want to eliminate the inclusion of spurious faint sources in your final `spec1d` file, you may *increase* `sig_thresh` to the point that only a single object is detected. Similarly, you could use the parameter `maxnumber` to limit the object finding to a limited number of objects (ordered by flux):

```
[reduce]
  [[findobj]]
    maxnumber = 1
```

Nights with Poor (or Really Excellent) Seeing If the seeing was poor for your data, you may need to specify the expected width of the sources in the spatial direction. The default FWHM expected is 5 pixels (1.7″), which should cover most conditions at LDT. If the seeing is significantly better or worse than this value, you may alter the value via

```
[reduce]
  [[findobj]]
    find_fwhm = 7.4
```

(for the instance of 2.5″ seeing and 1×1 binning; 0.34″/pixel). Note that poor seeing can be somewhat mitigated by binning the CCD in the spatial direction (see §4.1.7), and `find_fwhm` is specified in *pixels*, regardless of the binning.

A related parameter you may need to modify is the radius around the peak of the trace to use for boxcar extraction of the source. The default value is 1.5″ (for a total boxcar width of 3″ centered on the source). You will want this parameter to be something like 1.5× the seeing. So, for the aforementioned 2.5″ seeing, you should specify:

```
[reduce]
  [[extraction]]
    boxcar_radius = 3.75
```

in your PypeIt Reduction File. Note that, unlike `find_fwhm`, `boxcar_radius` is specified in arcseconds, which is unaffected by CCD binning.

All of the above applies equally well to nights with exceptional seeing ($\leq 0.8''$), where tightening up the finding and extraction parameters might be necessary to properly find and extract your spectra.

No 1D Spectra Extracted If you are missing 1D spectra (*i.e.*, `spec1d_[long filename].fits` doesn't exist), this means that PypeIt did not find any objects in the corresponding 2D frame. Below are some suggested modifications to your Parameter Block to help the code find your targets. The PypeIt developers suggest re-running the reduction on one or two frames at a time using the `run_pypeit -s` mode (which will show reduction steps via plots) to ensure your modifications to the reduction parameters are being implemented as expected.

- Modify the significance threshold for object finding (see above).
- Modify the maximum number of objects that you expect to see in your frames. The default is 10, but, for example, if your exposure only contains one object of interest, you will want to change your Parameter Block to set `maxnumber = 1` (see above).
- Modify the FWHM of your object of interest in pixels, as described above. The default is 5 pixels, but you may want to increase or decrease this, depending on the seeing or the object physical size (NOTE: $1'' = 3.0$ pix for DeVeny):
- If these do not work, then you will need to proceed with a Manual Extraction of your object.

Extraction with Extended Emission Lines It is common for bright emission lines to spatially extend beyond the source continuum, especially for galaxies or comets. In these cases, the code may reject the emission lines because they present a different spatial profile from the majority of the flux. While this is a desired behavior for optimal extraction of the continuum, it leads to incorrect and non-optimal fluxes for the emission lines.

The current mitigation is to allow the code to reject the pixels for profile estimation but then to include them in extraction. This may mean the incurrence of cosmic rays in the extraction. To utilize this strategy, add the following to the Parameter Block:

```
[reduce]
  [[extraction]]
    use_2dmodel_mask = False
```

It is likely that you will want to use the BOXCAR extractions instead of the OPTIMAL, but *caveat emptor*.

Emission Line Only or High-z Objects If you have a faint object with only emission lines or a high-z object what only appears on part of the trace, you may need to specify the spatial range on the CCD for the pipeline to search for the object. Do this with:

```
[reduce]
  [[findobj]]
    find_min_max = {minpixel}, {maxpixel}
```

where `minpixel` and `maxpixel` are the spatial pixels bounding the region you see your object in the 2D spectra as inspected with `pypeit_show_2dspec`.

H.5.3 Miscellaneous Parameters

Illumination Correction If your science program requires correcting for the illumination pattern along the slit, it is possible to turn on this function. While this would normally be included in the calibration processing steps, it has been turned off by default for DeVeny data. Flexure in the spatial direction is not yet accounted for, and a shifted illumination function correction can introduce systematic error into extracted spectra (see Appendix F.2). If you science program requires illumination correction for variations in throughput along the slit, you may do so using either dome flats or sky flats and adding the following to the Parameter Block of your PypeIt Reduction File:

```
[baseprocess]
  use_illumflat = True
```

Sky flats will automatically be labeled with frame type `illumflat`, but you may need to add this frame type to your dome flats in the Data Block of your PypeIt Reduction File. (As shown in Figure 30, the illumination function of dome flats matches that of the sky to $\sim 0.5\%$.)

Beyond the Red If your spectra are exclusively in the very red end of the DeVeny range ($\lambda \gtrsim 7000$Å), and you are flux calibrating your data, you will want to specify that PypeIt correct for telluric absorption (at wavelengths below this value, the UVIS extinction model is used for the sensitivity function). You will create a sensitivity function as part of the flux calibration process, and you must specify the infrared algorithm to correctly account for atmospheric absorption in this range of the spectrum, along with a telluric atmospheric model. LDT staff have not created a telluric atmospheric model grid for our site, but we suggest using the Mauna Kea values as being generically applicable.

Add the following to the Parameter Block of your `.sens` file:[15]

```
[sensfunc]
  algorithm = IR
  [[IR]]
    telgridfile = TelFit_MaunaKea_3100_26100_R20000.fits
```

The code will automatically download the telluric grid file from the cloud the first time you run the fluxing script – be warned that this file is $\sim$ 8GB, and may take a while to download. You may also use the `pypeit_install_telluric` script independently from the fluxing to download and cache the file.

This functionality has not yet been tested, but please contact LDT staff with the outcome if you attempt to use this feature.

H.6 Advanced Usage

H.6.1 Calibration Groups

PypeIt uses the concept of a "calibration group" to define a complete set of calibration frames (*e.g.*, arcs, flats, biases) and the science frame to which these calibration frames should be applied. By default, `pypeit_setup` uses the configuration identifier (*e.g.*, `A`) to assign frames to a single calibration group. No automated procedure exists to do anything except this. However, a user can edit the PypeIt Reduction File

[15]See the PypeIt sensitivity function documentation.

to, within a given configuration, assign specific calibration frames to specific science frames using the data in the `calib` column. For example, if the observer takes both evening and morning calibration frames, the PypeIt user can use the PypeIt Reduction File to associate calibrations taken at the end of the night with the morning calibrations and vice versa.

For DeVeny, this may be most useful for associating *in situ* comparison arcs with the temporally adjacent science frames. The PypeIt documentation describes how this feature works for the Keck/DEIMOS instrument; extension to any particular LDT science program is left as an exercise for the reader.

H.7 Cheat Sheet for Common DeVeny Workflows

Listed here is a brief "cheat sheet" of commands for a common DeVeny workflow for quick reference.

- Set up the PypeIt Reduction File(s)

```
pypeit_setup -s ldt_deveny -r <path_to_your_raw_data>
pypeit_setup -s ldt_deveny -r <path_to_your_raw_data> -c <all or subset ID>
```

- Edit the PypeIt Reduction File(s) as necessary
- Run PypeIt on the calibrations and inspect

```
run_pypeit ldt_deveny_<subset ID>.pypeit -c
pypeit_chk_edges ...
pypeit_chk_wavecalib ...
pypeit_chk_flats ...
pypeit_identify ...
```

- Run PypeIt on your science data

```
run_pypeit ldt_deveny_<subset ID>.pypeit -o
pypeit_show_2dspec ...
pypeit_show_1dspec ...
```

- Run any desired afterburner scripts

```
pypeit_sensfunc ...
pypeit_flux_calib ...
pypeit_coadd_1dspec ...
```

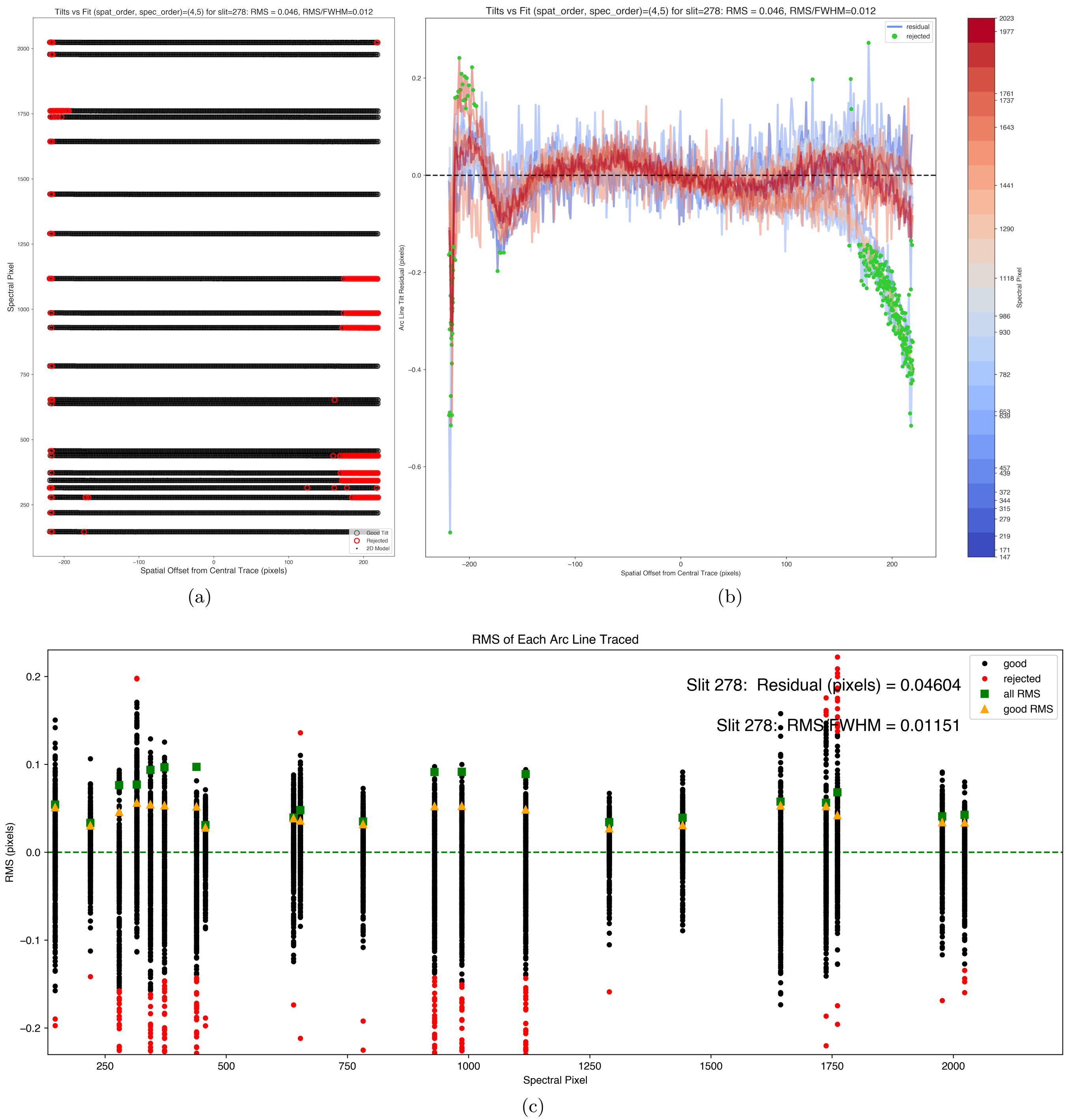


Figure 39: Example QA plots for the `MasterTilts` file associated with a DV2 data set. For a complete description, see the PypeIt Master Tilts documentation.