8 CCD Image Processing & Analysis: A Practical Example from Start to Finish

The purpose of CCD image processing is to seperate instrumental signals and imperfections (which includes CCD, instrument, telescope and atmosphere) from the astronomical signals. To do so requires (a large amount of) calibration observations, that observers must ensure to obtain along with the data on their science targets.

In this section, we will discuss the case of CCD imaging and point source photometry at a telescope with a camera with a single CCD detector. In the case of large CCD mosaic cameras, one has to rely to a much greater degree on calibration products provided to the observer by the observatory staff, and it may not always be possible to obtain the calibration data (in sufficient quantity or even at all) that one would ideally want. The same is true for very large aperture telescopes run in a *queue scheduling* mode. Telescopes like ESO's VLT have as their formal policy to provide calibration data sufficient to allow calibration of the science product to ∼10%. If larger accuracy is required, then *a calibration program on a smaller telescope* should be initiated in support of the program on the larger telescope.

8.1 Calibration Data to be Acquired at the Telescope

For CCD imaging applications of any type, the following calibration frames *must* be obtained at the telescope. Some will cut into the available time for observations on the scientific targets, while others may be taken in the afternoon before sunset and/or in the morning after sunrise.

- **Bias frames** (*biases*) — Bias frames are 0 sec dark exposures; the shutter stays closed. They are required to determine:
  - the *read-noise* and *gain* of the CCD (see §2.5),
  - whether the bias level shows structure across the *image region* (i.e., the illuminated pixels) of the CCD, and
  - whether the bias levels in the *overscan strip*(s) and in the image region are identical.

  Take at least 20 bias frames both before opening up in the afternoon and after closing down in the morning (this can usually be scripted, or with a command that takes as its argument the number of frames desired).

  △ Beware, that the first (few) bias frames taken in the afternoon — after the CCD has been idle for many hours —, and the first one or two frames after high light level exposures (e.g., flats) should be discarded (see also §2.7 *Transient Effects*).

- **Dark frames** (*darks*) — Dark frames are integrations with the shutter closed. Darks are required to determine:
  - the average bulk dark rate, *dc*, of the CCD [in e^-/pix/hr];
  - whether there are pixels with significantly ($\geq 4\,\sigma$) higher dark rates (i.e., warm/hot pixels or columns);
  - whether there is structure in the dark rate across the image region (e.g., a gradient in the direction of the often slightly warmer amplifier).

  The (maximum) integration time should be at least as long as your longest science exposure. Whenever possible during an observing run, take multiple set of integrations of different lengths (e.g., 10×600 s, 7×900 s, 5×1200 s and 5×1800 s), to allow consistency checks and ensure the (*small*) dark rate is truly detected. This will likely not be possible on a single-night run. Darks can be taken in the afternoon or in the morning, or when clouded out during the night.

  △ Beware, that one should take darks only following a series of biases, to reduce the impact of any transient effects.

  △ If the instrument has light leaks, it may only be possible to obtain reliable darks at night when clouded out — and with all lights in the dome off and with the dome closed.

- **Dome/Pupil/Internal flat exposures** (*dome/pupil/quarz flats*) — Dome flats are exposures of an evenly illuminated screen on the inside of the telescope dome, or of the inside of the dome itself. Pupil flats are only possible with some telescope designs that *have* a pupil between primary and secondary mirrors (in which case they are better than dome flats, because even illumination is not a concern). Most spectrographs have a facility to take *internal incandescence flats*, using a quarz halogen lamp and integrating sphere. Flats are required to determine:
  - the pixel-to-pixel variations in effective sensitivity of the CCD, whether intrinsic to the CCD (QE) or extrinsic (e.g., dust particles)

  These exposures are usually taken in the afternoon before opening up. To be able to correct for such sensitivity variations down to 0.1% (i.e., $S/N = 1000$), one needs to accumulate a total of at least 1,000,000 e^- per filter.

  △ Aim for a level per flat frame of $\sim\frac{1}{2}$ the lesser of the full-well capacity or A/D-saturation level.

  △ Since variations in sensitivity are color-dependent and since flat field lamps rarely ever have the same spectrum as your science object or even as the sky background, the resulting corrections are only approximately correct.

- **Shutter shading exposures** (*shutter flats*) — Dome or pupil flat exposures with a sequence of exposure times starting at very short integrations (e.g, 0.1 sec) up to exposures where shutter shading should no longer be significant (e.g., ∼5–10 sec). The exposures are required to determine:
  - ◦ the effective exposure time across the CCD for a given commanded exposure time *only if the science or calibration observations require short exposures (less than a few seconds).*

  Although shutters are fast, they have to cover a physically large distance. This means that the effective exposure time of pixels that first became illuminated is slightly longer than that of the pixels that became illuminated last. Linear shutters tend to be faster than diaphragm shutters.

  Typically, one needs to take shutter flats only once per observing run in the afternoon, along with regular dome/pupil flats

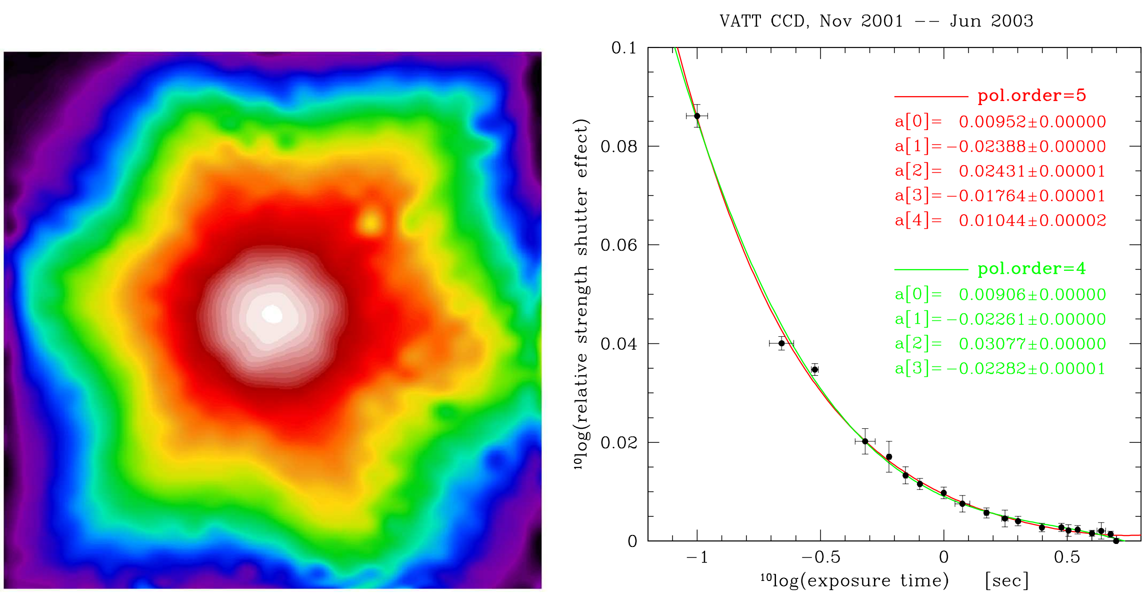

Figure 1: Example of the shading by the diaphragm shutter in the VATT CCD camera. Only the center of the CCD will be exposed during the full commanded integration time — the effective exposure time decreases toward the edges of the CCD in a hexagonal pattern that corresponds to the six blades of the shutter. Once the shape of the shading pattern has been established, a "strength" or scale factor can be fit as a function of commanded exposure time. By dividing the CCD images by the appropriately scaled pattern of the left panel, one can correct for shutter shading. For exposure times longer than $\sim 10^{0.5} \simeq 3\,\mathrm{sec}$, shutter shading becomes negligible for this particular shutter.

- **Twilight sky flat exposures** (*twilight flats*) — Exposures of the evening and morning twilight sky. They are required to determine:

  ◦ the large-scale *illumination* of the CCD. Since the path followed by the light when observing the inside of the dome differs from that when observing the sky, and since the illumination of the dome by the flat field lamps can show gradients in brightness, twilight sky flats are needed to correct for this to first or second order. The scale of brightness gradients on the twilight sky tends to be much larger than the usable field-of-view of a telescope.

    △ Since twilight in Arizona lasts only ∼40 min, you rarely have sufficient time to obtain $\gtrsim$1,000,000 e^- per filter and measure the pixel-to-pixel variations at high S/N in the twilight flats

    △ Since you constantly have to adjust the exposure times to the changing brightness of the twilight sky, the variations in signal level between flats in the same filter are much larger than those in dome flats. This means that rejection algorithms are less efficient, and that the S/N in combining twilight flats does not scale as $\sqrt{N_{e^-}}$ (or $\sqrt{S_S}$).

    △ *Dither your exposures*, i.e, offset the telescope by ∼10″–20″ between each exposure. This will ensure that stars are rejected in the combination of the twilight flats.

    △ *Don't point your telescope at zenith*: Alt-AZ telescopes cannot track there, so stars in the darker portion of twilight will trail and affect more pixels than they should.

- **Night sky flat exposures** (*night sky flats*) — Exposures of the night sky. They are required to determine:

  ◦ the large-scale *illumination* of the CCD *only if the very best quality flat fielding correction is required.*

  Taking night sky flats comes at a large cost, since it directly reduces the amount of time available to observe your science targets. The signal level in night sky flats tends to be a factor ∼10 or more lower than in twilight flats. For some programs it may be possible to use the exposures on the science targets to construct night sky flats.

  △ If you intend to use the science target exposures, then you must dither the exposures in a non-repeating pattern over a sufficient distance to ensure that the targets don't appear (or overlap) in the same spot on the CCD every time!

- **Orientation exposure** — A partly trailed exposure of a star. Such frame is used to determine:
  - which is E and which is W in CCD pixel coordinates.
  - how well aligned the pixel rows (or columns) are with the celestial axes, i.e., the rotation with respect to E–W.

  Unless the instrument is taken off the telescope during a run, one only needs to take one orientation exposure.

  To take such an exposure, center on a star that is bright but won't saturate in a 10 s exposure, then start an unguided exposure of approximate length

$$\sim 10\,\mathrm{s} + \frac{1}{2}\, n_{\mathrm{pix}} \cdot ps \cdot \frac{\cos(\mathrm{Dec})}{15} \quad [\mathrm{sec}]\ ,$$

  where n_{pix} denotes the size of the CCD along a row (or column), ps is the pixel scale (in $''$/pix), and 15$''$/s is the sidereal rate (15°/hour) at the equator, which needs to be corrected for the Dec of the star. After 10 sec, turn off tracking and let the star trail across the image while the exposure continues.

  The slope of the trail gives any slight rotation of the CCD with respect to the celestial axes, while the stellar trail points West from the stellar image in the center of the CCD.

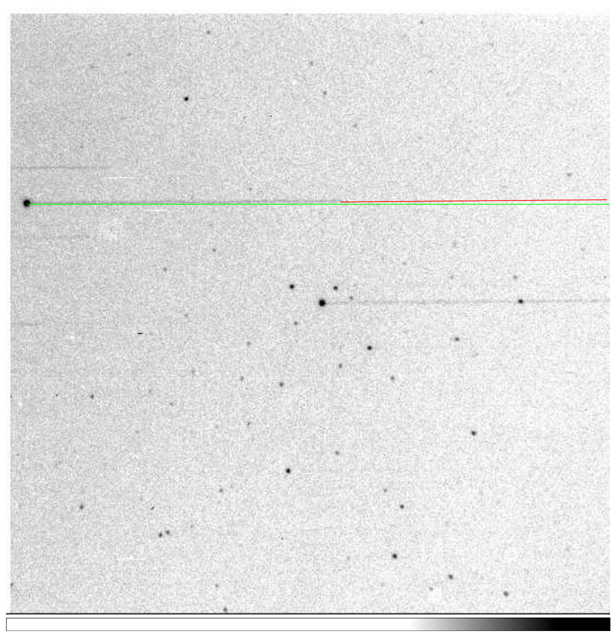

Figure 2: Example of a CCD orientation exposure, obtained at the FLWO 48" telescope. The star trail points W from the stellar image. In this case, the the CCD was rotated $\sim 0\overset{\circ}{.}4$ E of N.

- **Focus exposures** — Exposure or series of exposures at different focus settings. These frames are used to:

  ◦ determine the best current focus (in the current filter) and adjust the focus setting accordingly

  Focus exposures need to be taken periodically throughout a night. Particularly in the first few hours of a night, the telescope may be rapidly cooling down, which causes the focus to change as well. *Autocollimation* and *autofocussing* routines may try to alleviate the problem, but human tweaking of the focus is often required. For example, at the VATT, in the first two hours after opening up, one has to adjust the focus at least once every half hour, in the next $2\frac{1}{2}$–3 hours, once per ∼45 min, and once per hour or so thereafter.

  △ Filters of a particular matched set are often *parfocal*, i.e., changing filters does not change the optimal focus setting. When observing through filters of different prescriptions, one needs to adjust the focus every time when changing filters. Once you know the amount of this adjustment, you do not have to take focus exposures for each change.

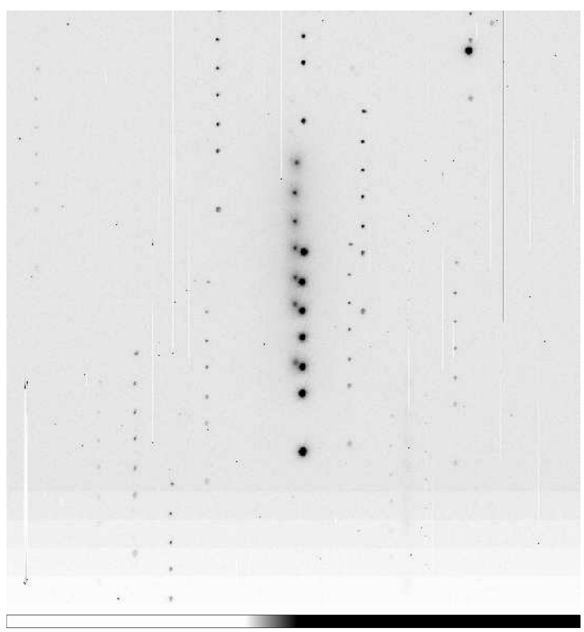

Figure 3: Example of a focus exposure. The exposure consisted of seven integrations, each at a different focus setting. In between each, the collected charge was shifted up 75 pixels along all columns. By measuring the sizes of the PSF's of a few stars at each setting, the correct focus is determined (or interpolated). Note that, in this case, the stars in the field of the science targets (appearing here as a faint and bright smudge) sufficed for taking a focus exposure.

- **(Spectro)Photometric standard star exposures** (*standards*) — Exposures of photometric or spectrophotometric standard stars or standard star fields. These frames are used to:

  - ∘ photometrically calibrate the science target exposures
  - ∘ establish the linearity of the CCD over its entire dynamic range

  The observed pixel intensities need to be calibrated onto a standard photometric system to be physically meaningfull. To do so and correct for atmospheric extinction as well, standard stars/star fields need to be observed 3 or 4 times during each night that is suspected to be (near-)photometric.

  ▷ With the term *photometric* we mean that *the transparency of the sky is* ***independent*** *of the direction in which we point the telescope.*
  (As a corollary: if there is even a single little cloud anywhere above the horizon, per definition conditions are *non-photometric*; if you hear anyone ever claiming that conditions were photometric between the clouds, *run!*).

  Exposures need to be taken in each filter in which science target exposures are taken. Even if the science targets are observed in only one filter, at least one other filter is needed for calibration.

  △ When interupting observations of science targets to observing standard stars, make sure you observe both a field at low airmass (A.M.$\lesssim$1.2) and one at intermediate ($\sim$1.5–1.6) or high airmass (A.M.$\sim$1.8–2.2).

  △ At least once, observe a standard star field in at least one filter using several exposure times that are a factor $\sim$3–5 apart, in order to establish the linearity of the CCD.

  In general, it is a good idea to observe each standard star/star field in each filter using two different exposure times, such that accurate photometry of both the brightest standards and the fainter ones is secured.

8.2 Observing Log of the Imaging Observations

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CCD LOG SHEET
-------------------------------------------------------------------------------
Date:      May  6, 2006                Observatory: Mt.Graham Observatory, VATT
Observers: Rolf A. Jansen              Instrument:  ccd26 (2048x2048,binned2x2)
Program:   Cluster RR-Lyrae variables  Tel.Focus: -186
Weather:   Photometric @ sunset; ~5/8 moon high overhead           Format: FITS

                                 Filterwheel  [1]   [2]    [3]    [4]    [5]
# local time  = UT - 7 h         TOP:          -     B      V      R      I
# pixel scale = 0.3746"/pix      BOTTOM:       -     U      -      -      D
# gain = 1.9
# Lat = 32:42:05 deg; Long = 109:53:31 deg W; Alt = 3191 m
===============================================================================
Obs.# Object       Filt  Texp  UTC     HA    A.M.  Comments
===============================================================================
001- BIAS 20x      -        0 22:00  +0:00  1.000  Biases
-020 BIAS          -        0 22:14  +0:00  1.000
# Filled dewar at 15:30PM; humidity in dome is 26%; temperature in dome is 16 C
# >> Started up telescope.
# Dome tracking is left OFF; Pointed telescope at clear spot on inside of dome.
# Set the RA bias rate to +14.5 "/sec.
021- FLAT 10x      R      1.8 23:12  -3:45  1.669  Dome flats
-030 FLAT          R      1.8 23:20  -3:45  1.669    ~33250 ADU
031- FLAT  5x      R      1.2 23:21  -3:45  1.669  Dome flats
-035 FLAT          R      1.2 23:25  -3:45  1.669    ~22750 ADU
036- FLAT  5x      R      0.7 23:26  -3:45  1.669  Dome flats
-040 FLAT          R      0.7 23:30  -3:45  1.670    ~13750 ADU
041- FLAT  5x      R      0.4 23:31  -3:45  1.670  Dome flats
-045 FLAT          R      0.4 23:34  -3:45  1.670    ~ 8250 ADU
046- FLAT  5x      R      2.5 23:35  -3:45  1.670  Dome flats
-050 FLAT          R      2.5 23:39  -3:45  1.670    ~46750 ADU
051- FLAT 10x      V      6.0 23:41  -3:45  1.670  Dome flats
-060 FLAT          V      6.0 23:50  -3:45  1.670    ~35500 ADU
061- FLAT  5x      V      3.0 23:51  -3:45  1.670  Dome flats
-065 FLAT          V      3.0 23:55  -3:45  1.670    ~17750 ADU
066- FLAT  5x      V      1.0 23:56  -3:45  1.671  Dome flats
-070 FLAT          V      1.0 23:59  -3:45  1.671    ~ 6250 ADU
# Reset RA bias rate to 0 (-> siderial rate); stowed telescope; turned Dome
#   tracking ON; turned off lamp.
# Cleared CCD with several test exposures...
071- BIAS 10x      -        0  0:02  +0:00  1.000  Biases
-080 BIAS          -        0  0:09  +0:00  1.000
# >> Opened up at 18:57PM; Conditions are photometric at sunset.
# Collimation guess: tipx=135, tipy=70, focus -170.
# Evening twilight sky flats...
081- SKY  12x      V      2.5  2:36  +2:54  1.204  Twilight flats B; ~36750 ADU
-092 SKY           V     21.0  2:48  +3:06  1.233  ~33250 ADU
093- SKY  7x       R     20.0  2:50  +3:08  1.237  Twilight flats V; ~32000 ADU
-099 SKY           R    150.0  3:00  +3:18  1.284  ~22500 ADU
# Collimated the telescope: tipx=135, tipy=10. Focus guess -170
0100 focus_run     R      5x7  3:24  +3:40  2.094  focus set to -135; fwhm~1.2"
0101 Rubin149      R       10  3:29  +3:44  2.157  Landolt standard; fwhm~1.13"
0102 Rubin149      R       30  3:30  +3:45  2.173
0103 Rubin149      V       15  3:32  +3:47  2.202
0104 Rubin149      V       45  3:33  +3:48  2.22?
0105 Rubin149      I       15  3:35  +3:50  2.245
0106 Rubin149      I       45  3:36  +3:51  2.263
0107 Rubin149      R       10  3:38  +3:54  2.298  photom.diff.~0.61%
0108 PG0918+029    R       10  3:40  +1:58  1.320  Landolt standard
0109 PG0918+029    R       30  3:41  +1:59  1.324
0110 PG0918+029    V       15  3:43  +2:00  1.329
0111 PG0918+029    V       45  3:44  +2:02  1.334
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0112 PG0918+029    I       15  3:46  +2:04  1.340
0113 PG0918+029    I       45  3:47  +2:05  1.344
0114 PG0918+029    R       10  3:50  +2:07  1.351  photom.diff.~1.16%
0115 PG1047+003    R       10  3:52  +0:41  1.206  Landolt standard; gradient
0116 PG1047+003    R       30  3:53  +0:42  1.208     due to proximity to Moon!!
0117 PG1047+003    V       15  3:54  +0:44  1.209
0118 PG1047+003    V       45  3:56  +0:45  1.211
0119 PG1047+003    I       15  3:57  +0:47  1.213
0120 PG1047+003    I       45  3:59  +0:48  1.214
0121 PG1047+003    R       10  4:01  +0:50  1.216  photom.diff.~0.62%
# It appears to be photometric, consistent with the latest satellite images...
0122 focus_run     R      7x7  4:06  +0:42  1.015  focus set to -185; fwhm~1.10"
0123 NGC9966       R       90  4:16  -2:11  1.354
0124 NGC9966       V      120  4:18  -2:09  1.352
0125 NGC9966       V      360  4:21  -2:06  1.349
0126 NGC9966       R      270  4:28  -1:59  1.341

...  gap of ~1.5 hr ...

0148 NGC9966       R       90  5:59  -0:25  1.089
0149 NGC9966       V      120  6:01  -0:23  1.088
0150 NGC9966       V      360  6:03  -0:21  1.088
0151 NGC9966       R      270  6:10  -0:14  1.087
0152 PG1047+003    R       10  6:20  +3:10  1.759  Landolt standard; gradient
0153 PG1047+003    V       20  6:21  +3:11  1.772     due to proximity to moon!!
0154 PG1047+003    I       20  6:22  +3:13  1.787
0155 PG1047+003    R       10  6:25  +3:14  1.799  photom.diff.~0.54%
0156 PG1323-086    R       15  6:27  +0:41  1.358  Landolt standard
0157 PG1323-086    V       25  6:29  +0:43  1.360
0158 PG1323-086    I       25  6:30  +0:44  1.362
0159 PG1323-086    R       15  6:32  +0:46  1.364  photom.diff.~0.66%
0160 PG1633+099    R       15  6:35  -2:20  1.296  Landolt standard
0161 PG1633+099    V       25  6:36  -2:18  1.290
0162 PG1633+099    I       25  6:38  -2:17  1.286
0163 PG1633+099    R       15  6:40  -2:15  1.280  photom.diff.~0.27%
0164 focus_run     R      7x7  6:44  -2:12  1.262  focus set to -177; fwhm~1.27"

...  gap of ~1 hr ...

0172 NGC9966       R       90  7:41  +1:17  1.244
0173 NGC9966       V      120  7:43  +1:19  1.246
0174 NGC9966       V      360  7:46  +1:22  1.249
0175 NGC9966       R      270  7:52  +1:29  1.256

...  gap of ~1 hr ...

0187 PG1633+099    R       10  8:51  -0:03  1.085  Landolt standard
0188 PG1633+099    R       30  8:52  -0:02  1.084
0189 PG1633+099    V       25  8:54  -0:00  1.084
0190 PG1633+099    I       25  8:56  +0:00  1.084
0191 PG1633+099    R       15  8:57  +0:02  1.085  photom.diff.~0.97%;fwhm~1.00"

...  gap of ~0.5 hr ...

0202 NGC9966       R       90 10:14  +3:51  1.892
0203 NGC9966       V      120 10:16  +3:53  1.908
0204 NGC9966       V      360 10:18  +3:55  1.932
0205 NGC9966       R      270 10:25  +4:01  2.028

... gap of ~1.5 hr ...

0227 PG1633+099    R       15 11:40  +2:45  1.401  Landolt standard
0228 PG1633+099    V       25 11:42  +2:47  1.410
0229 PG1633+099    I       25 11:43  +2:49  1.417
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0230 PG1633+099    R       15 11:45  +2:50  1.426  photom.diff.~0.48%
0231 MarkA         R       10 11:59  -1:03  1.437  Landolt standard; ~31250 ADU
0232 MarkA         V       15 12:00  -1:02  1.434  SATURATED!
# Morning twilight sky flats at "MarkA"...
0233 SKY           R      3.0 12:04  -0:59  1.428  ~39250 ADU
0234 SKY           R      2.5 12:05  -0:58  1.427  ~40750 ADU
0235 SKY           R      1.8 12:06  -0:57  1.426  ~35250 ADU
0236 SKY           R      1.3 12:07  -0:56  1.425  ~35620 ADU
0237 SKY           R      1.0 12:08  -0:55  1.424  ~34912 ADU
# Stowed telescope and closed down @ 5:15 AM. Conditions are photometric!
# Filled dewar at 5:30 AM; humidity 63%; temperature -0.5 C.
# - cleared CCD several times and took two test exposures
238- BIAS  23x     D        0 12:40  +0:00  1.000  Biases
-260 BIAS          D        0 12:50  +0:00  1.000
261- DARK   7x     D      600 12:51  +0:00  1.000  Darks
-267 DARK          D      600 12:    +0:00  1.000
268- DARK   5x     D     1200 1 :    +0:00  1.000  Darks
-272 DARK          D     1200 1 :    +0:00  1.000
273- DARK   5x     D     1800 1 :    +0:00  1.000  Darks
-277 DARK          D     1800 1 :    +0:00  1.000
# Conditions were photometric at sunrise and throughout the night as far as I
# could tell (based on satellite imagery, IR sky temperature, flux differences)
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