The Large Monolithic Imager User Manual

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About this manual: Although this document is a pdf, you should be able to click on references to section numbers and figures that are marked in red. If it says "we refer you to Section 6.2," clicking on the 6.2 will take you there. To return, you need to do a "previous view." On a Mac, in Preview, this is Go→Back, while on a Mac in Adobe this is View→Navigation→Previous. Please let me know what's missing and what could be made clearer in the manual: phil.massey@lowell.edu.

The above image of the Horsehead nebula was part of the LMI Commissioning Project, and was taken on March 6, 2023; image credit: Massey/Neugent/Lowell Obs./NSF.

Fun Facts

- e2v CCD231-SN-10382-14-01: 6144×6160 15μm pixels (92.16 mm $\times$ 92.40 mm). The spec sheet for the chip can be found at `http://www2.lowell.edu/users/massey/LMI/G5.pdf` although the QE values at short wavelengths are much better than what is stated.
- FOV $12'.3 \times 12'.3$
- Scale: $0''.120$/pixel (unbinned), $0''.240$/pixel (binned 2×2)
- Gain: 2.89 e-/ADU (amp A, but other amps similar)
- Readnoise: 2.1 ADUs, about 6.0 e- (amp A, but other amps similar)
- Normal operating temperature: -120° C
- One bad column: (1597 when binned 2x2)
- Linearity: All 4 amplifiers are linear to <1.5% over the full data range.
- Actual mid-time of exposure=[(UTCSTART + 2.05 sec)+(UTCEND-0.19 sec)]/2.
- Count rates at U=B=V=R=I=20th at an airmass of 1.0, integrated over a stellar profile:

U:	70 e/sec	Sloan u:	130 e/sec
B:	610 e/sec	Sloan g:	715 e/sec
V:	595 e/sec	Sloan r:	690 e/sec
R:	575 e/sec	Sloan i:	500 e/sec
I:	410 e/sec	Sloan z:	310 e/sec
VR:	890 e/sec	Y-ish	19 e/sec
HαON:	14 e/sec	HαOFF:	65 e/sec
OIII:	14 e/sec	WC,WN,CT:	32 e/sec

- To compute exposure times, use the Exposure Time Calculator.
- Typical transformations with an instrumental mag of 25 corresponding to 1 ADU/sec
  - $u = U + 0.9 + 0.60X - 0.13(U - B)$
  - $b = B - 1.0 + 0.25X - 0.05(B - V)$
  - $v = V - 1.0 + 0.15X + 0.02(B - V)$
  - $r = R - 0.9 + 0.10X - 0.04(V - R)$
  - $i = I - 0.4 + 0.05X - 0.05(V - I)$
- Orientation (within $0^\circ.1$) with Instrument Alignment Angle (IAA) set to $185^\circ.2$ ←ask operator to set.
  - Amplifier A: N is up, E is to the left.
  - Amplifier B: N is up, E is to the right.
  - Amplifier C: N is down, E is to the left.
  - Amplifier D: N is down, E is to the right.
- Readout (plus prescan) times:
  - Unbinned: 73 sec
  - 2×2 binning: 24 sec
  - 4×4 binning: 10 sec
- Recommended settings:
  - Amplifier: A
  - Binning: 2×2
  - Overscan: 32
- Computers
  - dct-obs1 and dct-obs2 (astronomer work stations, run LOUI, login: observer, password on whiteboard)
  - lemi (runs LOIS itself, login: obslemi, password on whiteboard)

Contents

1 What's New?

October 2023: (a) In order to assure a smoother start-up experience, we now recommend both initializing and homing the filter wheels when first bringing up the LMI LOUIE for the night. (b) Previously we reminded users that if they attempt to home a filter wheel that is already in filter position 1, nothing may happen, and that it's necessary to home after first moving to a different filter position. This is still true for the upper filter wheel, but not for the lower. (c) Many links were broken with the move of our "confluence" server; these have now all been fixed (I think). If not, let me know....(d) What's in a name? In late 2019 the "Discovery Channel Telescope" was officially renamed the "Lowell Discovery Telescope." As a result, the telescope is called LDT but all the computers, information links, and so on use the older DCT. Such is life.

2 Introducing LMI

The Large Monolithic Imager (LMI) is the LDT's workhorse camera, and contains the largest CCD that can be made using current manufacturing techniques. The instrument was funded by the National Science Foundation through AST-1005313. The camera is mounted in the direct through-put port on the instrument cube. A Stirling closed-cycle cooler chills the CCD to -120° C. There are 18 filter slots, and currently we have a UBVRI, VR, Hα on and off-band, an [OIII]λ5007, the WR filters (WC, WN, CT), the Sloan filters u', g', r', i', z', and even a UKIDSS/WFCAM Y-ish filter with an extended red cutoff (good luck with that). In addition, David Schleicher has kindly made his extensive set of comet filters available. The CCD is run using a Generation III Leach controller.

There are three 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 the astronomer computer, an iMac named **dct-obs1** and its twin, **dct-obs2**.

- **LOIS** (Lowell Observatory Instrument System) is the guts-level system that actually runs the CCD controller, setting the micro-code, generating the FITS header, and doing all the heavy lifting. It runs on the computer **lemi**.
- **LOUI** (LOis User Interface) is the means by which the astronomer controls the exposure (defining the type of exposure, exposure time, setting the filter...in other words, it's the user interface). It runs on the iMac astronomer's computer, **dct-obs1** or **dct-obs2**.
- **JOE** (Java Operator Executive) is a software "controller" that needs to be running in order for LOUI and lois to talk to the the filter wheel and obtain telemetry from the telescope control software for header information. JOE runs on the computer...(wait for it...) **joe**. Generally the astronomer doesn't have to worry about this one, other than to be aware that JOE needs to be alive in order to change filters.

In addition, the astronomer will probably want to run **IRAF** and **ds9** to perform real-time evaluation of the images. Sound confusing? Let's walk though the basic start up.

2.1 Getting Started at the Beginning of the Night

2.1.1 Start Everything Running

- Hopefully the previous observer has read the manual and killed their LOUI. But, if you see a LOUI open on the observers' computer, kill it by hitting the little red button.
- Now open LOUI by double-clicking the icon that says LOUI_lmi.
- Kill LOIS by clicking on "Exit LOIS" at the upper right of the LOUI window. You should see "LOIS Exiting Normally" in the LOIS log window very shortly; you will need to wait another 15 seconds or so for the process to complete.
- Restart **LOIS**:
  - Confirm that there is a terminal window open connected to lemi. (The previous observer should have left one up.) If not, In a terminal window, "ssh obslemi@lemi." The password is on the whiteboard.
  - Type "st" to confirm that LOIS is "Not Running." If instead it lists two 5-digit numbers (PIDs) next to LOIS, wait a bit and run "st" again. If need be, repeat the previous step: "Exit LOIS," on the LOUI, 15-20 seconds, and check with "st" again. If *that* doesn't work, check with the operator; you may have to do an explicit kill -9 [PID number] in the terminal window.
  - Type "lois &" to start LOIS. You will see some messages about "no authentication" appear; ignore them. We recommend that you leave this window open in order to catch any error messages in case of problems. In fact, it should stay open as long as LOIS is running, so you should leave it up when you're done.
- Click the green "initialize LOIS" in the upper right corner LOUI A red "Error Code: **NONE** will appear briefly in the log window at lower left; this message may safely be ignored. A stream of additional messages will go by for about six seconds. Among the last half dozen messages or so, in orange, it should say "LOIS Successfully Initialized."
- At the lower right, you'll see the "information view" exposure time counter marked in blue ("exposure 1/1 - 0.0/0.0 seconds (100%)") at start-up. (Figure 2, upper). Within this panel, scroll down below this until you can enter the Observer Name and Observer Affiliation section. Fill these out and click "Set Standard Image Path & Observer." This will create the datadirectory where the data will be be stored; it will have a name like 20160820a, where 20160820 corresponds to the UT date for that night. If you are the second (or third or...) observer for the night, first click the box labeled "New rundate directory." This will change the "a" to a "b" or a "c" or..... Once you've created the new directory and put an image in it (even a test image), your data will continue to go there; i.e., you can't set the pointer back to the previous letter. (Although you certainly may cd to it.)
- You can have sounds happen at the end of an exposure and/or at the end of the read-out and/or at the end of a series of exposures. Open the chevron labeled "sound effects" below the data path. By default, LOUI is silent, thank goodness. Note that you can also turn on a sound effect for exposures that are suddenly blocked due to missing telemetry or other issues that might impact the FITS header; see Section 8.
- Check that JOE is on: You should see "JOE: On" at the bottom of LOUI. If it hasn't been restarted, you won't be able to move the filter wheel, get good FITS headers, and so on. You can always ask your operator how JOE is doing: normally the operator stops and restarts JOE at the beginning of each night.

- Initialize and home the filter wheels. Click on the “initialize” button to the right of the filter wheel indicators. Click on the “Home Lower” button. Next, in order to home the upper filter wheel, select some other filter, such as DARK, and the click on “Move.” Next click on the “Home Upper” button. You’ll see that below the picture of each wheel it should say something like D:1/C:1 and Good. The “D” value is the demanded position of the wheel, and the “C” value is the current position. The “Good” indicates that the detent is in position.
- Grab the tab that says “Facilities Summary” at upper left and pull it to somewhere on the desktop. This will keep you up to date on where the telescope is pointing. (Figure 2, lower), status of important sub-systems (like,“Is the mirror cover open?”) and the focus value (bottom-most row). *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.*

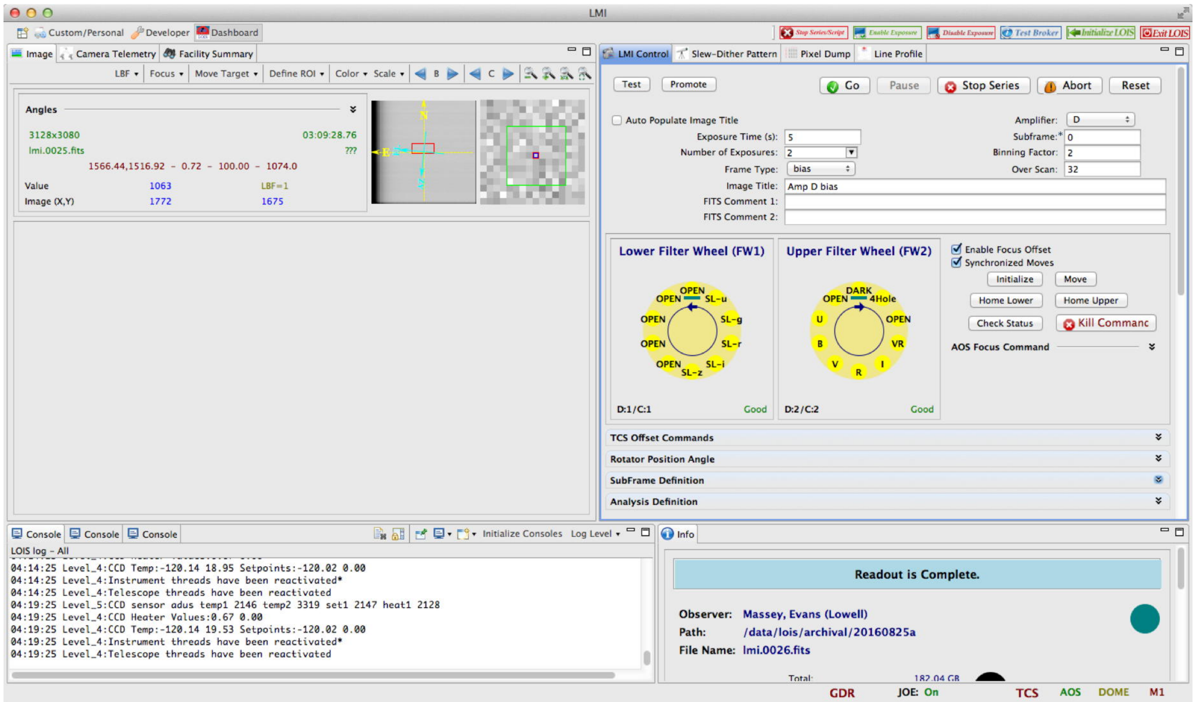


Figure 1: The LOUI screen upon startup. By default, LOUI comes up in the "dashboard" perspective (upper left) and "image" view (2nd row down on the left).

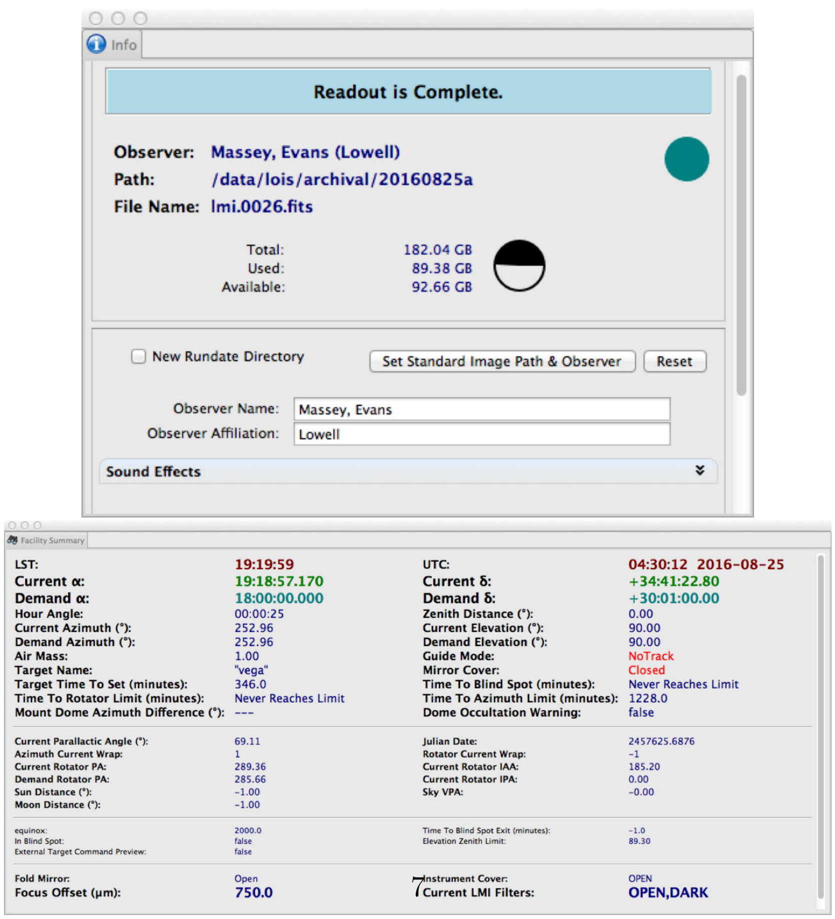


Figure 2: The Information view (top), with the later having its sections expanded by clicking on the chevrons, and the Facilities Summary view (bottom).

- Set up **IRAF: IRAF** *provides some very useful basic-quick look tools. We assume here some familiarity with* **IRAF***; for those not familiar with IRAF, we refer you to Section 6.2.*

  - Click on the "SAOImage DS9" icon in the Dock to start the ds9 image display window.
  - In a terminal window type "xgterm &" to start up an IRAF graphics window. Alternatively, click on the "XQuartz" icon in the dock, and then use the pull-down applications tab to select "xgterm."
  - When the xgterm window pops up, type "cd" in it to make sure you're in the home directory.
  - Type "cl" to bring up IRAF.
  - Go to tonight's data directory, i.e., "cd /lmi/<*ut date*a>" (or "b" or. c or...whatever it says on LOUI is your data path).

- Check the Facilities Summary to confirm that the Instrument Cover (IC) is open: *Note:* the IC is a dust cover at the top of the cube. It's not light tight, so keeping it closed doesn't help biases or darks. But you really do need it open before you try gathering photons.

2.1.2 Making Sure Things Are Working

Whew! After all that, we should at least take a bias and make sure that everything is copacetic (i.e., in excellent order).

- On LOUI (LMI Control view) check that:
  - Amplifier is set to "A."
  - Binning factor is set to 2.
  - Overscan is set to 32.
- Take a "test" bias frame:
  - Move the upper filter wheel to the "dark" position.
  - Set the Frame type to "bias."
  - Click "test." We note that a number of fun things should now happen in LOUI. If they don't, see Section 8.
    - The exposure meter will quickly update to 0/0 seconds.
    - You will be able to monitor the progress of the chip readout (about 22 seconds) two ways:
      - Right below the exposure meter there is a blue circle. This will fill in as the chip reads out.
      - In the LOIS Log window, you will see the percentage of the readout change.

      Note that there will be a variety of messages in the LOIS Log window. As mentioned earlier, don't be alarmed when you get a red "Error Code: **NONE** upon startup.
    - When the image finishes reading out, it will be displayed in the image view on the upper left panel.
- The output of LOIS' "box" will be automatically shown in red above the image area. This includes the (x,y) position, the maximum number of counts, the average number of counts, and the standard deviation. Check that the average counts are about 1200 and the standard deviation is about 2.5 ADUs on this bias frame.
- You can also move the cursor around in the image display window to see the counts at various x and y positions.

- This is probably a good time to make sure that the images are indeed in the right directory, and that the headers look reasonable. In the IRAF window do an "ls -l" and you should see test.fits with the current date and time. You can do an imhead test.fits l+ to see the headers. If the Telescope Control System (tcs) is up and running these should all be populated with reasonable values.

3 Calibration

We've gotten good results with the following:

1. **Biases**. There is a significant (20-30 ADUs) turn down in the bias frames on the left, so subtracting an average bias is a good idea. Here's what I do to obtain a suitable measurement of the bias structure.
   - The instrument is pretty light tight, but if the "DARK" filter is available, put that in place. (To move to a particular filter, click on the filter name, then click on "move.")
   - Set the "frame type" to bias, and the "Number of exposures" to 10. Hit "Go."

2. **Flats**. This chip is quite well behaved, but there is a 5% illumination function from center to edge on the broad-band filters, plus a very interesting "quilted" pattern at shorter wavelengths, amounting to about 9% at **U**, 2% at *B*, and sub-one- percent at *V*, as shown in Figure 3. This is a characteristic of the annealing process used by e2v, and the features flat-field out well, although the issue at *U* is complicated by the need to match the color of the flat-field to the color of the dark sky. Note that at the reddest filters (such as the "Y-ish") the chip is nearly transparent, and one sees some very ugly stuff in the CCD packaging, although the features flat fields out well.

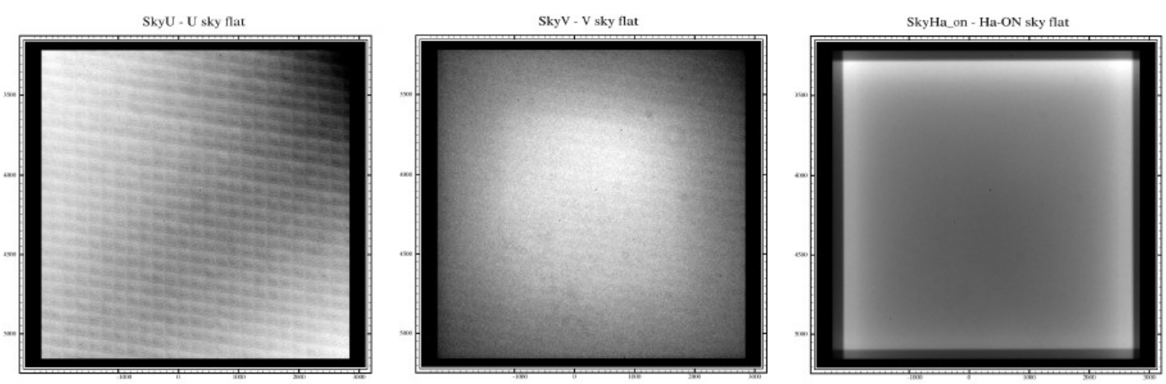


Figure 3: Sky flats. From left to right: U, V, and Hα on.

Currently there are two options for flat-fielding: the bright twilight sky (which is very blue) and the projector screen. We've had good success with twilights. The projector flats differ from the twilights and the dark sky by a few percent, due to illumination issues—the twilights are right, and agree very well with the illumination of the dark night sky on the chip. Although the chip has fringe suppression, there will be some fringe pattern visible in the reddest filters (I, i', z', and Y-ish).

   - Try to get on the sky right at sunset. Since our shutter is so uniform, there is no problem with using very short (0.1 sec) exposure times on the sky, and this will allow you to get plenty of flats through multiple filters before stars begin to appear. (Exposures of 0.05 sec or shorter are not uniform at the 1% level.)

- Ascertain from the telescope operator that the mirror cover is open, the dome shutter is open, and that you are in a comfortable place for twilight flats. The Chromey spot is a region that is most uniform; i it's about 1.5 hour east and a declination of $\sim +25°$.
- Start with the bluest filters (if broad band) or the interference filters (if using them) and take a 0.1 sec exposure. Evaluate the counts after it's read out. By moving the cursor around in the "image" window, you can see the counts. If it's 65000+, then the exposure is saturated and it's no good. Raw counts of 4500 ADUs will give you 1% statistics.
- After each exposure, while the chip is reading down, offset the telescope by 20 arcsec using a tplane relative offset of 20. You'll find the control for this directly under the filter wheel GUI; open the chevron that says "TCS Offset Commands." Make sure you use "Relative" and not " Absolute."
- Keep increasing the exposure time to maintain counts of 4,500-50,000 for each exposure, offsetting between each exposure.

4 Observing

4.1 Logs

Many astronomers like to take logs as a backup to the header information. Larry Wasserman has kindly provided paper logs; you should be able to find these in the control room. Alternatively, you can download an editable log sheet that comes from Las Campanas Observatory, courtesy of Sergio Castellon. (Note: this shows up properly on Macs; for mysterious reasons, there's some problems with the electronic version under OpenOffice on Linux systems.)

4.2 Moving the filter wheel

The filter wheel has absolute encoding; thus, it is usually not necessary to "home" the filter wheel. If JOE is running, the camera GUI should display the location of the filters (**D:3/C:3**, for example). It will also show whether the detent is in ("GOOD") and not ("BAD"). Starting from a "GOOD" state, in order to change filters simply click on the filter name you want. When you're ready to move it, click on "move". Wait until you get a valid reading below the filter wheel, and the detent reports GOOD, before starting your exposure.

If it's "BAD" then you need to home the filter wheel. Due to a quirk in the system design, if you're starting in filter position 1 and you go to home that filter, nothing will happen and you will be sad and frustrated. (Currently this is only true for the upper filter wheel; home works reliably from position 1 on the lower filter wheel.) So, if you get a "BAD," and you're in position 1 on the upper filter wheel, move to some other position first, and then home it. If you're not in position 1, just home it. Probably it wouldn' hurt to home each filter wheel at that point. (If that doesn't work, it may be necessary to initialize the motor controller card; this is a rare circumstance that occurs only if the cards have been powered off during the day.) Make sure that the focus is what you expect when you're done futzing around.

4.3 Moving the telescope into position

There are currently three ways for the astronomer to cause the telescope to move into position:

1. Give the operator your coordinates (either on paper or by shouting across the room).

2. Construct a simple text file ahead of time and load it into the Target Observing List in order to select coordinates to send to the telescope operator. The latter is detailed in Appendix A.

3. Construct a "Slew Pattern List" that includes your targets, exposure times, and so on. This is documented in Section 4.6.2.

4.4 Focusing

The excellent image quality of the LDT is both a blessing and a curse. It's a blessing because...well, because good image quality is a blessing. It's a curse, as it behooves the observer to stay in focus.

Staying in focus with LMI is actually quite straightforward. There is a relatively strong dependence on the telescope elevation and mount temperature which are automatically taken into account. When you specify a focus value, it is actually an offset on top of the baseline value that is corrected for temperature and elevation. If the system were perfect, you would be able to focus once at the beginning at the night (or not even that) and stay in focus, other than for small, relative focus offsets between filters. But it's not. One "focus quantum" is about 20μm in excellent seeing. (If the seeing is lousy, you'll have to use a number like 50.) We recommend the following for good image quality:

- At the start of the night, home both filter wheels, leaving them in the "clear" and "clear" position.

- You'll find the "AOS Focus Command" next to the filter controls. Open the chevron, enter 150 (or whatever the whiteboad claims), and click the send button. This will set the focus to a reasonable value.

- Ask the operator to perform a wavefront at the start of the night. This will remove any higher order aberrations in the system. It will take about ten minutes, and can be performed in twilight.

- Now it's time to actually focus. Check that the "Enable focus offsets" is indeed checked, and go to the filter in which you want to focus. We recommend in the the yellow or red, as the seeing is better there. Note the new focus value (displayed at the bottom of the Facilities Summary) when the filter is in place, as you'll want to use this as your base focus value.

- Take a 3-sec image using the "test" button. **Given our usual seeing, it makes sense to do your focusing in 2×2 mode even if you're observing in 3×3 binning, but that's up to you. However, in that case, note the caveat below.**

- Look at the image display after the image reads down. Measure the approximate fwhm by clicking on the display window, and then typing a "c" when positioned over the star. You will see the x and y centroid displayed, along with the peak counts, average counts, and RMS. Find a star where the peak counts are 6,000-30,000 ADUs.

- On the second row of the "Image View" over on the left side of LOUI (right above the image area) pull down the menu from the arrow next to the word "Focus". Select "Focus Parameters." Change the exposure time to 3 seconds and the base focus to whatever you saw on the Facilities Summary when you moved to your filter. **Make sure that the "bin" value matches the binning you used for the test image. Normally this will be 2 (for 2×2 binning) but if your test image was in some other binning (say, 3×3), then you'll have to set this accordingly or focus sweep will fail.**

- Now select “Mark & Initiate Focus Run.” Click on the star. You need to click within a half dozen pixels or so; this is easier if you have magnified the view.
- A small image will be taken centered on the star you selected. Next, a focus run will then be made consisting of 9 exposures centered on the base focus and moved by focstep.
- When it’s done, the log will report “Focus script complete.” A few seconds later (be patient) a plot will pop up showing the widths as a function of the focus values. (See Figure 4.) If you’re happy with the value displayed in the text box, click “OK” and the value will be sent to the AOS as the new focus value.
- Check that the focus has been set to the new value by looking at the bottom of the Facilities Summary.
- Take another short (∼3-sec) test frame and confirm that the full width at half maximum (FWHM) of a few stars are reasonably good. The easiest way to do this would be to put the cursor on a star in the image display and type a “c”.

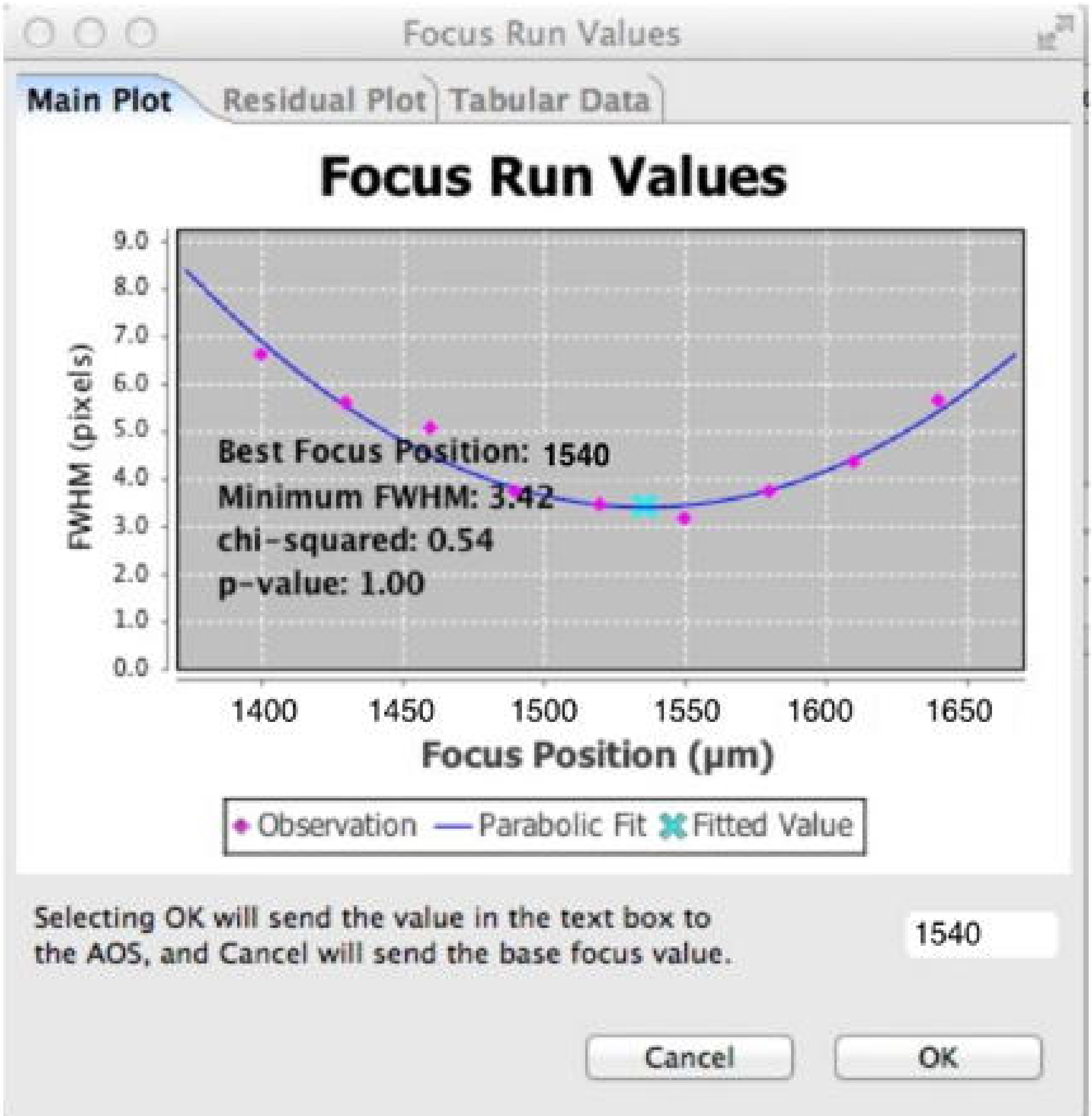


Figure 4: Plot produced from the focus run. Note that in this case we clearly went through the focus, and that the best focus is well defined. This will not always be the case.

Occasionally the focus script will fail: Maybe clouds came by and made the star too faint with the adopted exposure time. Maybe you picked a star that was a bit too bright or too faint. You will notice that no plot has been generated. Regardless, the last message you see will still say "Focus script complete." Right before this message you will see either "Focus Script Has Succeeded" (which is good, and there should be a plot) or "Focus Script Failed" (in red, and this is bad). You can scroll further back in the log for details, which are usually related to photometry of the field, such as "Max pixel saturated." If the best focus appears to be outside the range you just tried, the script will automatically do a second sweep with a starting value based upon the results of the first try. If you do simply need to repeat the focus run on the same star (possibly changing the exposure time, or maybe the focus step size or base focus) you can easily do this without even taking another test image: just go to the "Focus parameter" menu, change what needs to be changed, and click on "Redo Focus Run." But you **must** have just done a focus run—the point is that this will use the identical x and y values for finding the star.

Note: "c" does a nice job, but when the FWHM get tight (less than a 3 or 4 pixels, say), "c" tends to over-estimate the FWHM. Some of us prefer to use IRAF in this case. In the IRAF window, do the following:

- **display test.fits 1; imexamine**
- Position the cursor over a star in the ds9 window and hit "r". You'll have a nice radial plot of the star. The fwhm will be the last number shown in the graphics window.
- Type a "q" to leave the graphics window, and another "q" in the ds9 window to quit **imexamine**.

Note to the IRAF-savy. Yes, you can use **imexamine** *imagename* **1** directly; however, if the *imagename* matches what you've just previously displayed, IRAF will fail to display the new image. So, if you are trying to examine a new *test.fits* after a previous *test.fits*, things will get rapidly confused.

4.5 Observing

Once you are satisfied with the focus, begin your exposure: set image type to "object" and specify the number of exposures and the exposure length. When the pointing model is working well, you can track for several minutes without appreciable smearing even without guiding. Pressing the "go" button will begin taking data. Note that you can always stop a single exposure with the "Abort" button, or terminate a series of exposures early using the "Stop Series" button (Figure 1). *Note: if you've taken a test image using "test" and want to save it as the next numbered image, you can now use the "promote" button. But, don't put it off—"promote" will only promote the test image if it is the most recent image (of any kind) taken.*

LOUI provides some very valuable guidance to you as to whether or not the telescope is ready. Note that at the bottom of LOUI screen (see, e.g., Figure 1) the words TCS, AOS, and DOME. Wait for these to all be green before starting your exposure. These indicate, respectively, that the telescope is in position, that the secondary mirror is in position (and the primary mirror supports tweaked and stable), and that the dome is in position. If you're using the guider, and the guider is guiding, GDR will be green as well. (The AOS light may occasionally flicker; this is just due to the secondary being tweaked to adjust for temperature and elevation changes; don't worry about it.)

4.6 Some Useful Observing Tips

4.6.1 Offsets

Directly below the filter wheel display, you will find a "TCS Offset Commands." This is minimized by default; open it by clicking on the chevron. There two categories of offsets, absolute and relative, and three projections that can be used, "tplane", "simple", or "pa." Let us explain:

- Categories:
  - **Absolute**. Before you apply any offset, the current telescope position can be considered the "home" position. If you apply a 10", 10" offset you will move 10" and 10" from that home position. Applying it again will not move the telescope because you're already 10", 10" away from the home position. If you were to then enter 20", 20", the telescope would move another 10", 10". Furthermore, whatever you've applied here will continued to be applied to every new pointing (yikes!) until explicitly cleared by hitting "clear." (The telescope will also return to the home position once you clear the offsets.) To reset the home position to the current location, use the "absorb" button.
  - **Relative**. This commands allows you to enter an offset of 10", 10". Clicking it a second time will move the telescope an additional 10", 10". Pressing the "clear" button will return the telescope to its position before applying any offsets, and the "absorb" button will define a new "home" position. However, since the moves are all relative anyway, it's not clear under what circumstances this might be a useful thing to do.
- Projections:
  - **tplane**. In "tplane" coordinates you are basically specifying how many arcseconds you'd like to move left/right or up/down on the image. To an astrometrist, these would be known as "standard coordinates," and they are usually referred to as ξ and η. (See, for example, http://nexsci.caltech.edu/workshop/2005/presentations/Girard_coordinates.pdf.) But if you're just trying to shift things left and right on the image, you want to be using "tplane." Enter the units as arcseconds remembering that each pixel is $0\farcs240$ when binned 2×2.
  - **simple**. In "simple" coordinates you tell the telescope to offset a certain number of time seconds in RA and a certain number of arc seconds in DEC. This is most useful, perhaps, if you want to move between two targets whose coordinates you know, such as an offset star and a target when doing spectroscopy.
  - **pa**. In "pa" you specify an offset in polar coordinates: a radius (in arc seconds) and a position angle (in degrees). No one has yet figured out why we have this option.

Note that there is also an offset hand-paddle, which is useful for accomplishing small moves. There is a similar hand-paddle for tweaking the rotator angle if desired.

4.6.2 Dither Patterns and Slew Patters

What if you knew that once you were happy and focused you'd like to move to object A, take some exposures, move to object B, take some exposures, and so on. If you were doing this over and over, it should be nice to be able to do this automatically. Alternatively, you might want to perform some dithers on a particular target, or just take groups of exposures with different filters and exposure times, and the telescope fixed. We now have a function that allows you to execute such a string of commands, a "Slew-Dither Pattern," where each setting is a successive command line in a text file. The function is very versatile, and the choice of parameters to be specified in the command lines is set by the user in the top (control) line of the text file. The operations specified in the pattern file act concurrently in the sense that once the shutter closes and the CCD begins to read out, the specified telescope and filter motions for the next exposure are initiated, and are likely to be complete by the time the current exposure's FITS file is written. Guided offsets *are* supported with this function, but the maximum that will work for a star in the center of the guide annulus is 90 arcsecs, and smaller values will fail if the guide star your operator has selected is not located optimally. So, make sure your operator knows the details of dithering plans.

Let us consider the simple case of wanting to slew to a variety of objects. An example is given in Figure 5.

```
#title=true ra=true dec=true exposureTime=true numExposures=true filter=true muR
A=false   muDec=false epoch=false dRA=false dDec=false rotatorPA=false rotatorFr
ame=false xi=false eta=false comment=false commandOption=false
#
"Field1 " 01:34:16.88 +30:49:53.4   10 3 V
"Field1 " 01:34:16.88 +30:49:53.4   20 5 B
"Field2 " 01:34:12.16 +30:43:45.9    7 3 V
"Field2 " 01:34:12.16 +30:43:45.9   14 5 B
"Field3 " 01:33:47.79 +30:36:59.1   20 3 V
"Field3 " 01:33:47.79 +30:36:59.1   40 5 V
"Field4 " 01:33:22.79 +30:32:47.2   20 3 V
"Field4 " 01:33:22.79 +30:32:47.2   40 5 B
"Field5 " 00:45:17.89 +41:52:09.5   15 3 V
"Field5 " 00:45:17.89 +41:52:09.5   30 5 B
"Field6 " 00:44:25.83 +41:50:19.4   15 3 V
"Field6 " 00:44:25.83 +41:50:19.4   30 5 B
"Field7 " 00:45:17.56 +41:39:22.0   25 3 V
"Field7 " 00:45:17.56 +41:39:22.0   50 5 B
"Field8 " 00:42:19.18 +41:28:09.4   90 3 V
"Field8 " 00:42:19.18 +41:28:09.4  180 5 B
```

Figure 5: A sample slew pattern. In this particular example, the user is specifying the title name, the RA and DEC, the exposure time, the number of exposures, and the filter.

Now consider the somewhat different case of a dither pattern. An example is given in Figure 6. Note that the sequence ends with a 0,0 offset. This is because the offsets are "absolute" and are not cleared; therefore, ending with a non-zero offset will affect the pointing of all subsequent targets (!) until explicitly cleared. See 4.6.1. The user *must* specify the number of exposures and the exposure times.

Important side-bar: Why might you want to dither? One good reason is to ameliorate the effects of the single bad column. If you've broken your exposure into 3-5 pieces and moved the telescope slightly between them, your flat-fielding will be better, and you will have been able to filter out the effects of any rascally recalcitrant pixels, including those in the bad column.

Finally, let us see what a really complicated file might look like: we go to an object, perform some dithers, and then go to a new object and perform some more dithers. An example is given in Figure 7.

Options include:

- **title**: This will be treated the same as the "Object name" in the LMI Control view.

```
#title=true ra=false dec=false exposureTime=true numExposures=true filter=false muRA
=false   muDec=false epoch=false dRA=false dDec=false rotatorPA=false rotatorFrame=f
alse xi=true eta=true comment=false commandOption=false
#
"M27 Pos 1" 60 3 10 0
"M27 Pos 2" 60 3 -10 0
"M27 Pos 3" 60 3 0 10
"M27 Pos 4" 60 3 0 -10
"M27 Pos 5" 60 3 0 0
~
~
~
```

Figure 6: A sample dither pattern. In this particular example, the user is specifying the title name, exposure times, number of exposures, and offsets for the dither. Note that the file ends with a zero offset, avoiding the necessity of clearing the offsets after running the pattern.

- **RA** and **DEC**: Only J2000.0 coordinates are allowed.
- **exposureTime**: The exposure time in seconds. This must be present.
- **numExposures**: If this is not specified, it will default to 1.
- **filter:** If this is not specified, it will default to whatever filter is in place at the time the sequence starts.
- **muRA**, **muDEC**, and **epoch**: the proper motion (in mas/yr) to be applied and the corresponding epoch. Note that muRA is really muRA*cos DEC; this is the form that most catalogs (and SIMBAD) provide.
- **dRA** and **dDEC**: any non-sidereal rates that need to be applied for tracking. The units are arc seconds per hour.
- **rotator PA**: By default the rotator PA is set to 0°, but there may be occasions where the user would like a non-standard orientation.
- **rotator Frame**: Either Target or Fixed. This is a rather obscure parameter and we suggest leaving it at the default.
- **xi** and **eta**: Rather than provide RA and DEC, it is possible to simply specify tplane offsets from the current position. The offsets are in arc seconds, and will be performed as an "absolute" offset. See Section 4.6.1.
- **comment**: This character string will be to added the header. The comment must be enclosed by double quotes.
- **commandOption**: This determines if the command is a "slew" or a "dither."

A few things that are worth emphasizing:

```
#title=true ra=true dec=true exposureTime=true numExposures=true filter=true muR
A=false   muDec=false epoch=false dRA=false dDec=false rotatorPA=false rotatorFr
ame=false xi=true eta=true comment=false commandOption=true
#
"Field1-Pos1" 01:34:16.88 +30:49:53.4  10 1 V  0 0 Slew
"Field1-Pos2" 01:34:16.88 +30:49:53.4  10 1 V 10 0 Dither
"Field1-Pos3" 01:34:16.88 +30:49:53.4  10 1 V 0 10 Dither
"Field1-Pos4" 01:34:16.88 +30:49:53.4  10 1 V -10 0 Dither
"Field1-Pos5" 01:34:16.88 +30:49:53.4  10 1 V -10 -10 Dither
"Field2-Pos1" 01:34:12.16 +30:43:45.9 100 1 V 0 0 Slew
"Field2-Pos2" 01:34:12.16 +30:43:45.9 100 1 V 10 0 Dither
"Field2-Pos3" 01:34:12.16 +30:43:45.9 100 1 V 0 10 Dither
"Field2-Pos4" 01:34:12.16 +30:43:45.9 100 1 V -10 0 Dither
"Field2-Pos5" 01:34:12.16 +30:43:45.9 100 1 V -10 -10 Dither
~
```

Figure 7: A sample combined slew and dither pattern. In this particular example, the user is specifying the title name, the ra and dec, the exposure length, the number of exposures at each point, the filter, the offsets, and whether the move is a slew or a dither.

1. The error recovery is not very robust so it is imperative for the observer not simply start the sequence and walk away. Always check on the progress of the pattern, at least the first time it is being used.

2. The format of the "meta-data" at the start of the file must be specified *exactly* as in the example shown in Figure 5; your only option is to change things from "true" to "false," or "false" to "true," with the above restrictions. If you want to just change filters and exposure times, then don't respecify any coordinates; i.e., both RA/DEC and xi/etc can be set to false.

3. **It is absolutely essential that you do not attempt to interact with the filter wheel or otherwise mess around with the exposure parameters using the "LMI Control" view once the Slew Pattern has started. Very Bad Things May Result! Do NOT expect the filters shown on the LMI Control view GUI to reflect what is going on with the instrument once the Slew Pattern is activated—instead, the Slew Pattern view will show what filter is in use.**

4. The slew pattern will use whatever set of image parameters were used for the previous exposure. So, if your last exposure was a bias frame, all of your exposures will be wind up being a bias frame, even if you've specified the exposure time. **Before you start the slew pattern, make sure that you have at least taken a "test" exposure from the LMI control view that has the same image type, binning, etc. that you want to use.**

5. Remember what we said about relative vs. absolute offsets above in Section 4.6.1? Well, if you use **xi** and **eta** to specify offsets, these will be absolute, and if the last one you specify isn't 0, your pointing is going to be off until someone realizes this and explicitly clears the offsets. There are several things you can do about this, but the easiest one to describe is to just **make sure your last offset has xi=0.0 and eta=0.0.**

Full documentation can be found at `https://confluence.lowell.edu/display/DCTIC/Automated+Functions`.

5 At the End of the Night

There are a few things we'd like you to do (and don't do) before you call it a night:

- Fill out the Astronomer's report using the "nightlyreport.app" you'll find on the desktop.
- Kill the LOUI by clicking on the red button at upper left. (Do *not* "Exit LOIS" first; this would disable monitoring the instrument temperatures. Just. Kill. the. LOUI.)
- Don't kill the terminal window for LOIS either.
- Kill the Target List if you have it up
- Remind the operator to close the instrument cover.
- Gracefully log out of IRAF: type "logout" in the xgterm window. You might even want to close the window.
- Kill the ds9 display.

6 A Quick Look at Quick Look

As you observe you'll of course want to be keeping tabs on how things are going. There are two basic ways to do this; I like to use a combination of them.

6.1 LOUI/LOUIS Quick-look tools

- Every time an image reads down, you will find the peak counts, average counts, and standard deviation displayed in brown. These come from a 100×100 box at the center.

- Moving the cursor around in the image area will also show x, y, and value. (If this isn't working, make sure that the image display is "active" by clicking in the imager window.)

- Typing a "c" with the cursor on a star will give the x and y centroid, the, the FWHM, a magnitude, and the peak counts. "c" keystroke invokes LOIS' "phot" command with a reasonable set of defaults. Note that this can only be run when LOIS is idle; otherwise, the command will simply queue.

If you are unsure what is what, simply positioning the cursor over the string of numbers will identify the output.

LOUI provides additional quick-look options which we describe here, but there's an important caveat: in order to display the large LMI images, LOUI uses an internal "binning" (actually, sampling). You can see the LOUI Binning Factor (LBF) listed in the image view. That means that most LOUI quick-look functions, such as pixel dumps, line and column plots are not actually showing you the values for all of the pixels—but (likely) every other pixel.

You will see Pixel Dump and Line Profile tabs next to the LMI Control and User Button at upper right.

- PixelDump: This allows one to get a pixel dump of the image in the image view. You place the cursor in the image, and hit "p". But, be warned: these are "sampled" values because of the additional sampling that LOUI does for the display, so the peak intensity of a star won't be correct (except by accident), and similarly a bad column or other defect may escape notice. Note also that the x and y values are off by a factor of 2, due to the LOUI Binning Factor. This is a known bug, and will be fixed some day, perhaps.

- LineProfile: This allows the user to make line and column plots: a "l" in the image display will display just the region that is expanded in the image view, while an "L" will provide line and column plots of the whole image. But, again, be warned: because of sampling, you're not seeing all the pixel values. Note also that the x and y values are off by a factor of 2, due to the LOUI Binning Factor. This is a known bug, and will be fixed soon.

6.2 IRAF quick look

Because LOUI is sampling the images, only the output of "phot" (invoked by a "c") and "box" (automatically invoked when an image reads down) are telling you the complete truth; the other LOUI specific quick-look routines are giving you the results from sampled images. For that matter, "c" also tends to overestimate the FWHM when the values get small (<3). Thus, for critical work I like to use IRAF. Some users are probably well familiar with IRAF, others not. Here is quick guide.

- **Displaying and analyzing images:** The most useful command in IRAF for checking on images is the task **imexamine**. Here are some simple ways to use it. You can also do a "help imexamine" at the IRAF prompt to learn a great deal more.
  - First, display an image in ds9 by doing: **display** <*imagename*> **1**, where <*image name*> is something like lmi.0032. You can then adjust the contrast and brightness by holding down the right side of the mouse and moving the cursor in ds9. If that doesn't work sufficiently, you can be specific about the data range that you are windowing about by doing a **display lmi0032 1 zrange- zscale- z1=900 z2=2000** in order to send the data range 900 to 2000 to ds9.
  - To check the average value and rms in a 51× 51 box near the cursor, use an "m".
  - To determine the radial profile and full-width-at-half-maximum (fwhm) of a star image, position the cursor over the image of the star and type an "r". The fwhm is the last value shown on the graph. This also displays the total number of counts above sky background. See Figure 8.
  - You can do a line plot or a column plot using "l" or "c". But, this is not terribly useful as you can't do much by way of statistics when you do. We prefer to use **implot**; see below.
  - Recall you can always do a "?" while in **imexamine** to see a full list of commands.
  - To quit, type a "q".
- **Examining lines or columns in images:** It's often useful to plot a single column or line of an image and check the background level or the rms. A simple task to do this is **implot**.
  - implot <*image name*> will display a cut through the middle of the image. At the top it will tell you what row ("line") has been plotted.
    * An "s" at two points will tell you the mean and rms between those two points.
    * A ":l 230" will plot line 230. A ":c 512" will plot column 512.
    * To plot an AVERAGE of 53 rows or columns, do a ":ave 53" before issuing the ":l" or ":c" commands.
- Header contents: **imhead** and **hselect**
  - We find that it's useful to see what images we've taken; an **imhead *.fits** will list the sizes and titles of each image.
  - If you'd like to substantiate that what is going into the headers is what you need to be going into the headers (always a good idea), select an image and do an **imhead** <*imagename*> **l+**. The "l+" tells it to make a *long* listing, including all of the FITS key words.

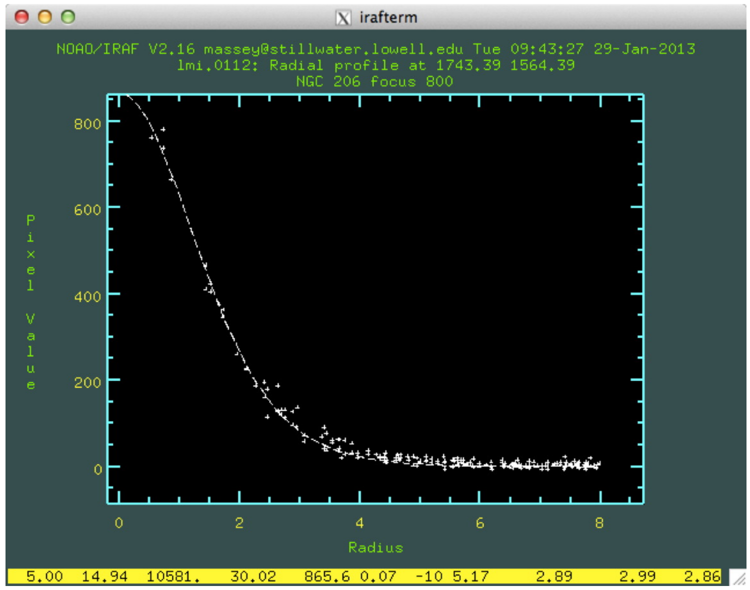


Figure 8: . A radial plot from imexamine produced by centering the cursor on a star in ds9 and hitting an "r". Note from the graph that the peak counts are roughly 800 (above sky). The output below the plot gives the size of the measuring radius (5.00 in this case), the instrumental magnitude (14.94), the total number of counts above sky in the 5-pixel radius aperture (10,581), the mean background (30.02), the peak value above sky (865.6), the ellipticity and position angle (0.07 and -10°, respectively), the beta value for the Moffat profile fit (5.17). There are then three measures of the fwhm, of which I prefer the last. (For more information see the IRAF help page for imexam). In this case, the fwhm is about 2.9 pixels, or 0″.7.

- Just want to see what a single value is from your header? Do an **hselect** <*imagename*> **exptime yes** in order to see the value for the exposure time. Or you can list such values for all images: **hselect *.fits $I,exptime yes**. The $I prints out the name of the image.

7 Taking Your Data Away With You

Remember those awkward days of writing exabyte or DLT tapes, or spending half an hour while you burn a DVD? What I find works really well is one of the following:

- Bring an external USB disk with you to the telescope. I have a fine 0.5TB drive that fits into my shirt pocket, and now a days costs about $50. Once you've plugged it in to dct-obs1' or dct-obs2' USB port (behind the screen), just do a "cp /lmi/<*ut date*>" to your drive.
- Alternatively, simply sftp to observer@dct-obs1 (password on the whiteboard), cd /lmi/<*ut date*>, and **get *.fits**.

To keep in mind the storage capability and transfer times, consider that each 2×2 binned image is about 19.3MB. If you took a 100 images in a night (likely), this would be 1.9GB. If you took 1000 (unlikely!) that would be 19GB. So, this is hardly big stuff. If you haven't binned, the storage requirements are 4× larger.

The files you see on the observing computer are actually just a copy of the "original" data, and the data is also backed up off-site. 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.

8 Trouble Shooting

So far, our experience with LOUI/lois as implemented at the LDT has been that it has been remarkably trouble free. Here are a few of the more common gotchas.

- Problem focusing in non-2x2 binning mode? If you're trying to focus using some binning other than 2x2, and the star isn't there there in the subframe, make certain that the parent image you're using to identify the star has the binning you want, *and* that the same binning value is set in the focus parameter menu. **These values must match.** For instance, if you've taken an image in 3x3 mode and now want to run a focus sweep using one of the stars on that image, make sure that you've set the value after "bin" in the focus parameter menu to 3. If you haven't, the focus sweep will definitely fail. If you're still having problems, try exiting lois, killing the LOUI, and bringing things up afresh. Make sure that your TO notes this in the log.

- Filter move fails. Very occasionally a filter move fails to complete. The problem is that this is likely to mess up the focus value as well. Here's what you should do to recover:
  - Home the relevant filter wheel. You might as well home the other filter wheel too. *Note that if you're starting from filter position 1 in the upper wheel, and go to home it, nothing will happen. Move to some other filter before doing the home.*
  - Move the filter to whatever you used for your last successful focus run.
  - Manually enter the focus value you adopted after your last successful focus run.
  - Move the filter to what you now want to use.
  - Note that if the filter doesn't move, something is messed up. Try closing LOUI and reopening it. If that doesn't solve the problem, consult with your TO about rebooting JOE. Note that there's little (no) point in restarting LOIS: the LOUI talks to JOE, and JOE talks to the filter wheel.

- Pattern/dither file hangs during execution. Oh, boy. Look, the pattern/dither files are "delicate." Treat them gently, particularly in aborting them. If you do have to abort them, don't expect an immediate clean recovery experience. I always close and restart LOUI if I have to abort a pattern file. Also, remember, when you have a script (pattern file) running, the display is in the LMI control view is not going to show you the correct position of the filters, and you will definitely mess things up if you try to interact with the filter wheel if a pattern is running or hung. If a filter wheel issue caused the hang-up, abort the pattern, close and reopen LOUI, and follow the above instructions for recovering from a filter move failure.

- In order to avoid unpleasant surprises, LOIS has been configured so that a number of conditions result in the exposure being "blocked". For instance, if the telemetry stream coming from the telescope is missing some information when you go to take the exposure, you'll be issued a warning in the LOIS log window and the exposure won't happen. However, as the message tells you, if you are insistent and press "go" a second time the exposure will happen. However, if the condition leading to the block still prevails after you have taken the exposure anyway, you will get red messages in the LOIS log at the end of the exposure traffic, saying something like “The telemetry is still bad.” These messages will disappear at the next exposure you take after the problem is resolved. We thought that a good way of getting your attention might be to not let the exposure proceed, but after that what you do is up to you.

- If nothing seems to be happening when you go to take data with LOUI, maybe LOIS is not running or else is “busy”. Do an “st” in the lemi terminal window. Does it list LOIS as “busy”? If so, click on “Stop series”. This should get LOIS to stop doing whatever it is that it’s doing. If that doesn’t solve the problem, click on “Exit LOIS”, and check with an “st” on lemi that LOIS is not running. Restart it by doing a “lois &”. Do a new “initialize LOIS” on LOUI.

- If you’re like me, you’ve pulled the various views onto the desktop at some point to see if you liked the arrangements, and then failed miserably to put them back where they belonged. You can put things back to normal by going to window→Reset Perspective at the top menu bar when LOUI is active.

- You’ve started things up, but nothing, but nothing, seems to work, and all you get are scary looking red error messages or pop-up windows. Take a deep breath. Did you remember to hit the green “initialize LOIS” button in the upper right corner? Give it another shot. If that fails, I would ssh obslemi@lemi in a terminal window, do an “st”, and see if lois is running.. I’d also close LOUI, reopen it, and do “initialize LOIS” again. My experience is that the system behaves very solidly, but because the start-up is complex, it’s easy to have overlooked a step. If need be you can kill lois from the terminal window and start over. This can be perilous particularly if it is done with an exposure under way. It is best to solicit advice via the operator first. If you do kill lois, do it at level 9 (kill -9 ¡pid¿). An ordinary kill will usually do nothing and sometimes leaves lois in an unresponsive state.

- What if you accidentally delete an image (or images)? The good news is that each image is stored in two place, one on dct-obs1 on /lmi as described elsewhere, and on in an “undisclosed location” on an archiver. You can’t get to the archiver, but the telescope operator can. So, talk to the TO if you’ve done something you wish you hadn’t.

Who Are You Going to Call? For things that go significantly wrong at night so that they hamper observing, let the telescope operator know, and she/he will initiate the appropriate phone calls to get you back on the air and happy. For questions that can readily wait until the next morning (“How do I change the size of the measuring radius in **imexamine**?”) email phil.massey@lowell.edu.

9 Acknowledgements and Credit Line

LMI was designed by Edward Dunham, and built by Ralph Nye, Rich Oliver, and Steve Lauman. The control software and user interface for LMI were written by Peter Collins and Saeid Zoonemat Kermani; Saeid also provided the Observer Target List application described in Appendix A. Funds for the construction of the instrument were obtained from the National Science Foundation through AST-1005313 (PI: Philip Massey). Edward Dunham, Jeff Hall, Deidre Hunter, and David Schleicher all made invaluable contributions to the NSF proposal. Lowell’s Millennium Fund has also provided important support for finishing many of the commissioning tasks. The Mount Cuba Astronomical Foundation provided funds for some of the filters as well as for the replacement of the front element of the corrector. The original concept of basing the LDT’s imager around a single large chip was due to Bob Millis, who also came up with the

name. This manual is a work in progress, and so far has received useful comments from Peter Collins, Deidre Hunter, Matthew Knight, Stephen Levine, Larry Wasserman, and Saeid Zoonemat Kermani, although any errors or omissions remain the responsibility of the author.

And don't forget that in any publications that use LMI, please, please, please include the following in the acknowledgements: "These results made use of the Lowell Discovery Telescope at Lowell Observatory. Lowell is a private, non-profit institution dedicated to astrophysical research and public appreciation of astronomy and operates the LDT in partnership with Boston University, the University of Maryland, the University of Toledo, Northern Arizona University and Yale University. The Large Monolithic Imager was built by Lowell Observatory using funds provided by the National Science Foundation (AST-1005313)."

10 What Time Is It, Anyway?

We've always known that there was some small offset between when the shutter actually opens and what is recorded in the header information. Although this might not be of concern to many observers, an accurate knowledge is useful to others, such as those doing astrometry of near-earth objects. Nick Moskovitz proposed an intriguing experiment to measure this delay accurately using observations of near-earth satellites whose ephemerides. The data were collected by Teznie Pugh and Jason Sanborn, and analyzed by Stephen Levine. The full details are giving in their writeup. In summary, the shutter opens 2.05 ± 0.06(ran) $\pm\, 0.1$ (sys) seconds *later* than what is recorded in UTCSTART and closes 0.19 ± 0.06(ran) $\pm\, 0.1$ (sys) seconds *earlier* than what is recorded in UTCEND.

A Observer Target List

Probably shouting the coordinates over to the telescope operator is not the most efficient way of conveying the information, and it has some potential error associated with it. Instead, there is an astronomer-friendly interface that allows one to construct an observing list and send the object coordinates to the operator. Full details can be found at `http://confluence.lowell.edu/display/DCTIC/Observer+Target+List`. The format of the file is similar to that of the Slew-Dither files: at the top of the file there should be a line that specifies what information will be included. A simple example is shown in Fig. 9.

```
#title=true ra=true dec=true epoch=false muRA=false muDec=false magnitude=false dRA=
false dDec=false rotatorPA=false rotatorFrame=false
#
"Field 1" 01:34:16.88 +30:49:53.4
"Field 2" 01:34:12.16 +30:43:45.9
"Field 3" 01:33:47.79 +30:36:59.1
```

Figure 9: A simple observer target list. Only the object name, RA, and DEC are specified.

The possible fields for inclusion are:

- **title**: This needs to be surrounded by double quotes and will be sent to the TCS as the science target name. It cannot be blank. REQUIRED.
- **ra**: The J2000 right ascension in hh:mm:ss.sss format. The seconds can be either an integer or a floating-point number. REQUIRED.

- **dec**: The J2000 declination in in +/-dd:mm:ss.ss format. The seconds can be either an integer or a floating-point number. The "+" is option. REQUIRED.

- **epoch**: the epoch for the proper motion. The only allowable value is J2000.0, no leaving epoch=false is probably the best idea.

- **muRA**: proper motion in RA (mas/yr). Note that this is actually $\mu_\alpha \times \cos\delta$, which is what most catalogs (and SIMBAD) provides.

- **muDEC**: Proper motion in Dec (mas/yr).

- **magnitude**: Magnitude. The option to include magnitude is in case the observer wishes to sort the table based on brightness. It is not used by the TCS.

- **dRA**: non-sidereal tracking rate in RA in units of arcseconds/hour.

- **dDec**: non-sidereal tracking rate in DEC in until of arcseconds/hour.

- **rotatorPA**: The rotator position angle in degrees. With the rotatorFrame="Target", the default angle of of 0 results in LMI having images whose columns are rows are aligned with the cardinal directions as given in in Section , i.e., N up and E to the left when using the default amplifier A. Setting this the rotator PA to 30° will change this orientation by 30° from north through east. In rotatorFrame="Fixed" mode this angle is instead the mechanical angle of the rotator, ignoring the sky orientation. (This mode is primarily an engineering mode.)

- **rotatorFrame**: Valid choices are either "Target" or "Fixed," without the quotes. The use of "Target" (the default) is the only reasonable one for normal observing.

The fields should all be separated by at least one space. The columns do not have to line up but extra spaces can be inserted if it makes you happy.

Note: in constructing this file, make sure you use a text editor such as vi or emacs. Do *not* use TextEdit, as this doesn't use the standard ASCII double quote character. It will be helpful if you give the file the extension ".tls" (for target list), as this is what the program will look for.

To use the tool, do the following:

1. If you've brought the file with you on your laptop, sftp it over to "observer@dct-obs1)." A convenient place to put it is the desktop, but it sure would be nice if you moved the file to the trash at the end of your run.

2. Start the tool by double-clicking the "observerTargetListTool" icon on the desktop.

3. Once started, the "Observer Target List" menu will appear at the upper left on the screen. Go to File → Open Target List:

4. Open Target List will open a standard dialog box for selecting the input file. The default extension for the input file is ".tls" (for "target list") and all other types are greyed out simply to make it easy to recognize the file among all the other files that might be in a directory. The input file has to be a standard ASCII text file but it can have any extension (or none at all). Binary files will not be read correctly.

   The open file dialog box allows selection of other file extensions via a drop down menu. The user can choose "All Files (.)" from the file type drop down menu and that allows selection of any file in the directory. The files other than *.tls would still be grey but they can be selected and loaded into the app.

Multiple input files can be used during one session and each file would be loaded into a separate tab.

5. The process of sending the target to the TCS is a 2 step process. First a target is selected from the table. The data is loaded into the upper view for a final check by the observer. It can be sent to the TCS as a science target by pressing the button. Issuing this command can result in either the telescope moving immediately to the target, or simply loading the target into the preview pane for the telescope operator's approval. The behavior can be selected on the TCS's UI and cannot be controlled by the observer from the app. The selection is persistent until changed by the operator. You can check which mode the system is in by looking at the "External Target Command" label, which will either say "Preview" (the operator checks) or "Direct" (the telescope just goes there).

Note that we provide several observing lists in the **PhotStds** folder on the desktop.

- AA2014_ubvri.tls—Astronomical Almanac for 2014 list of UBVI standards (section H), which is basically the list from Landolt (2009). This is there in case you need it, but most observers will prefer landolt09.
- clem13.tls—Clem & Landolt (2013): Faint UBVRI standard star fields
- landolt09.tls—Landolt (2009): UBVRI photometric standards around the celestial equator. This is the preferred list. Finding charts are available locally on dct-obs1 by going into the landolt09 subdirectory in the PhotStds folder.
- landolt02.tls—Landolt (1992): UBVRI photometric standard stars in theMagnitude Range $11.5 < V < 16.0$ around the celestial equator. This is available if you need it for a particular reason, but most observers will preferred landolt09.tls.
- clem07—Clem, Vandenberg, & Stetson (2007): Secondary standard stars for the u'g'r'i'z' photometric system.
- hbstand.tls—Farnham, Schleicher, & A'Hearn (2000), The HB narrowband comet filters: standard stars and calibration.

B How To Reduce Your Data with IRAF

Here is a fairly complete list of everything I did to reduce some recent images. I'm assuming you've reduced a bunch of images with IRAF before. If not, please have a look at `http://iraf.net/irafdocs/ccduser3/`

1. **hselect lmi*.fits $I,imagetyp,filters,exptime,title** This allowed me to check that the filter values were fine, that the images were what I thought they were, and so on. If you've used sky flats as your primary flats (as recommended) then they need to have image-types of "DOME FLAT" rather than "SKY FLAT." You can readily change this by **hedit imagename.fits IMAGETYP 'DOME FLAT' up+ ver- show+**. If that offends your sensibilities, you can do a copy ccddb$kpno/kpnoheaders.dat lmi.dat, and then edit lmi.dat so that an imagetyp of 'SKY FLAT' translates to a 'flat' and not an 'object'. If you do this, you must reset "instrum" to lmi.dat in ccdred. **If you want to interpolate over the one bad column at 1597 (binned 2x2), download the bad pixel mask bad.pl.**

2. Do the basic combination of bias frames and flats after overscan removal:
   - Create a backup directory called "Raw": **mkdir Raw**
   - **imred**
   - **ccdred**
   - **setinstrument direct** You'll be thrown into the parameter editor for ccdred. Change backup to Raw/, and exit with a CNTL-D. You'll then find yourself in the parameter editor for ccdproc. For now, set images=lmi*, fixpix=yes, overscan=yes, trim=yes, zerocor=no, flatcor=no, illumcor=no, fixfile='bad.pl', biassec=[3100:3124,3:3079], trimsec=[30:3094,3:3079], interact=no, function=chebyshev, order=1
   - Create a master bias frame by running **zerocombine lmi*.fits process=yes**.
   - epar ccdproc and turn zerocor to yes, and zero=Zero.
   - **flatcombine lmi*.fits**. Be sure to examine the result FlatX frames to make sure that any stars present in your sky flats have disappeared.

3. Now process all of your images:
   - **epar ccdproc** and turn flatcor to yes, and flat=Flat*
   - **ccdproc lmi*.fits**

Note: the above assumes that you want to interpolate over the one bad column. You may, or may not. First, the bad column isn't really that bad; it's a partial charge trap and how much it affects your data depends upon the exposure level. Second, interpolating over it isn't going to give you good photometry for stars along that column. Maybe instead you want to flag it as something awful by setting all the pixels along the column equal to whatever you use as your saturation limit.

Probably the best thing to do, though, is to dither your data when you observe: take three or more exposures using a dither pattern similar to what we present in Figure 6. Then you can do the photometry separately on your images and combine the results judiciously. Alternatively you can make a combined image by using **imalign** or a similar tool.

The LMI chip is a deep-depletion device has fringes minimally, but once you get to the z-band, minimally is still a lot. If you've observed in 3×3 mode in the z-band, you may find Nick Moskovitz's master fringe frame to be of benefit: `https://github.com/astromosk/imred/blob/master/fringe_med_cr_norm.fits`.See the IRAF ccd reduction manual referenced above for how to interactively scale and remove fringes.

C Filter Transmission Specifications

- U: Andover ANDV12683 S136-01
  - Construction: 1mm UG-1 + 1.25mm S8612 + 3mm WG-305
  - Transmission data: http://www2.lowell.edu/users/massey/LMI/U.txt.
  - Transmission plot: http://www2.lowell.edu/users/massey/LMI/U.eps.
  - $4.752 \times 4.752 \times 0.206$ inches.
- B: Andover ANDV12684 S138-01
  - Construction: 1mm GG385 + 2mm S8612 + 1mm BG12
  - Transmission data: http://www2.lowell.edu/users/massey/LMI/B.txt.
  - Transmission plot: http://www2.lowell.edu/users/massey/LMI/B.eps.
  - $4.752 \times 4.752 \times 0.157$ inches.
- V: Andover ANDV12685 S141-01
  - Construction: 2mm GG495 + 2mm S8612
  - Transmission data: http://www2.lowell.edu/users/massey/LMI/V.txt.
  - Transmission plot: http://www2.lowell.edu/users/massey/LMI/V.eps.
  - $4.752 \times 4.752 \times 0.157$ inches.
- R (Kron-Cousins): Andover ANDV12686 S136-01
  - Construction: 2mm OG570 + 3mm KG3
  - Transmission data: http://www2.lowell.edu/users/massey/LMI/R.txt.
  - Transmission plot: http://www2.lowell.edu/users/massey/LMI/R.eps.
  - $4.751 \times 4.751 \times 0.198$ inches.
- I (Kron-Cousins): Andover ANDV12687 S147-01
  - Construction: 2mm BK7 + 3mm RG9
  - Transmission data: http://www2.lowell.edu/users/massey/LMI/I.txt.
  - Transmission plot: http://www2.lowell.edu/users/massey/LMI/I.eps.
  - $4.752 \times 4.752 \times 0.196$ inches.
- HαON: Andover ANDV12688 S183-01
  - Construction: Interference filter λ=6564.9Å, $\Delta\lambda$=30.1Å(50%)
  - Transmission data: http://www2.lowell.edu/users/massey/LMI/HaON.txt.
  - Transmission plot: http://www2.lowell.edu/users/massey/LMI/HaON.eps.
  - $4.753 \times 4.753 \times 0.215$ inches.
- HαOFF: Andover ANDV12689 S138-01
  - Construction: Interference filter λ=6459.1Å, $\Delta\lambda$=114.6Å(50%)
  - Transmission data: http://www2.lowell.edu/users/massey/LMI/HaOFF.txt.
  - Transmission plot: http://www2.lowell.edu/users/massey/LMI/HaOFF.eps.
  - $4.753 \times 4.753 \times 0.215$ inches.

- VR: Andover ANDV12690 S160-01
  - Construction: Interference filter λ=6091.7Å, $\Delta\lambda$=1763.9Å(50%)
  - Transmission data: http://www2.lowell.edu/users/massey/LMI/VR.txt.
  - Transmission plot: http://www2.lowell.edu/users/massey/LMI/VR.eps.
  - 4.753×4.753× 0.265 inches.
- OIII: Andover ANDV13944 U317-02
  - Construction: Interference filter λ = 5011.7Å, $\Delta\lambda$ = 25.5Å(50%)
  - Transmission data: http://www2.lowell.edu/users/massey/LMI/OIII.txt.
  - Transmission plot: http://www2.lowell.edu/users/massey/LMI/OIII.eps.
  - 4.751×4.751×0.275 inches
- WC: Andover ANDV15240 X259-02
  - Construction: Interference filter λ=4660.4Å, $\Delta\lambda$=49.5Å(50%)
  - Transmission data: http://www2.lowell.edu/users/massey/LMI/WC40.txt.
  - Transmission plot: http://www2.lowell.edu/users/massey/LMI/WC.eps.
  - 4.727×4.726× 0.232 inches.
- WN: Andover ANDV15241 X259-02
  - Construction: Interference filter λ=4690.9Å, $\Delta\lambda$=49.6Å(50%)
  - Transmission data: http://www2.lowell.edu/users/massey/LMI/WN41.txt.
  - Transmission plot: http://www2.lowell.edu/users/massey/LMI/WN.eps.
  - 4.724×4.725× 0.238 inches.
- CT: Andover ANDV15242 X259-02
  - Construction: Interference filter λ=4756.1Å, $\Delta\lambda$=54.6Å(50%)
  - Transmission data: http://www2.lowell.edu/users/massey/LMI/CT42.txt.
  - Transmission plot: http://www2.lowell.edu/users/massey/LMI/CT.eps.
  - 4.728×4.727× 0.239 inches.
- Sloan u: Asahi
  - Construction: 2mm KG3 + 1mm UG11 + 4mm fused silica + interference film
  - Transmission data: http://www2.lowell.edu/users/massey/LMI/u-band.txt
  - Transmission plot: http://www2.lowell.edu/users/massey/LMI/Sloanu.eps
  - 4.750×4.750×0.277 inches
- Sloan g: Asahi
  - Construction: 2mm GG400 + 2mm BG40 + 3mm fused silica + interference film
  - Transmission data: http://www2.lowell.edu/users/massey/LMI/g-band.txt
  - Transmission plot: http://www2.lowell.edu/users/massey/LMI/Sloang.eps
  - 4.750×4.750×0.277 inches
- Sloan r: Asahi
  - Construction 4mm OG550 + 3mm fused silica + interference film
  - Transmission data: http://www2.lowell.edu/users/massey/LMI/r-band.txt

– Transmission plot: http://www2.lowell.edu/users/massey/LMI/Sloanr.eps
– 4.750×4.750×0.277 inches

- Sloan i: Asahi

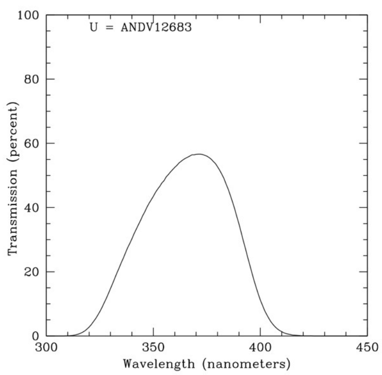
  – Construction: 4mm RG695 + 3mm fused silica + interference film
  – Transmission data: http://www2.lowell.edu/users/massey/LMI/i-band.txt
  – Transmission plot: http://www2.lowell.edu/users/massey/LMI/Sloani.eps
  – 4.750×4.750×0.277 inches

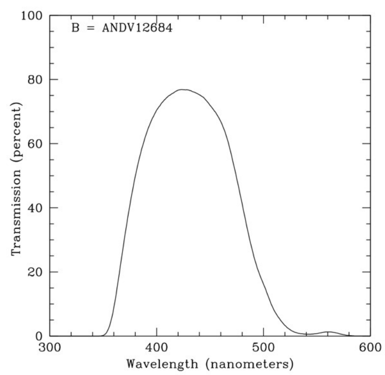
- Sloan z: Asahi

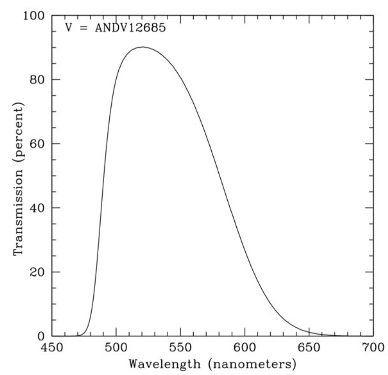
  – Construction: 4mm RG695 + 3 mm fused silica + interference film
  – Transmission data: http://www2.lowell.edu/users/massey/LMI/z-band.txt
  – Transmission plot: http://www2.lowell.edu/users/massey/LMI/Sloanz.eps
  – 4.750×4.750×0.277 inches

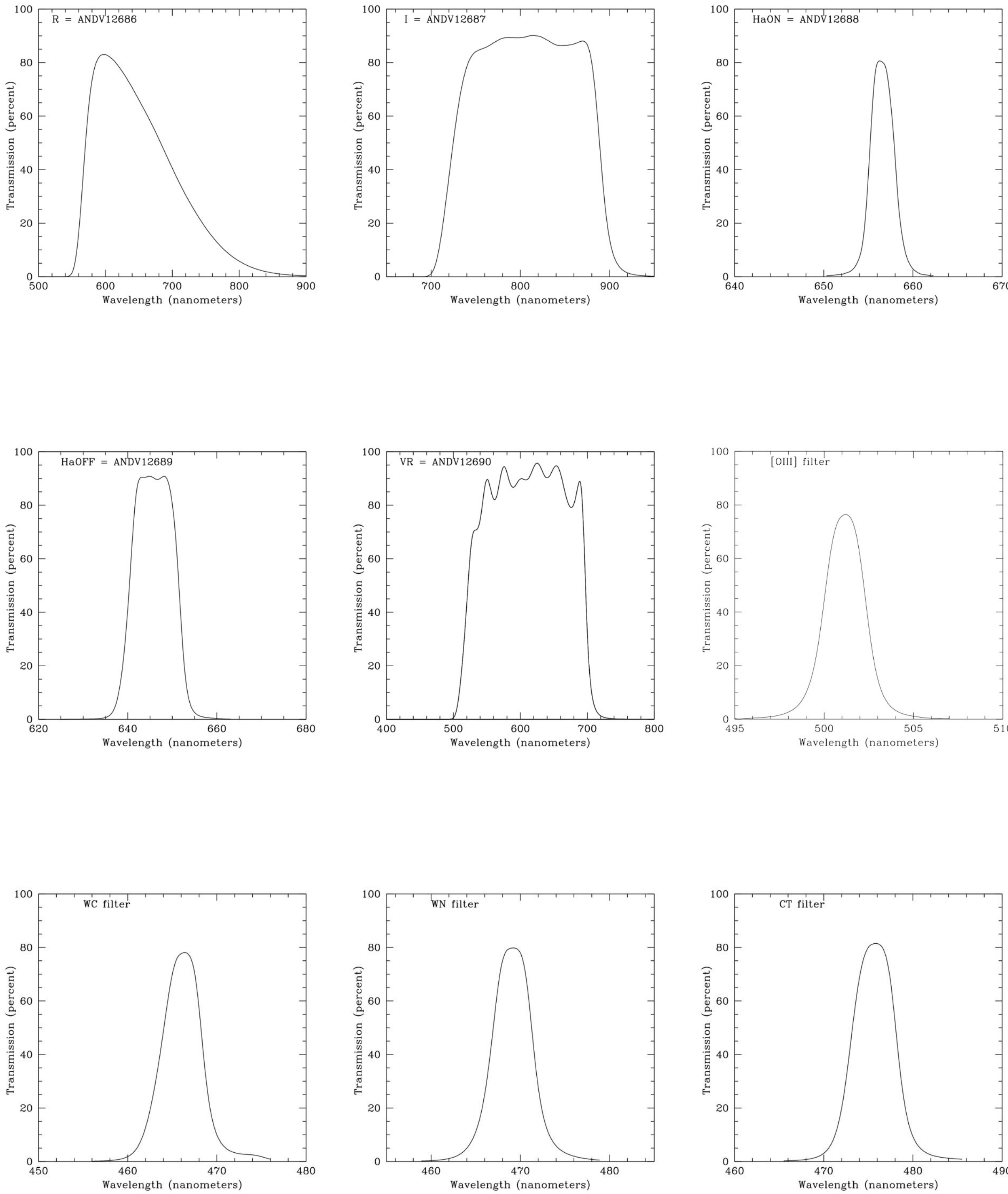
- Y-ish: Asahi

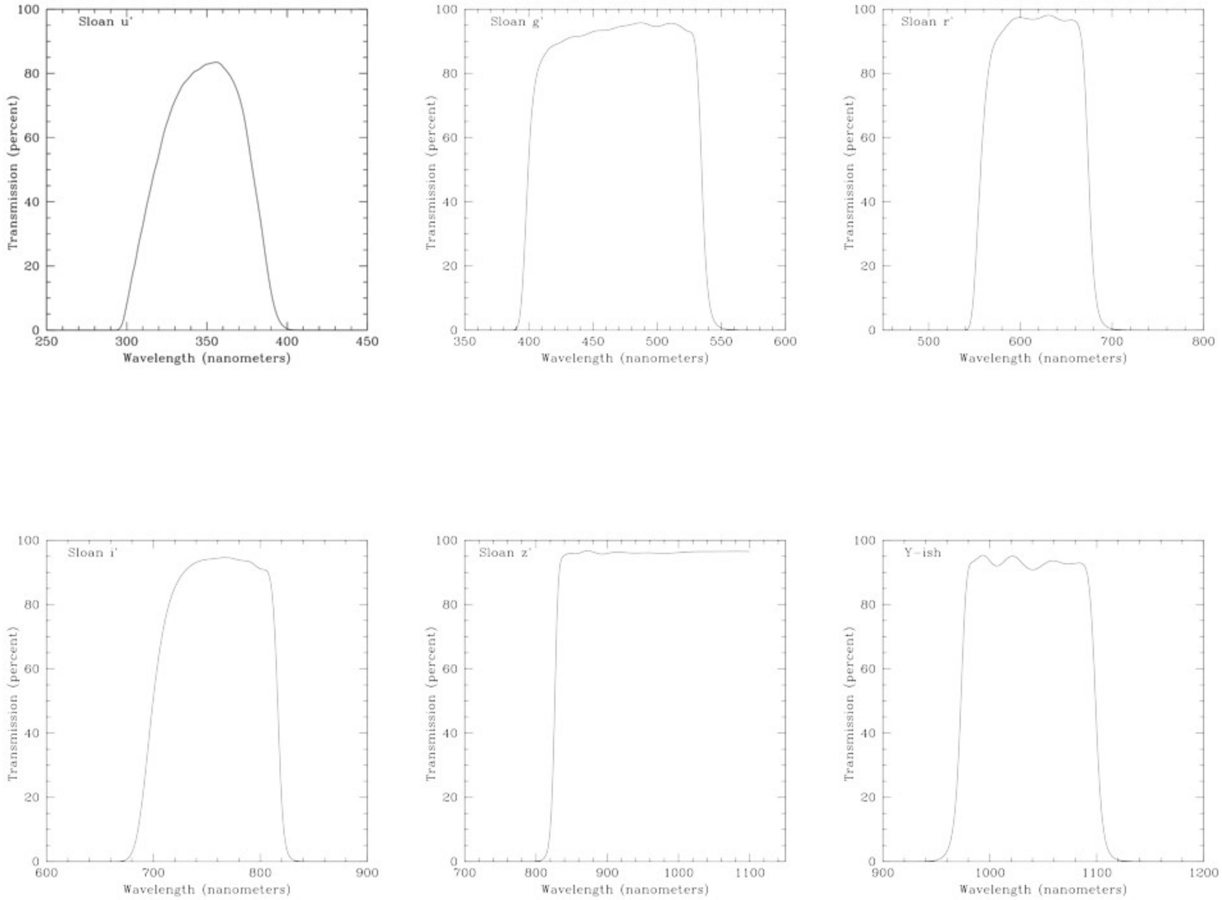
  – Construction: 4mm RG695 + 3 mm fused silica + interference film
  – Transmission data: http://www2.lowell.edu/users/massey/LMI/Y-band.txt
  – Transmission plot: http://www2.lowell.edu/users/massey/LMI/Y.eps
  – 4.750×4.750×0.277 inches

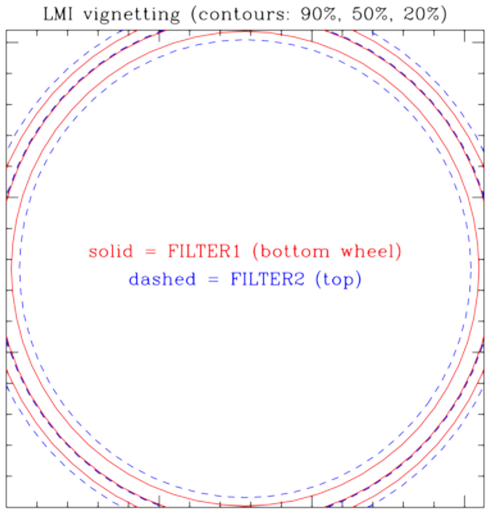


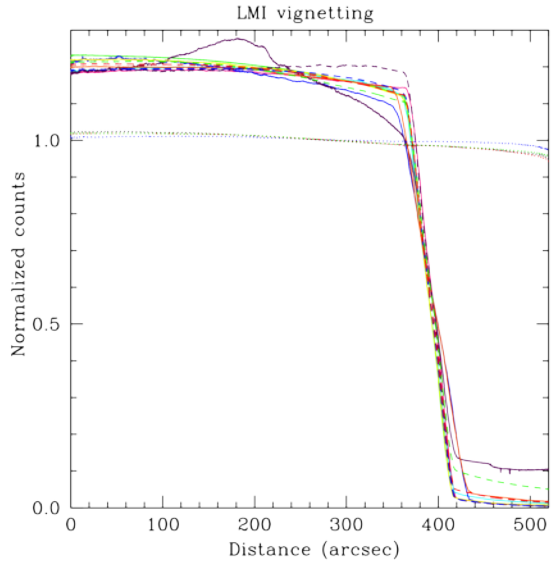





R = ANDV12686
I = ANDV12687
HaON = ANDV12688
HaOFF = ANDV12689
VR = ANDV12690
[OIII] filter
WC filter
WN filter
CT filter
Transmission (percent)
Wavelength (nanometers)


Sloan u'
Sloan g'
Sloan r'
Sloan i'
Sloan z'
Y-ish
Transmission (percent)
Wavelength (nanometers)





In addition, a set of 11 narrowband HB comet filters is also available; check with Dave Schleicher for access. These interference filters are all either 4 or 5-cavity designs, intended to isolate comet emission bands and associated continuum points. The filters and associated calibrations are described in (Farnham, Schleicher, & A'Hearn 2000, Icarus 147, 180).

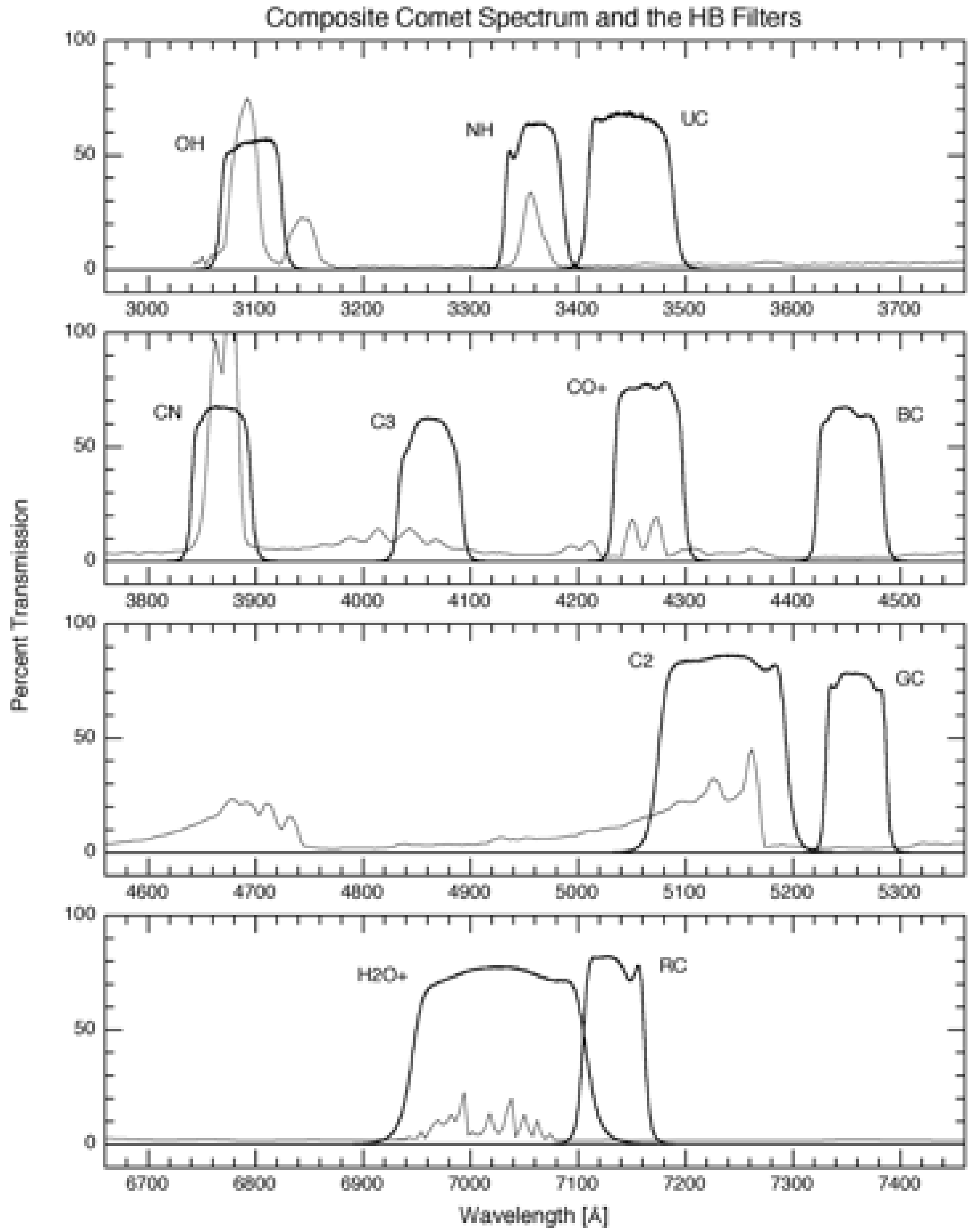
The 11 filters are 4 inches round and suffer some vignetting, differing somewhat for the two filter wheels, as shown in above. The characteristics are shown below.

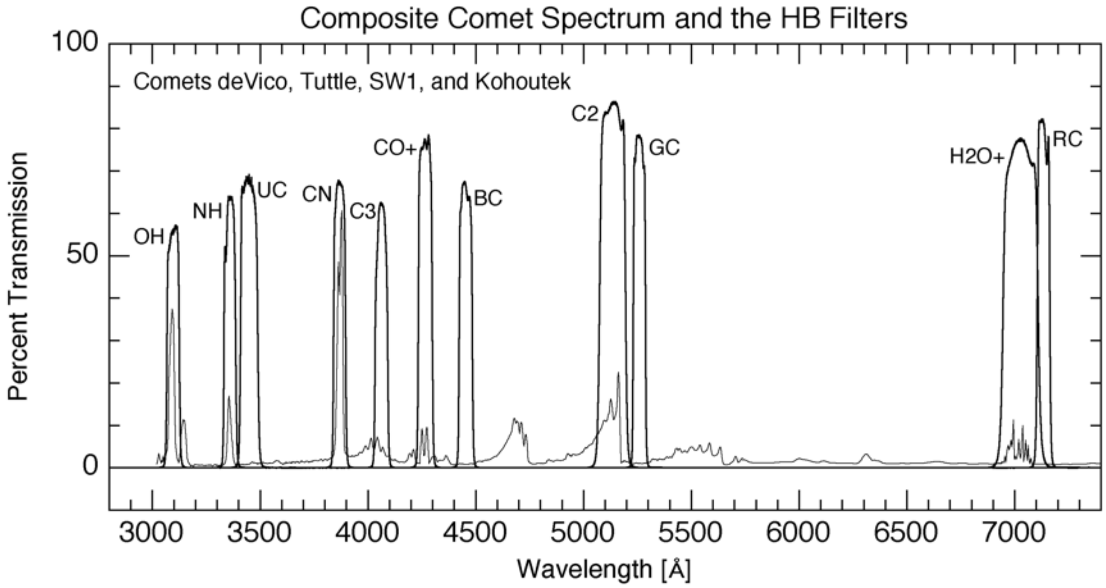
TABLE I

Representative Filter Characteristics

Species	ID	Designation	Transmission[a] (%)	CW[b] (Å)	Power point width[c] (Å) 80%	50%	10%	1%
OH (0-0)	OH	3090/62	56	3097	52	58	68	87
NH (0-0)	NH	3362/58	63	3361	47	54	64	81
UV continuum	UC	3448/84	67	3449	72	79	93	116
CN (Δv=0)	CN	3870/62	67	3869	50	56	65	82
C_3 (Swings system)	C3	4062/62	62	4063	43	58	69	84
CO^+ (2-0)	CO+	4266/64	77	4266	58	64	74	90
Blue continuum	BC	4450/67	65	4453	55	61	71	86
C_2 (Δv=0)	C2	5141/118	85	5135	109	119	140	171
Green continuum	GC	5260/56	78	5259	52	56	65	79
H_2O^+ (0,6,0)	H2O+	7020/170	75	7028	148	164	193	239
Red continuum	RC	7128/58	80	7133	53	58	71	92

[a] Measured mean peak transmission.
[b] Measured center wavelength.
[c] Measured full-width power points.


Composite Comet Spectrum and the HB Filters
Percent Transmission
Wavelength [Å]
OH
NH
UC
CN
C3
CO+
BC
C2
GC
H2O+
RC


Composite Comet Spectrum and the HB Filters
Comets deVico, Tuttle, SW1, and Kohoutek
OH
NH
UC
CN
C3
CO+
BC
C2
GC
H2O+
RC
Percent Transmission
Wavelength [Å]
0
50
100
3000
3500
4000
4500
5000
5500
6000
6500
7000