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

The purpose of CCD image processing is to separate 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 $\sim$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).

$\triangleright$ 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:
  
  o the average bulk dark rate, $dc$, of the CCD [in $e^-$/pix/hr];
  
  o whether there are pixels with significantly ($\geq 4\sigma$) higher dark rates (i.e., warm/hot pixels or columns);
  
  o 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 sets of integrations of different lengths (e.g., $10\times600$ s, $7\times900$ s, $5\times1200$ s and $5\times1800$ 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.

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

\(\triangle\) 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/quartz 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 quartz halogen lamp and integrating sphere. Flats are required to determine:

  o the pixel-to-pixel variations in effective sensitivity of the CCD (see Fig. 10), 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 $1,000,000e^-$ per filter.

\(\triangle\) Aim for a level per flat frame of $\sim 2^{-}$ the lesser of the full-well capacity or A/D-saturation level.

\(\triangle\) 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 ~$10^{0.5} \approx 3$ 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 $>1,000,000$ $e^-$ 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 $\sim$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 $\sim$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:

  o which is E and which is W in CCD pixel coordinates.
  o 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

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

where $n_{\text{pix}}$ 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 CCD was rotated \(\sim 0.4\) E of N.](image)
• **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 $\sim45$ min, and once per hour or so thereafter.

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

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:

  o photometrically calibrate the science target exposures
  o 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 meaningful. 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 interrupting observations of science targets to observing standard stars, make sure you observe both a field at low airmass (A.M.≤1.2) and one at intermediate (∼1.5–1.6) or high airmass (A.M.∼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 ∼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

In this section we reproduce the relevant portions of the observing log files of the six nights from which we will process and/or analyse data.

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<th>Observers</th>
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<th>Program</th>
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<th>Filterwheel</th>
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Probably photometric, but horrendous seeing due to high winds and unstable atmosphere. Not much useful science data...

```
0175 SKY R 60 12:29 -0:06 1.018 ~29000 ADU
0176 SKY B 30 12:32 -0:03 1.018 ~46250 ADU
0177 SKY B 15 12:34 -0:02 1.018 ~31750 ADU
0178 SKY B 11 12:35 -0:01 1.018 ~30000 ADU
0179 SKY B 10 12:36 -0:00 1.018 ~34750 ADU
0180 SKY B 8 12:37 +0:00 1.018 ~36500 ADU
```

... Probably photometric night, but horrendous seeing (mostly >3") due to high winds

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CCD LOG SHEET

Date: Apr 5, 2005
Re: Mount Graham Observatory, VATT

Observers: R. Jansen, N. Grogin & K. Tamura
Instrument: ccd26 (2048x2048, binx2)
Program: H-alpha imaging of void galaxies
Tel. Focus: -140
Weather: Photometric, but windy @ sunset
Format: FITS

TOP: B U V I
BOTTOM: R Ha668 Ha663 D

# local time = UT - 7 h
# pixel scale = 0.3746"/pix
# gain = 1.9 e-/ADU, rdnoise = 5.7 e-
# Lat = 32:42:05 deg; Long = 109:53:31 deg W; Alt = 3191 m
# exposures marked * were not stored on CDROM.

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<th>Object</th>
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|      | Filled dewar at 18:05; temperature in dome 7 C; humidity in dome 36%.
|      | >> Started up telescope.
|      | >> Opened up at 18:45PM; Conditions are photometric (but windy) at sunset.
|      | Collimation guess: tipx=105, tipy=130, focus_guess=-140
|      | Evening twilight flats...
| 0029 | SKY           | B    | 2.0  | 2:03 | -0:46 | 1.016 |
|      | Twilight flats B; ~24500 ADU
| 0030 | SKY           | B    | 2.5  | 2:04 | -0:45 | 1.016 |
|      | ~24750 ADU
| 0031 | SKY           | B    | 3.2  | 2:05 | -0:44 | 1.015 |
|      | ~25500 ADU
| ...  | ...           | ...  | ...  | ...  | ...  | ...  |
| 0036 | SKY           | R    | 12   | 2:09 | -0:39 | 1.012 |
|      | Twilight flats R; ~24250 ADU
| 0037 | SKY           | R    | 15   | 2:10 | -0:38 | 1.012 |
|      | ~23250 ADU
| 0038 | SKY           | R    | 20   | 2:11 | -0:37 | 1.011 |
|      | ~23750 ADU
| 0039 | SKY           | R    | 25   | 2:12 | -0:36 | 1.011 |
|      | ~22250 ADU
| ...  | ...           | ...  | ...  | ...  | ...  | ...  |
| 0044 | optaxis_test  | R    | 60   | 2:25 | +2:59 | 1.270 |
|      | DUST MOTE BACK AGAIN!!!
| 0045 | focus_run     | R    | 7x5  | 2:44 | +1:02 | 1.243 |
|      | best focus near -150
| 0046 | focus_run     | R    | 7x5  | 2:50 | +1:07 | 1.253 |
|      | focus set to -150; fwhm~2.0"
| 049- | Rubin149      | B    | 20,60| 3:00 | +1:14 | 1.259 |
|      | Twilight sky flats at "BD+28d4211"
| 057- | Rubin149      | R    | 3:13 | +1:27 | 1.287 |
|      | photom.diff."0.4%"
| 058- | Rubin149      | B    | 20,60| 3:22 | +1:49 | 1.322 |
| 068- | Rubin149      | R    | 10   | 3:37 | -1:34 | 1.294 |
|      | photom.diff."1.3%; fwhm~3"
| ...  | ...           | ...  | ...  | ...  | ...  | ...  |
| 122- | PG1047+003    | R    | 10,30| 8:11 | +3:00 | 1.681 |
|      | photom.diff.~0.9%
| 124- | PG1047+003    | B    | 20,60| 8:14 | +3:03 | 1.702 |
|      | focus set to -169; fwhm~1.2"
| 0132 | PG1047+003    | R    | 8:28 | +3:17 | 1.821 |
|      | fwhm~1.3"
| 0134 | A16006+4302   | R    | 8:40 | +1:42 | 1.084 |
| 0135 | A16006+4302   | B    | 8:44 | +1:38 | 1.079 |
| 0136 | A16006+4302   | V    | 8:51 | -1:31 | 1.070 |
| ...  | ...           | ...  | ...  | ...  | ...  | ...  |
| 0175 | PG1528+062    | R    | 12   | 8:32 | -1:50 | 1.094 |
|      | sky getting rapidly brighter
| 0176 | PG1528+062    | B    | 40   | 12:13 | +2:22 | 1.354 |
|      | jog 5" W
| 0180 | PG1528+062    | R    | 15   | 12:20 | +2:29 | 1.385 |
|      | focus set to -169; fwhm~1.2"
| 0181 | PG1633+099    | B    | 15   | 12:22 | +1:26 | 1.158 |
| 0182 | PG1633+099    | B    | 15   | 12:23 | +1:28 | 1.161 |
| 0186 | PG1633+099    | R    | 15   | 12:31 | +1:35 | 1.175 |
| ...  | Twilight sky flats at "BD+28d4211"
| 0187 | SKY           | R    | 2.0  | 12:33 | -3:37 | 1.450 |
|      | Twilight flat R; ~13k ADU
| 0188 | SKY           | R    | 2.0  | 12:34 | -3:36 | 1.449 |
|      | ~16k ADU

(Probably) photometric night, reasonable seeing after the first couple of hours.

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### CCD LOG SHEET

**Date:** Apr 6, 2005  
**Observatory:** Mt. Graham Observatory, VATT  
**Observers:** R. Jansen & K. Tamura  
**Instrument:** ccd26 (2048x2048, binx2)  
**Program:** H-alpha imaging of galaxies observed with HST  
**Tel.Focus:** -140  
**Weather:** Overcast with cirrus clouds @ sunset  
**Format:** FITS

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- Local time = UT - 7 h  
- Pixel scale = 0.3746"/pix  
- Gain = 1.9 e-/ADU, rdnoise = 5.7 e-  
- Lat = 32:42:05 deg; Long = 109:53:31 deg W; Alt = 3191 m  
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<td>1.035</td>
<td>~43500 ADU</td>
</tr>
<tr>
<td>0114</td>
<td>SKY</td>
<td>B</td>
<td>3.0</td>
<td>12:37</td>
<td>0:23</td>
<td>1.037</td>
<td>~45000 ADU</td>
</tr>
<tr>
<td>0115</td>
<td>SKY</td>
<td>B</td>
<td>2.0</td>
<td>12:38</td>
<td>0:23</td>
<td>1.038</td>
<td>~30000 ADU</td>
</tr>
<tr>
<td>0116</td>
<td>SKY</td>
<td>B</td>
<td>1.8</td>
<td>12:39</td>
<td>0:24</td>
<td>1.038</td>
<td>~35500 ADU</td>
</tr>
<tr>
<td>0117</td>
<td>SKY</td>
<td>B</td>
<td>1.5</td>
<td>12:40</td>
<td>0:25</td>
<td>1.038</td>
<td>~30500 ADU</td>
</tr>
<tr>
<td>131</td>
<td>BIAS</td>
<td>D</td>
<td>0</td>
<td>13:15</td>
<td>0:00</td>
<td>1.000</td>
<td>Biases</td>
</tr>
<tr>
<td>-145</td>
<td>BIAS</td>
<td>D</td>
<td>0</td>
<td>13:25</td>
<td>0:00</td>
<td>1.000</td>
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</table>

Non-photometric night; fair seeing at start of night, later variable up to ~2"
<table>
<thead>
<tr>
<th>Obs.</th>
<th>Object</th>
<th>Filt</th>
<th>Texp</th>
<th>UTC</th>
<th>HA</th>
<th>A.M.</th>
<th>comments</th>
</tr>
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<tbody>
<tr>
<td>001</td>
<td>BIAS</td>
<td>D</td>
<td>15x</td>
<td>0:25</td>
<td>-0:00</td>
<td>1.00</td>
<td>Biases</td>
</tr>
<tr>
<td></td>
<td>015 BIAS</td>
<td>D</td>
<td>0:38</td>
<td>-0:00</td>
<td>1.00</td>
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<td></td>
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<tr>
<td>0030</td>
<td>SKY</td>
<td>B</td>
<td>0.6</td>
<td>1:58</td>
<td>-0:43</td>
<td>1.01</td>
<td>~36500 ADU</td>
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<tr>
<td>0031</td>
<td>SKY</td>
<td>B</td>
<td>0.7</td>
<td>1:59</td>
<td>-0:42</td>
<td>1.01</td>
<td>~34250 ADU</td>
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<tr>
<td>0032</td>
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<td>B</td>
<td>0.8</td>
<td>2:00</td>
<td>-0:41</td>
<td>1.01</td>
<td>~32500 ADU</td>
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<tr>
<td>0036</td>
<td>SKY</td>
<td>R</td>
<td>2.1</td>
<td>2:03</td>
<td>-0:37</td>
<td>1.01</td>
<td>~20000 ADU</td>
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<tr>
<td>0037</td>
<td>SKY</td>
<td>R</td>
<td>2.5</td>
<td>2:04</td>
<td>-0:37</td>
<td>1.01</td>
<td>~19000 ADU</td>
</tr>
<tr>
<td>0038</td>
<td>SKY</td>
<td>R</td>
<td>3.0</td>
<td>2:05</td>
<td>-0:36</td>
<td>1.01</td>
<td>~19000 ADU</td>
</tr>
<tr>
<td>0039</td>
<td>SKY</td>
<td>R</td>
<td>4.0</td>
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<td>-0:35</td>
<td>1.01</td>
<td>~21500 ADU</td>
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<tr>
<td>0052</td>
<td>focus_run</td>
<td>R</td>
<td>7x10</td>
<td>3:23</td>
<td>+0:42</td>
<td>1.01</td>
<td>focus set to -127; fwhm~1.2&quot;</td>
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<tr>
<td>103</td>
<td>FLAT</td>
<td>R</td>
<td>7x1</td>
<td>12:11</td>
<td>-3:37</td>
<td>1.65</td>
<td>Dome flats (25W lamp)</td>
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<tr>
<td>-109</td>
<td>FLAT</td>
<td>R</td>
<td>12:16</td>
<td>-3:37</td>
<td>1.65</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Non-photometric night; fair seeing at start of night, later variable up to ~2"
# CCD LOG SHEET

**Date:** Apr 8, 2005  
**Observatory:** Mt. Graham Observatory, VATT  
**Observers:** R. Jansen & K. Tamura  
**Instrument:** ccd26 (2048x2048, binx2)  
**Program:** H-alpha imaging of galaxies observed with HST  
**Tel.Focus:** -120  
**Weather:** Near-photometric @ sunset (small cloud low on N horiz) Format: FITS

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>TOP:</td>
<td>B</td>
<td>U</td>
<td>V</td>
<td>I</td>
<td></td>
</tr>
<tr>
<td>BOTTOM:</td>
<td>R</td>
<td>Ha668</td>
<td>Ha663</td>
<td>D</td>
<td></td>
</tr>
<tr>
<td>gain = 1.9 e-/ADU, rdnoise = 5.7 e-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lat = 32:42:05 deg; Long = 109:53:31 deg W; Alt = 3191 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

# Filled dewar at 18:15; temperature in dome 7 C; humidity in dome 37%.

# Considerably colder than yesterday...

# >> Started up telescope.

# >> Opened up at 18:45 PM. Conditions are (near-)photometric at sunset.

# Collimation guess tipx=105, tipy=130; focus_guess=-120

# Evening twilight flats...

<table>
<thead>
<tr>
<th>Obs. #</th>
<th>Object</th>
<th>Filt</th>
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<th>UTC</th>
<th>HA</th>
<th>A.M.</th>
<th>Comments</th>
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<tbody>
<tr>
<td>0014</td>
<td>SKY</td>
<td>B</td>
<td>5</td>
<td>2:08</td>
<td>-0:29</td>
<td>1.007</td>
<td>Twilight flats B; ~27750 ADU</td>
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<tr>
<td>0015</td>
<td>SKY</td>
<td>B</td>
<td>7</td>
<td>2:09</td>
<td>-0:28</td>
<td>1.007</td>
<td>~30000 ADU</td>
</tr>
<tr>
<td>0016</td>
<td>SKY</td>
<td>B</td>
<td>8</td>
<td>2:10</td>
<td>-0:27</td>
<td>1.006</td>
<td>~26500 ADU</td>
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<tr>
<td>0020</td>
<td>SKY</td>
<td>R</td>
<td>30</td>
<td>2:15</td>
<td>-0:22</td>
<td>1.005</td>
<td>Twilight flats R; ~19250 ADU</td>
</tr>
<tr>
<td>0021</td>
<td>SKY</td>
<td>R</td>
<td>40</td>
<td>2:16</td>
<td>-0:21</td>
<td>1.004</td>
<td>~18000 ADU</td>
</tr>
<tr>
<td>0022</td>
<td>SKY</td>
<td>R</td>
<td>55</td>
<td>2:17</td>
<td>-0:19</td>
<td>1.004</td>
<td>~16500 ADU</td>
</tr>
<tr>
<td>0027</td>
<td>focus_run</td>
<td>R</td>
<td>7x10</td>
<td>2:55</td>
<td>-2:05</td>
<td>1.389</td>
<td>focus set to -97; fwhm '1.4&quot;</td>
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<tr>
<td>0028</td>
<td>PG1047+003</td>
<td>R</td>
<td>15</td>
<td>3:04</td>
<td>-1:56</td>
<td>1.357</td>
<td>forgot to set focus</td>
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<tr>
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<td>PG1047+003</td>
<td>B</td>
<td>25</td>
<td>3:05</td>
<td>-1:55</td>
<td>1.354</td>
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<td>0033</td>
<td>PG1047+003</td>
<td>R</td>
<td>15</td>
<td>3:12</td>
<td>-1:48</td>
<td>1.331</td>
<td>photom.diff. ~1.8%</td>
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<tr>
<td>034-</td>
<td>Rubin149</td>
<td>R</td>
<td>10,30</td>
<td>3:17</td>
<td>+1:43</td>
<td>1.326</td>
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<tr>
<td>036-</td>
<td>Rubin149</td>
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<td>20,60</td>
<td>3:20</td>
<td>+1:46</td>
<td>1.335</td>
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<tr>
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<td>Rubin149</td>
<td>R</td>
<td>15</td>
<td>3:33</td>
<td>+1:59</td>
<td>1.377</td>
<td>photom.diff. ~0.7%</td>
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<tr>
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<td>PG0918-029</td>
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<td>15</td>
<td>3:40</td>
<td>+0:08</td>
<td>1.153</td>
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<tr>
<td>0046</td>
<td>PG0918-029</td>
<td>B</td>
<td>25</td>
<td>3:41</td>
<td>+0:10</td>
<td>1.153</td>
<td></td>
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<tr>
<td>0050</td>
<td>PG0918-029</td>
<td>R</td>
<td>15</td>
<td>3:47</td>
<td>+0:16</td>
<td>1.155</td>
<td>photom.diff. ~0.8%</td>
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<tr>
<td>0105</td>
<td>PG1047+003</td>
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<td>15</td>
<td>8:21</td>
<td>+3:22</td>
<td>1.866</td>
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<tr>
<td>0106</td>
<td>PG1047+003</td>
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<td>30</td>
<td>8:22</td>
<td>+3:23</td>
<td>1.882</td>
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<tr>
<td>0110</td>
<td>PG1047+003</td>
<td>R</td>
<td>15</td>
<td>8:29</td>
<td>+3:30</td>
<td>1.947</td>
<td>photom.diff. ~1.4%</td>
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<tr>
<td>0111</td>
<td>PG1323-086</td>
<td>R</td>
<td>15</td>
<td>8:35</td>
<td>+1:01</td>
<td>1.387</td>
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<tr>
<td>0112</td>
<td>PG1323-086</td>
<td>B</td>
<td>30</td>
<td>8:37</td>
<td>+1:02</td>
<td>1.389</td>
<td></td>
</tr>
<tr>
<td>0116</td>
<td>PG1323-086</td>
<td>R</td>
<td>15</td>
<td>8:43</td>
<td>+1:08</td>
<td>1.402</td>
<td>photom.diff. ~0.4%</td>
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<tr>
<td>0117</td>
<td>PG1528+062</td>
<td>R</td>
<td>15</td>
<td>8:51</td>
<td>-0:48</td>
<td>1.142</td>
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<tr>
<td>0118</td>
<td>PG1528+062</td>
<td>B</td>
<td>30</td>
<td>8:52</td>
<td>-0:47</td>
<td>1.141</td>
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</tr>
<tr>
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<td>PG1528+062</td>
<td>R</td>
<td>15</td>
<td>8:58</td>
<td>-0:41</td>
<td>1.135</td>
<td>photom.diff. ~1.1%</td>
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<tr>
<td>0149</td>
<td>A16006+4302</td>
<td>R</td>
<td>180</td>
<td>11:49</td>
<td>+1:38</td>
<td>1.079</td>
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<tr>
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<td>A16006+4302</td>
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<td>360</td>
<td>11:53</td>
<td>+1:42</td>
<td>1.084</td>
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<td>0152</td>
<td>MarkA</td>
<td>B</td>
<td>15</td>
<td>12:09</td>
<td>-2:42</td>
<td>1.896</td>
<td>sky getting brighter!</td>
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<tr>
<td>0153</td>
<td>MarkA</td>
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<td>30</td>
<td>12:10</td>
<td>-2:41</td>
<td>1.886</td>
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<td>20</td>
<td>12:18</td>
<td>+1:34</td>
<td>1.172</td>
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<tr>
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<td>40</td>
<td>12:19</td>
<td>+1:35</td>
<td>1.175</td>
<td>~13000 ADU</td>
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</table>

# Stowed telescope; tracking OFF!...

# Morning twilight flats...

<table>
<thead>
<tr>
<th>Obs. #</th>
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<th>Filt</th>
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<th>A.M.</th>
<th>Comments</th>
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<tbody>
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<td>0169</td>
<td>SKY</td>
<td>B</td>
<td>1.5</td>
<td>12:40</td>
<td>+0:00</td>
<td>1.000</td>
<td>Twilight flats B; ~50250 ADU</td>
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<tr>
<td>0170</td>
<td>SKY</td>
<td>B</td>
<td>0.8</td>
<td>12:40</td>
<td>+0:00</td>
<td>1.000</td>
<td>~33250 ADU</td>
</tr>
<tr>
<td>0171</td>
<td>SKY</td>
<td>B</td>
<td>0.65</td>
<td>12:41</td>
<td>+0:00</td>
<td>1.000</td>
<td>~33000 ADU</td>
</tr>
</tbody>
</table>

# Closed down @ 5:50 AM; temperature ~5 C; humidity 57% ; strongs winds

Photometric night; but wind afffecting seeing after ~1:00 UT
Date: Sep 29, 2005                 Observatory: Mt.Graham Observatory, VATT
Observers: R.Jansen, N.Grogin & A.Mott Instrument: ccd26 (2048x2048, binx2)
Program: H-alpha imaging of void galaxies                     Tel.Focus:
Weather: Clear @ sunset                                       Format: FITS

TOP:       -     R     Ha668  Ha663  D
BOTTOM:     -     U     B     V     I

# local time = UT - 7 h
# pixel scale = 0.3746"/pix
# gain = 1.9 e-/ADU, rdnoise = 5.7 e-
# Lat = 32:42:05 deg; Long = 109:53:31 deg W; Alt = 3191 m

================================================================================
Obs.#  Object        Filt  Texp UTC   HA   A.M.  Comments
================================================================================
0025 SKY           B        8  1:31 +0:07  1.055  Twilight flats B; ~40000 ADU
0026 SKY           B        8  1:32 +0:08  1.055  ~30500 ADU
0027 SKY           B       10  1:33 +0:09  1.055  ~29500 ADU
0028 SKY           B       12  1:34 +0:10  1.056  ~27250 ADU
0029 SKY           B       16  1:35 +0:11  1.056  ~27750 ADU
0030 SKY           R       45  1:41  +0:17  1.057  Twilight flats R; ~18000 ADU
0031 SKY           R       60  1:43  +0:19  1.058  ~17250 ADU
0032 SKY           R       90  1:44  +0:21  1.059  ~17500 ADU
0033 SKY           R      180  1:46  +0:23  1.060  ~17750 ADU
0034 SKY           R      210  1:47  +0:24  1.061  ~17900 ADU
0035 SKY           R      240  1:48  +0:25  1.062  ~18050 ADU
0036 SKY           R      270  1:49  +0:27  1.063  ~18200 ADU
0037 SKY           R      300  1:50  +0:28  1.064  ~18350 ADU
0038 SKY           R      330  1:51  +0:29  1.065  ~18500 ADU
0039 SKY           R      360  1:52  +0:30  1.066  ~18650 ADU
0040 SKY           R      390  1:53  +0:31  1.067  ~18800 ADU
0041 focus_run    R      7x5  2:35  +2:52  1.465  focus set to -121; fwhm=1.1"
0042 A16006+4302  R     450  2:56  +4:10  1.538  SN2005bk follow-up; fwhm=1.3"
0043 A16006+4302  R     450  3:07  +4:21  1.604  SN2005bk follow-up
0044 A16006+4302  R     600  3:17  +4:31  1.670  SN2005bk follow-up; fwhm=1.4"
0050 PG2213-006   R      15  4:24  -0:35  1.204
0052 PG2213-006   B      40  4:28  -0:30  1.201
0055 PG2213-006   R      15  4:32  -0:26  1.198  photom.diff. in R < 0.65%
0056 MarkA        R      15  4:37  +1:10  1.450  = 100%*abs(x-y)/(0.5*(x+y))
0058 MarkA        B      30  4:40  +1:13  1.460
0061 MarkA        R      15  4:44  +1:17  1.470  photom.diff. < 0.26%
0081 PG0231+051   R      15  6:49  -2:27  1.385
0083 PG0231+051   B      30  6:52  -2:23  1.372
0086 PG2336+004   R      15  6:57  -2:19  1.355
0087 PG2336+004   R      15  7:03  +0:41  1.196
0089 PG2336+004   B      40  7:07  +0:45  1.200  trailed -- secondary jumped!
0092 PG2336+004   R      15  7:12  +0:50  1.205  photom.diff. < 1.1%
0093 PG2336+004   B      40  7:15  +0:53  1.209  (redo of 0089) OK
0111 PG2336+004   R      15  9:42  +3:21  1.833  fwhm=1.2"
0113 PG2336+004   B      35  9:46  +3:24  1.865
0116 PG2336+004   R      15  9:50  +3:29  1.914  photom.diff. < 0.77%
0117 PG0231+051   R      15  9:54  +3:38  1.139
0119 PG0231+051   B      35  9:58  +3:41  1.142
0122 PG0231+051   R      15 10:02  +4:46  1.146  photom.diff. < 0.19%

# Collimated telescope: tipx=120 , tipy=120
# Evening twilight sky flats...

...
0142 Rubin149 R 10 12:40 -1:26 1.284
0144 Rubin149 B 30 12:42 -1: 1.2 OVEREXPOSED!!
0147 Rubin149 R 10 12:47 -1:19 1.269 too bright ~60000 ADU

# Morning twilight sky flats at "Rubin149"
0148 SKY R 3.0 12:48 -1:17 1.266 Twilight flats R; ~23500 ADU
0149 SKY R 2.6 12:49 -1:16 1.264 ~25500 ADU
0150 SKY R 2.2 12:50 -1:16 1.262 ~28500 ADU
0151 SKY B 4.0 12:51 -1:15 1.261 Twilight flats B; OVEREXPOSED
0152 SKY B 2.0 12:52 -1:14 1.259 ~41500 ADU
0153 SKY B 1.2 12:53 -1:13 1.257 ~30000 ADU
0154 SKY B 0.9 12:53 -1:12 1.256 ~28500 ADU

# Stowed telescope @ 6:05 AM; closed mirror cover, then dome slit.
# Conditions are photometric at sunrise. Most likely photometric all night!
# Dome tracking is turned OFF; Pointed telescope at clear spot on inside of
# dome. Set the RA drive bias rate to +15.0 */sec to counter tracking...
168- FLAT R 2.0 13:23 -3:30 1.693 Dome flats (40W lamp)
172- FLAT R 2.0 13:26 -3:30 1.694
173- FLAT R 0.4 13:43 -3:30 1.696 Dome flats (2x60W+25W lamps)
177- FLAT R 0.4 13:
178- FLAT R 0.8 13:47 -3:30 1.696 Dome flats (2x60W+25W lamps)
-182 FLAT R 0.8 13:
243- FLAT R 0.1 15:03 -3:31 1.702 Dome flats (2x60W+300W)
-247 FLAT R 0.1 15:
248- FLAT R 1.2 15:12 -3:31 1.702 Dome flats (60W+25W lamps)
-252 FLAT R 1.2 15:
253- FLAT R 5.0 15:18 -3:31 1.703 Dome flats (25W lamp)
-260 FLAT R 5.0 15:
261- FLAT B 30 15:39 -3:31 1.705 Dome flats (300W + daylight
-270 FLAT B 30 15: from open door to outside).
# >> Stowed telescope and reset RA bias rate to 0 (-> sidereal rate).
# >> Shutdown telescope @8:55AM.
# Filled dewar at 9:05AM; humidity in dome 47%; temperature in dome 11 C.
271- BIAS D 0 16:17 +0:00 1.000 Biases
-290 BIAS D 0 16:
=========================================================================
Most likely photometric all night!
=========================================================================
8.3 Starting IRAF and DS9, and retrieving the raw data

Start an xgterm terminal window (a modified xterm, with extra graphical capabilities built in specifically for use with IRAF). In the following, we will denote the command prompts of xterm, xgterm and IRAF cl as $>, %> and cl>:

$> xgterm

In the following, a standard IRAF (version 2.12.2) installation is assumed in /iraf/, with compatible versions of the stdas, tables and cti0 packages already installed in /iraf/extern/. IRAF can be obtained from http://iraf.noao.edu/ or http://iraf.net/downloads/.

If this is the first time you ever ran IRAF, then you first have to create a subdirectory in your home directory and name it “iraf”. Then, in that subdirectory, run mkiraf, which will prepare a user login macro named “login.cl” and a user parameters directory named “uparm”:

%> mkdir iraf ; cd iraf
%> mkiraf

(where prompted for the terminal type, enter xgterm)

In the “login.cl” file just created, change imdir to an empty string and add a username entry:

set imdir = ""
set username = "A.Student"

This needs to be done only once (unless IRAF gets upgraded to a newer version).

If not installed on your machine already (check in /iraf/extern/), download and install IRAF external layered package rjtools, available as a gzip-compressed tar archive from http://www.public.asu.edu/~rjansen/. In your “iraf” home directory:

%> (g)tar -xvpzf rjtools_2.12_16Jun2005.tgz

The tar file can be deleted once rjtools is installed.

Create a file named “loginuser.cl” (or edit the existing one) and insert the following lines (before the keep statement in the case of an existing file):

reset rjtools = home$rjtools/
task rjtools.pkg = rjtools$rjtools.cl
printf ("reset helpdb=%s,rjtools$lib/helpdb.mip\nkeep\n",envget("helpdb"))| cl
flpr

A final note: in order to find the tasks within the rjtools package using task apropos within the stdas package, its database needs to be updated. Since apropos is a simple ASCII text file, all that needs to be done is to append file “rjtools$lib/apropos.db” to “stdas$lib/apropos.db”. Unfortunately, this may require administrator privileges, so you may have to ask the administrator to type in your iraf home directory:

%> cat rjtools/lib/apropos.db >> /iraf/extern/stdas_version/lib/apropos.db

In the following, we’ll also use a unix/linux utility called nargs, which is a C-shell script around executable arg. These can also be downloaded from http://www.public.asu.edu/~rjansen/ as a gzip-compressed tar file, and either installed in /usr/local/src/ (as ‘root’) or in your home directory (as ‘user’). You may need a Fortran77 compiler to recompile the source code.
Start up the IRAF command language interface in that xgterm terminal window:

%> cd ~/iraf
%> cl

Enter the working directory containing the data:

    cl> cd /data1/raj/ast598/

Load any required packages that are not loaded by default upon startup (loaded by default are: noao, language, system, lists, dataio, images, imutil, tv, plot, utilities):

   cl> stsdas
   cl> imred
   cl> bias
   cl> rjtools

(Note that in reality, the cl> prompt changes after loading each subsequent package).

Start up an image display program that knows how to communicate with IRAF, e.g., ds9, and do so from within IRAF (i.e., not from a unix command prompt!):

   cl> !ds9 &

Since ds9 is a unix program and not an IRAF task, we need to precede its name with an exclamation mark (!) to temporarily escape to the unix shell. The ampersand (&) causes ds9 to run in the background and gives us back the cl> prompt.

Find an IRAF display buffer that is sufficiently large to include the entire 1044×1044 pixel CCD image (need not be an exact match to the actual image size — just find the next larger one):

   cl> gdevices
       imt1  imt512   512  512
       imt2  imt800   800  800
       imt3  imt1024  1024 1024 ← cuts off the overscan strips
       ...
       imt44  imt1100 1100 1100 ← choose this one
       ...

Set the default image display buffer (twice for good measure):

   cl> set stdimage=imt44
   cl> set stdimage=imt44
Assume that we have read from tape or copied from CDROM/DVD all “raw” FITS data we wish to process as it came from the telescope. To reduce their volume, all these raw, 16-bit integer data were stored in gzip-compressed format. They currently reside in a subdirectory named “raw/”.

Copy the contents of the “raw/” subdirectory to the present working directory, and uncompress all data:

```bash
cl> dir raw
050404  050405  050406  050407  050408  050929
cl> !du -sh raw
388M    raw
cl> !cp -pr raw/* . ← don't forget the period as I did in class!
cl> !gunzip 050???/*.fits.gz
cl> !du -sh
1.2G    
```

During data processing, one often makes a mistake that renders the partially processed data useless. For that reason we always want to keep an original copy of the raw data around. Since we will copy and also convert the data from their original 16-bit encoding to 32-bit floating point encoding, and since we may keep some partially processed data and calibration images around, the total free disk space required for the present image processing amounts to several (~3) Gigabytes!
8.4 Preparations before CCD image processing

- Create a list of all data in the subdirectories per night:

  cl> !ls -1 050??/*.fits > all.lis

Print an inventory of the unique “object” names (FITS header keyword OBJECT) as they occur in the image headers:

  cl> hselect @all.lis object yes | sort | unique

A16006+4302 ← our science target
BIAS
DARK
FLAT ← dome flats
MarkA ← Landolt photometric standard field
PG0231+051 ""
PG0918-029 ""
PG1047+003 ""
PG1323-086 ""
PG1528+062 ""
PG1633+099 ""
PG2213-006 ""
PG2336+004 ""
Rubin149 ""
SKY ← twilight sky flats
focus-run
optaxis_test ← orientation exposure

Now we know what they are called, create separate lists for biases, darks, dome flats, twilight flats, and science target frames:

  cl> hselect @all.lis $I 'object="BIAS"' > bias.lis
  cl> hselect @all.lis $I 'object="DARK"' > dark.lis
  cl> hselect @all.lis $I 'object="FLAT"' > flat.lis
  cl> hselect @all.lis $I 'object="SKY"' > sky.lis
  cl> hselect @tmp.lis $I 'object="SKY"&object="focus"' > sci.lis

Note, that the science exposures were defined by what they are not. Since that wouldn’t all fit on my command line, I used a temporary list (“tmp.lis”) from which I selected further. In the following, any files with names starting with “tmp” or “_” are temporary files, to be deleted when no longer needed, whose names may be re-used.

  cl> delete tmp.lis yes verify-
• Construct a bad pixel/bad column list using the median of a few twilight sky flat exposures (a convenient task to do so is getregion, which is part of the rjtools package). Make sure ds9 is already open:

```bash
cl> head sky.lis nlines=7 > tmp.lis
cl> unlearn imcombine
cl> imcombine (@tmp.lis", "tmp.fits", combine="average", reject="avsigclip",
>>> scale="mean", zero="none", weight="mean", statsec=[16:1015,1:1000])
cl> unlearn getregion
cl> getregion (@tmp.fits", "tmp.reg", format="basic", chkbound+, append+,
>>> verbose+)
# GETREGION: NOAO/IRAF V2.12.2-EXPORT raj@andromeda Oct 4 09:50:10 2006
image = tmp.fits [1044 x 1044]
output= tmp.reg (format="basic")
Displaying image "tmp.fits": z1=11624.57 z2=53420.01
Wait for the cursor cross to appear in the image display area,
then mark all regions by hitting "b" once at each of two dia-
gonally opposite corners to mark an arbitrary rectangular region,
or "c" once to mark a single pixel. Hit "q" to quit.
...

# GETREGION Finished.
```

Overlay the defined regions onto the image to verify using task tvmarkall (which can also be found in the rjtools package):

```bash
cl> unlearn tvmarkall
cl> tvmarkall (@tmp.fits", gal-, star-, cosmic-, del-, region+,
>>> regfil="tmp.reg", regclr=204)
```

If we're happy with it (no missed or incorrectly defined bad pixels/columns), save the file under a more descriptive name with a descriptive header line prepended:

```bash
cl> printf("# Loral 2048 x 2048 back-illum. 15mu-pixel ", > "badpix.ccd26")
cl> printf("thinned CCD, binned 2x2, untrimmed\n", >> "badpix.ccd26")
cl> !cat tmp.reg >> badpix.ccd26
cl> delete tmp.lis,tmp.reg yes verify-
```

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Figure 4: Bad pixel columns (*green*), interactively marked on the image display using task *getregion*. Also indicated (*red*) is the 1000×1000 pixel section that we will excise (“trim”) in later processing steps, to avoid problems due to poor response near the left, right and upper edge of the illuminated portion of this CCD.
Determine the location of the virtual overscan strip, which will be used to track the (somewhat varying) bias level. Note that the noise within the virtual overscan strip should be only read-noise, regardless of the signal level in the illuminated region (image region) of the CCD, while the physical overscan strip may suffer from deferred charge and leaked light, that will result in additional signal and noise:

```
cl> implot tmp.fits
    :c 1 1044  →  [16:1015,1032:1044]
    :l 1 1044  →  [1032:1044,1:1000]
```

So, this particular CCD has two possible overscan strips (see Fig 5). Let’s see which one is the virtual overscan strip.

Figure 5: Screen shots of implot graphs of the average of columns 1–1044 (top) and of lines 1–1044 (bottom) in a temporary image created by averaging 7 twilight sky flats. Two possible overscan strips are identified, only one of which is the virtual overscan strip.
Compute the pixel statistics in both strips identified in Fig. 5, both in biases and in twilight sky flats:

```bash
cl> !head -20 bias.lis | sed 's/$/[16:1015,1032:1044]/g' > tmp.lis
cl> imstat @tmp.lis fields="image,mean,stddev,min,max"
050404/e0004.fits[16:1015,1032:1044] 1060. 2.934 1048. 1073.
... 
cl> !head -20 sky.lis | sed 's/$/[16:1015,1032:1044]/g' > tmp.lis
cl> imstat @tmp.lis fields="image,mean,stddev,min,max"
... 
```

From which we find that the mean $\sim 1060-1120$ ADU and the rms ("stddev") $\sim 14-500$ ADU. This is not consistent with pure read-noise which, from the statistics computed in the bias frames, we know should be $\sim 2.95$ ADU. Hence, this is not the virtual overscan strip.

Let’s try the other option:

```bash
cl> !head -20 bias.lis | sed 's/$/[1032:1044,1:1000]/g' > tmp.lis
cl> imstat @tmp.lis fields="image,mean,stddev,min,max"
050404/e0001.fits[1032:1044,1:1000] 1059. 2.850 1050. 1071.
050404/e0002.fits[1032:1044,1:1000] 1060. 2.829 1049. 1070.
050404/e0004.fits[1032:1044,1:1000] 1060. 2.859 1048. 1070.
... 
cl> !head -20 sky.lis | sed 's/$/[1032:1044,1:1000]/g' > tmp.lis
cl> imstat @tmp.lis fields="image,mean,stddev,min,max"
050404/e0176.fits[1032:1044,1:1000] 1078. 3.006 1066. 1090.
050404/e0177.fits[1032:1044,1:1000] 1076. 2.934 1066. 1088.
... 
```

Here we find that the mean $\sim 1060-1080$ ADU and the rms $\sim 2.9-3.1$ ADU. This does look like the virtual overscan strip. Note also, that the minimum and maximum values reported are all consistent with the mean $\pm 4\sigma$.

So, in the following, we will adopt (see also Fig. 6):

\[ \text{TRIMSEC} = \text{STATSEC} = \{16:1015,1:1000\}, \text{BIASSEC} = \{1032:1044,1:1000\} \]
Figure 6: Layout of the CCD area in pixel coordinates, with overscan strips indicated. We will trim the outer edges of the illuminated area because their response is poor (see also Fig. 4).
Next we need to measure the CCD gain and read-noise using Janesick’s method using pairs of flats and biases. A convenient task to do so is findgain, which is found within the noao.obsutil package. First load that package (noao is already loaded):

```bash
cl> obsutil
```

For usage information, view the parameter file of this task, or its help file:

```bash
cl> lpar findgain and/or: help findgain
```

Prepare some matched lists of biases and (dome) flats — we almost always have fewer flats than biases:

```bash
cl> !grep '050404' flat.lis | wc -l
7
cl> !grep '50404' flat.lis | head -6 | sed 's/.fits//g' > f1
cl> !grep '50404' flat.lis | tail -6 | sed 's/.fits//g' > f2
cl> !grep '50404' bias.lis | head -6 | sed 's/.fits//g' > b1
cl> !grep '50404' bias.lis | tail -6 | sed 's/.fits//g' > b2
```

To check these lists, type:

```bash
cl> !paste f1 f2 b1 b2
050404/e0016 050404/e0017 050404/e0001 050404/e0002
050404/e0017 050404/e0018 050404/e0002 050404/e0003
050404/e0018 050404/e0019 050404/e0003 050404/e0004
050404/e0019 050404/e0020 050404/e0004 050404/e0005
050404/e0020 050404/e0021 050404/e0005 050404/e0006
050404/e0021 050404/e0022 050404/e0006 050404/e0007
```

Since we want to avoid a lot of typing, we create a little template script, where the variable entries are symbolically denoted $1$, $2$, etc... We then use a unix utility called narg to replicate this template script, while substituting the variables with entries taken from the above matched lists, i.e., $1$ from “f1”, $2$ from “f2”, etc.:

```bash
cl> !echo 'findgain ("$1", "$2", "$3", "$4", section=[16:1015,1:1000], verbose-)' > getccdpar.tem
cl> !echo ' findgain ("$1", "$2", "$3", "$4", section=[16:1015,1:1000], verbose-)' >> getccdpar.tem
cl> type getccdpar.tem
findgain ("$1", "$2", "$3", "$4",
section=[16:1015,1:1000], verbose-)

cl> !narg getccdpar.tem f1 f2 b1 b2 $4' > getccdpar.cl
```

Verify that the replication and entry substitution into the template script was successful:

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Execute this IRAF CL script and compute the gain, \( G \), and read-noise, \( R \); the syntax to do so may look odd (we call the IRAF CL itself from within the currently running CL, but reading its command input from script \("getccdpar.cl\"):

```
cl> cl < getccdpar.cl
1.95  5.60
1.95  5.60
1.95  5.60
1.95  5.60
... ...
```

This is close to, but slightly different from, the advertised values that were recorded in the observing log files (§ 8.2): \( G = 1.9 e^-/\text{ADU} \) and \( R = 5.7 e^- \).

Let’s repeat this for the nights of Apr 7 2005 and Sep 29 2005 to see if the differences found are significant:

```
cl> !grep '050407' flat.lis | wc -l
7
cl> !grep '050407' flat.lis | head -6 | sed 's/.fits//g' > f1
cl> !grep '050407' bias.lis | head -6 | sed 's/.fits//g' > b1
cl> !narg getccdpar.tem f1 f2 b1 b2 > getccdpar.cl
cl> cl < getccdpar.cl
1.96  5.62
1.96  5.62
1.96  5.63
1.96  5.63
... ...
```
(The \texttt{range} command below is used to specify only the exposure numbers of the five 2 sec and eight 5 sec $R$-filter flats of Sep 29 2005):

\begin{verbatim}
c1> !range -pre "050929/b" -d 4 168 - 172 253 - 259 > f1
c1> !range -pre "050929/b" -d 4 169 - 172 253 - 260 > f2
c1> !grep '50929' bias.lis | head -12 | sed 's/.fits//g' > b1
c1> !grep '50929' bias.lis | head -13 | tail -12 | sed 's/.fits//g' > b2
c1> !narg getccdpar.tem f1 'f2' 'b1' 'b2' '$1' '$2' '$3' '$4' > getccdpar.cl

c1> cl < getccdpar.cl

1.96 5.72
1.95 5.69
1.95 5.69
1.95 5.80
...
...
\end{verbatim}

In the mean, we find $\overline{\gamma} = 1.953 \pm 0.005$ $e^-$/ADU and $\overline{\mathcal{R}} = 5.66 \pm 0.07$ $e^-$. The read-noise does, therefore, not differ significantly from the one advertised, but the gain is slightly ($\sim 3\%$) higher.

Clean up the temporary lists we created:

\begin{verbatim}
c1> delete f1, f2, b1, b2 yes verify-
\end{verbatim}

Since we won't need the \texttt{obsutil} package further, unload it:

\begin{verbatim}
c1> bye
\end{verbatim}

(Note, that \texttt{bye} unloads the last package loaded. Packages can be unloaded up to the \texttt{cl} level, but one can unload (i.e., exit) the IRAF CL itself only by typing \texttt{logout}).
8.5 Processing of the calibration frames

8.5.1 Bias frames

Our goal is to construct a “master” bias reference frame to check for structure in the bias level across the CCD and for offsets with respect to the level in the virtual overscan strip. That frame should have a high enough $S/N$, that it will add only negligible noise when subtracted from any of the other types of images. We will:

(0) visually inspect all bias frames and convert to 32-bit floating-point format
(1) interpolate over the bad pixels/columns we defined earlier
(2) subtract the level measured in the overscan strip
(3) average the individual biases together into a single, high $S/N$ frame
(4) verify that the level in the overscan region of the combined frame is exactly 0; if not, subtract the residual level.

- Visually inspect all bias frames (remove any biases with problems):
  
  ```
  cl> imexamine @bias.lis 1 allframes- nframes=1
  (the n-key will proceed to the next image in the list; the p-key will go to the previous one. Hit q to quit.
  ```

Convert all biases from 16-bit integer ("ushort") to 32-bit floating-point ("real") format (remember that an A/D converter only returns integer ADUs). The smallest number of bits that can store the floating-point equivalent of a 16-bit integer is 32:

```
cl> chpixtype @bias.lis @bias.lis "real" oldpixtype="all" verbose+
```

Add a line to the image headers indicating the start of the processing log entries, and add an entry logging the pixel data type conversion. Since we’ll do this for every other type of data as well, it pays to put this in a little script. In the following, whenever the argument of a type command is a template script ("*.tem"), that template script should be created — with !echo commands or with your favorite ASCII text editor. The displayed output of type just shows what the template script should look like.

```
cl> type hdrlog_init.tem
gdate() ; sysinfo() ; unlearn hedit ; hedit.add=yes ; hedit.verify=no
s1="CCD image processing -- //sysinfo.username//"@"//sysinfo.host
s1="------- //s1/" -------
hedit ("@%.lis", "HISTORY", s1)
hedit ("@%.lis", "CHPXTYPE", "COMPLETE")
hedit ("@%.lis", "CHPXDATE", gdate.fdate)
```

```
cl> !sed 's:%:bias:g' hdrlog_init.tem > hdrlog_init.cl
ci> cl < hdrlog_init.cl
```
This added the following log entry to the FITS headers of all bias frames:

```plaintext
HISTORY = '------- CCD image processing -- R.A. Jansen@andromeda -------'
CHPXTYPE= 'COMPLETE'
CHPXDATE= '2006-10-11T17:09:22'
```

- Interpolate over the bad pixels/columns identified earlier, and log relevant information to the image headers:

  ```plaintext
cl> fixpix (@bias.lis", "badpix.ccd26", verbose+, >> "ccdproc.log")

cl> type hdrlog_fpx.tem
gdate()
heedit (@%.lis", "FIXPIX", "COMPLETE")
heedit (@%.lis", "FXPXFILE", "/data1/raj/ast598/badpix.ccd26")
heedit (@%.lis", "FXPXDATE", gdate.fdate)

cl> !sed 's/%/bias/g' hdrlog_fpx.tem > hdrlog_fpx.cl
cl> cl < hdrlog_fpx.cl
```

This added the following log entry to the FITS headers of all bias frames:

```plaintext
FIXPIX = 'COMPLETE'
FXPXFILE= '/data1/raj/ast598/badpix.ccd26'
FXPXDATE= '2006-10-11T17:10:41'
```

- Subtract the bias level as measured in the virtual overscan strip. First, we’ll measure that level and record it in a log file:

  ```plaintext
cl> !sed 's/$/[1032:1044,1:1000]/g' bias.lis > _bias.lis
cl> imstat (@@bias.lis", fields="image,midpt", lower=INDEF, upper=INDEF,
>>> nclip=3, lsigma=3., usigma=3., format-, cache-, > "overscan.dat")
cl> delete _bias.lis yes verify-
```

Now fit and remove the overscan level from all biases using task colbias:

```plaintext
cl> unlearn colbias
cl> colbias (@@bias.lis", @bias.lis", bias="[1032:1044,1:1000]", trim="",
>>> median+, interactive-, function="legendre", order=1, low_reject=3.,
>>> high_reject=3., niterate=3, logfiles="ccdproc.log")
```
And update the headers (first create the following two template scripts):

```bash
cl> type hdrlog\_ovsc.tem
gdate()
hdedit ("@%\_lis", "BIASSEC,TRIMSEC,DATASEC,CCDSEC,ORIGSEC", add=, del+)
hdedit ("@%\_lis", "OVERSCAN", "COMPLETE")
hdedit ("@%\_lis", "ORIGSEC", "[1:1044,1:1044]")  \→  original size of full frame
hdedit ("@%\_lis", "BIASSEC", "[1032:1044,1:1000]")  \→  overscan section
hdedit ("@%\_lis", "TRIMSEC", "[16:1015,1:1000]")  \→  excised from original frame
hdedit ("@%\_lis", "IMAGSEC", "[1:1000,1:1000]")  \→  output image section
!narg addovscmean.tem %.lis \$1' > addovscmean.cl
cl < addovscmean.cl
hdedit ("@%\_lis", "OVSCDATE", gdate.fdate)
```

```bash
cl> type addovscmean.tem
match "$1" "overscan.dat" | fields "-" 2 | scanf("%8f", x)
hdedit "$1", "OVSCMEAN", x
cl> !sed 's:%:bias:g' hdrlog\_ovsc.tem > hdrlog\_ovsc.cl
cl> cl < hdrlog\_ovsc.cl
```

△ But we didn’t actually trim the bias frames (we will trim the frames for all other
data types — hence the above script), so:

```bash
c1> hdedit ("@bias.lis", "TRIMSEC", "[1:1044,1:1044]", add=)
c1> hdedit ("@bias.lis", "IMAGSEC", "[1:1044,1:1044]", add=)
```

- Average the overscan-subtracted biases using task `imcombine`. Note, that no scal-
ing — and in particular no multiplicative scaling — should be allowed, and that each
bias frame should be given equal weight.

```bash
c1> unlearn imcombine
c1> imcombine ("@bias.lis", "BIAS.fits", logfile="ccdproc.log",
>>> combine="average", reject="avsigclip", outtype="real", scale="none",
>>> zero="none", weight="none", statsec="[16:1015,1:1000]", lthreshol=INDEF,
>>> hthreshold=64000., nkeep=1, mclip+, lsigma=3., hsigma=3., sigscale=0.1)
```

And update the headers:

```bash
c1> gdate()
c1> hselext BIAS.fits ncombine yes | scanf ("%d", i)
c1> print ("Combined ",i,"individual bias frames.")
Combined 179 individual bias frames.
c1> hdedit ("BIAS.fits", "NCOMBINE", add=, del+)
c1> hdedit ("BIAS.fits", "BIASCOMB", "COMPLETE")
c1> hdedit ("BIAS.fits", "NCOMBINE", i)
c1> hdedit ("BIAS.fits", "BSCBDATE", gdate.fdate)
```

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• Verify that the level in the overscan region of the combined frame is exactly 0. If not, subtract the residual level.

```
c1> imstat BIAS.fits[1032:1044,1:1000] fields="mean" format-
   -4.836262E-4

c1> unlearn imarith

c1> imarith ("BIAS.fits", ",", "-4.836262E-4", "MASTERBIAS.fits",
   >>> title="MASTERBIAS", divzero=0., hparams="", pixtype="real",
   >>> calctype="real", verbose+, noact-, >> "ccdproc.log")
```

Inspect the resulting “MASTERBIAS.fits” frame; does the noise agree with our theoretical expectations?

```
c1> display MASTERBIAS.fits 1 zscale- zrange- z1=-2. z2=4.
c1> implot MASTERBIAS.fits  ← see Fig. 7

c1> s1="MASTERBIAS[1:1044,1:1044],MASTERBIAS[16:1015,1:1000]"
c1> s1=s1//",MASTERBIAS[1032:1044,1:1000]"
c1> imstat (s1, fields="image,mean,midpt,stddev,min,max", lower=INDEF,
   >>> upper=INDEF, nclip=3, lsigma=3., usigma=3.)
```

<table>
<thead>
<tr>
<th>IMAGE</th>
<th>MEAN</th>
<th>MIDPT</th>
<th>STDDEV</th>
<th>MIN</th>
<th>MAX</th>
</tr>
</thead>
<tbody>
<tr>
<td>MASTERBIAS[1:1044,1:1044]</td>
<td>0.2325</td>
<td>0.2236</td>
<td>0.2349</td>
<td>-0.5484</td>
<td>0.9989</td>
</tr>
<tr>
<td>MASTERBIAS[16:1015,1:1000]</td>
<td>0.2368</td>
<td>0.2289</td>
<td>0.2279</td>
<td>-0.4581</td>
<td>0.9302</td>
</tr>
<tr>
<td>MASTERBIAS[1032:1044,1:1000]</td>
<td>-8.871e-4</td>
<td>-0.009762</td>
<td>0.2128</td>
<td>-0.6350</td>
<td>0.6331</td>
</tr>
</tbody>
</table>

Figure 7: Screen shot of `implot` graphs of the average of lines 1–1000 of the MASTERBIAS frame and a detail thereof, showing (a) a strong roll-on of the bias level at low column numbers, and (b) a small but systematic offset of ~0.24 ADU between the bias level in the overscan strip and in the image (illuminated) region of the CCD.
Assuming Gaussian read-noise, the expected noise in the absence of genuine variations in the column-to-column bias level would be:

$$\frac{1}{\sqrt{179}} \cdot \frac{5.66 [e^-]}{1.953 [e^-/ADU]} = 0.2166 \text{ [ADU]}$$

This is indeed what we measure in the overscan region ($\sigma = 0.2128$). In the image region (see Fig. 7a), several columns with higher levels contribute to the noise, as does the “roll-on” at low column numbers. The excess with respect to the theoretically expected noise is only:

$$100\% \cdot \frac{0.2279 - 0.2166}{0.2166} \sim 5\%$$

and can, therefore, be ignored.

From the computed image statistics, it is clear that the bias level in the image region shows a small but systematic offset with respect to that in the virtual overscan strip. The value for the mean in the “clean” portion of the illuminated region is 0.2368 ADU (see Fig. 7b). This offset, the few columns with elevated bias level, and the strong roll-on at low column numbers, require that we correct for the structure in the bias by subtracting the MASTERBIAS frame from all other types of CCD data in the subsequent image processing steps.

The noise level in the MASTERBIAS frame is much smaller ($\sim 25\times$) than the read-noise, and its subtraction in subsequent image processing steps will therefore not add any appreciable noise.

If you’re sure that everything is as it should be, then it is OK to delete the individual bias frames at this point:

```
c1> imdelete @bias.lis yes verify- default+
```
8.5.2 Dark frames

Our goal is to construct a dark reference frame to try and measure the bulk dark rate of the CCD, to find whether there are pixels with significantly higher dark rates, and to check whether there is structure in the dark level.

(0) visually inspect all dark frames and convert to 32-bit format
(1) interpolate over the bad pixels/columns we defined earlier
(2) subtract the MASTERBIAS frame to correct for structure in the bias
(3) subtract the level measured in the overscan strip and trim the image (cut off the overscan and other bad/non-illuminated pixels)
(4) average the darks together, scaling by integration time
(5) measure the bulk dark rate; identify hot pixels and add them to the bad pixel file
(6) normalize the combined dark frame to a dark time of 1 sec

- Visually inspect all dark frames (remove any darks with problems):
  ```
  cl> imexamine @dark.lis 1 allframes- nframes=1
  ```

- Convert all darks from 16-bit integer to 32-bit floating-point format:
  ```
  cl> chpixtype @dark.lis @dark.lis "real" oldpixtype="all" verbose+
  ```

- Add a line to the image headers, indicating the start of the processing log entries, and add an entry logging the pixel data type conversion:
  ```
  cl> !sed 's:%:dark:g' hdrlog_init.tem > hdrlog_init.cl
  cl> cl < hdrlog_init.cl
  ```

- Interpolate over the bad pixels/columns identified earlier; log relevant information to the image headers:
  ```
  cl> fixpix (@dark.lis, "badpix.ccd26", verbose+, >>"ccdproc.log")
  ```

- Correct for the structure in the bias level by subtracting the MASTERBIAS frame:
  ```
  cl> imarith (@dark.lis, ",-", "MASTERBIAS.fits", @dark.lis, title="",
  >>> divzero=0., hparams="", pixtype="real", calctype="real", verbose+,
  >>> noact-, >> "ccdproc.log")
  ```
And update the headers:

```bash
cl> type hdrlog_zrcr.tem
gdate()
hedit (@%.lis, "ZEROCOR", "COMPLETE")
hedit (@%.lis, "ZRCRIMAG", "/data1/raj/ast598/MASTERBIAS.fits")
hedit (@%.lis, "ZRCRDATE", gdate.fdate)
```

```bash
cl> !sed 's:%:dark:g' hdrlog_zrcr.tem > hdrlog_zrcr.cl
cl> cl < hdrlog_zrcr.cl
```

- Subtract the bias level as measured in the virtual overscan strip. First, we’ll measure that level and record it in a temporary log file:

```bash
cl> !sed 's/$/[1032:1044,1:1000]/g' dark.lis > dark.lis
cl> imstat (@dark.lis, fields="image,midpt", lower=INDEF, upper=INDEF,
>>> nclip=3, lsigma=3., usigma=3., format=, cache=, >> "overscan.dat")
cl> delete _dark.lis yes verify-
```

Now fit and remove the overscan level from all dark frames using task `colbias`:

```bash
cl> colbias (@dark.lis, "@dark.lis", bias=[1032:1044,1:1000], median=,
>>> trim=[16:1015,1:1000], interactive=, function="legendre", order=1,
>>> low_reject=3., high_reject=3., niterate=3, logfiles="ccdproc.log")
```

```bash
cl> !sed 's:%:dark:g' hdrlog_ovsc.tem > hdrlog_ovsc.cl
cl> cl < hdrlog_ovsc.cl
```

- Average the darks using task `imcombine`. Note, that when combining darks with different integration times, multiplicative scaling according to the elapsed dark time should be allowed. We will also combine the darks separately for each dark time, to verify that we indeed detect the bulk dark rate.

```bash
cl> hselect @dark.lis $I 'abs(darktime-600.)<=1.' > dark600.lis
cl> hselect @dark.lis $I 'abs(darktime-900.)<=1.' > dark900.lis
cl> hselect @dark.lis $I 'abs(darktime-1200.)<=1.' > dark1200.lis
```

```bash
cl> type dkcomb.tem
imcombine (@$1.lis", output="$2.fits", logfile="ccdproc.log",
combine="average", reject="avsigclip", outtype="real", scale="none",
zero="none", weight="none", statsec="[1:1000,101:1000]", lthresho=INDEF,
hthreshold=64000., nkeep=1, mclip+, lsigma=3., hsigma=3., sigscale=0.1,
grow=1.0)
```
Note that we use \texttt{grow=1.0}, to reject the four pixels nearest a pixel with a significantly deviant value. To reject pixels affected by cosmic rays, it is often necessary to also reject the neighbours of the pixel that received most of the charge. Note also, that we explicitly specified the header keyword to use for determining the integration time, \texttt{DARKTIME}, since the standard \texttt{EXPTIME} keyword will be 0. sec for dark frames.

Update the headers:

\begin{verbatim}
c1> gdate()
c1> hselect DARK.fits ncombine yes | scanf ("%d", i)
c1> print ("Combined ",i,"individual dark frames.")
Combined 12 individual dark frames.
c1> hedit ("DARK.fits", "NCOMBINE", add-, del+)
c1> hedit ("DARK.fits", "IMCMB*", add-, del+)
c1> hedit ("DARK.fits", "DARKCOMB", "COMPLETE")
c1> hedit ("DARK.fits", "NCOMBINE", i)
c1> hedit ("DARK.fits", "DKCBDATE", gdate.fdate)
\end{verbatim}

Note that, because the first frame in the list of darks was a 601 second integration, all other frames were scaled to 601 sec as well, and the effective dark time of the DARK calibration image will be 601 sec:

\begin{verbatim}
c1> hselect DARK*fits $I,darktime yes
DARK.fits 601.
DARK600.fits 601.
DARK900.fits 901.
DARK1200.fits 1200.
\end{verbatim}

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Inspect the resulting frames. Do we see structure? Do we indeed detect the bulk dark rate?

```cl
imexamine DARK*.fits 1 allframes- nframes=1
display DARK.fits 1 zscale- zrange- z1=-2. z2=4.
```

```cl
s1="[101:900,101:900]"
s2=DARK.fits"//s1//",DARK600.fits"//s1//",DARK900.fits"//s1
s2=s2"//",DARK1200.fits"//s1
imstat (s2, fields="image,mean,midpt,stddev,min,max", lower=INDEF,
upper=INDEF, nclip=3, lsigma=3., usigma=3.)
```

<table>
<thead>
<tr>
<th>#</th>
<th>IMAGE</th>
<th>MEAN</th>
<th>MIDPT</th>
<th>STDDEV</th>
<th>MIN</th>
<th>MAX</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>DARK600.fits[101:900,101:900]</td>
<td>0.2145</td>
<td>0.2032</td>
<td>1.672</td>
<td>-4.808</td>
<td>5.237</td>
</tr>
<tr>
<td>0</td>
<td>DARK900.fits[101:900,101:900]</td>
<td>0.1549</td>
<td>0.1397</td>
<td>1.660</td>
<td>-4.835</td>
<td>5.144</td>
</tr>
<tr>
<td>0</td>
<td>DARK1200.fits[101:900,101:900]</td>
<td>0.1277</td>
<td>0.1198</td>
<td>1.192</td>
<td>-3.454</td>
<td>3.708</td>
</tr>
<tr>
<td>0</td>
<td>DARK.fits[101:900,101:900]</td>
<td>0.1157</td>
<td>0.1119</td>
<td>0.6041</td>
<td>-1.698</td>
<td>1.930</td>
</tr>
</tbody>
</table>

Our best estimate for the bulk dark rate from the combination of all individual darks is \( dc = 3600 \cdot ((0.1119 \pm 0.0641)/601) = 0.67 \pm 3.62 e^-/\text{pix/hr} \), which is not particularly significant (only \( \sim 0.18 \sigma \)). From the frames averaged for each individual exposure time we get:

- 600 sec: \( dc = (1.22 \pm 10.0) e^-/\text{pix/hr} \)
- 900 sec: \( dc = (0.56 \pm 6.63) e^-/\text{pix/hr} \)
- 1200 sec: \( dc = (0.36 \pm 3.58) e^-/\text{pix/hr} \)

Although, at face value, all dark rate estimates agree within a factor \( \sim 3 \), and with a measurement derived over multiple observing runs from many more dark frames \( (dc = 1.08 \pm 0.50 e^-/\text{pix/hr}; \text{see Fig. 8}) \), we must conclude that we did not actually detect the bulk dark rate.

Now, warm and hot pixels will have much larger \( (> 4 \sigma) \) dark rates than the bulk of the pixels. So even though the S/N in the combined dark is rather low, we may still use this frame to identify such pixels. Do we find pixels that are consistently ”hot” in each of the four combined frames?

The easiest way to find out is by masking the pixels that deviate by more than \( +4 \sigma \) in each of DARK600, DARK900, DARK1200 and DARK (although the latter frame is not really independent of the former three).
Figure 8: Example of the measurement of the bulk dark rate using data from multiple observing runs at the VATT, between 2002 and 2006. Since the dark rate of modern CCD’s can be very low (1.08 ± 0.50 e⁻/pix/hr here), it may not be trivial to obtain a sufficient number of high-quality dark frames for a reliable detection. In the lower left panel, the magenta data points and curve show how omitting subtracting the MASTERBIAS frame (and therefore of the offset in bias level of the image regions compared to that in the overscan strip) could lead one to an erroneous dark rate.
First, we need to fit out any gradients (the lower several tens of rows in the combined dark images appear somewhat brighter):

```cl
unlearn fit1d ; unlearn imreplace
fit1d.interactive=no ; fit1d.function="legendre"
f1t1d.naverage=-5 ; fit1d.order=3
fit1d.low_reject=3. ; fit1d.high_reject=3. ; fit1d.niterate=3
fit1d ("DARK.fits", "tmp1.fits", "difference")
x = 4.*0.6041
imreplace ("tmp1.fits", 0., lower=INDEF, upper=x)
imreplace ("tmp1.fits", 1., lower=x, upper=INDEF)
imstat tmp1.fits fields="image,min,max"
fit1d ("DARK600.fits", "tmp2.fits", "difference")
x = 4.*1.672
imreplace ("tmp2.fits", 0., lower=INDEF, upper=x)
imreplace ("tmp2.fits", 1., lower=x, upper=INDEF)
fit1d ("DARK900.fits", "tmp3.fits", "difference")
x = 4.*1.660
imreplace ("tmp3.fits", 0., lower=INDEF, upper=x)
imreplace ("tmp3.fits", 1., lower=x, upper=INDEF)
fit1d ("DARK1200.fits", "tmp4.fits", "difference")
x = 4.*1.192
imreplace ("tmp4.fits", 0., lower=INDEF, upper=x)
imreplace ("tmp4.fits", 1., lower=x, upper=INDEF)
unlearn imsum
imsum ("tmp1,tmp2,tmp3,tmp4", "tmp.fits")
display tmp.fits 1 zs- zr- z1=-1. z2=5.
```

We want a warm/hot pixel to show up in at least 3 of the four combined images (assuming we might lose one detection due to image noise), so the lower limit for a genuine warm pixel in the combined mask image should be 3:

```cl
cpio (if not already loaded)
pixselect ("tmp.fits", lower=3.0, upper=INDEF, verbose-) | count
26
pixselect ("tmp.fits", lower=3.0, upper=INDEF, verbose-)
698 10 3.
843 23 4.
184 27 3.
982 39 4.
... ...
```
Since none of the identified warm/hot pixels is extremely hot (i.e., hot enough to come close to saturating that pixel in a long exposure), if we had a very high $S/N$ DARK frame we would opt to scale and subtract that DARK image from all science exposures. That way, we would subract the excess dark signal without distroying the collected astronomical source signal in that pixel. However, since our DARK image has relatively poor $S/N$, we will add the pixels identified to the bad pixel list, and interpolate over them. We will have to be careful when interpreting the signals in these pixels.

We need to reformat the $x$ and $y$ coordinates from the output of `pixselect` into the “$x1$ $x2$ $y1$ $y2$” format of the bad pixel file:

```
cl> pixselect ("tmp.fits", lower=3.0, upper=INDEF, verbose-, >> "hotpix.lis")
cl> !awk '{print $1,$1,$2,$2}' hotpix.lis >> badpix.ccd26
```

Clean-up of temporary files that are no longer needed:

```
cl> delete tmp* yes verify-
```

- Normalize the combined dark image to a dark time of 1 sec to produce a “master” dark image.

If we had detected a bulk dark rate and, particularly, if the dark rate showed any systematic structure across the CCD, we would normalize our combined dark frame to a dark time of 1 sec (i.e, divide the frame by the integration time in seconds):

```
cl> imarith ("DARK.fits", "/", "601.", "MASTERDARK.fits", title="MASTERDARK",
>>> divzero=0., hparams="darktime", pixtype="real", calctype="real",
>>> verbose+, noact-, >> "ccdproc.log")
```

Note, that by specifying “darktime” for the `hparams` task parameter, the value of FITS header keyword `DARKTIME` will be updated to reflect the executed arithmetic operation, i.e., will be divided by 601. $\rightarrow$ 1.0 sec.
8.5.3 Dome flat frames

Our goal is to construct a reference frame for each filter, that records the wavelength-dependent pixel-to-pixel (small-scale) variations in the effective sensitivity of the CCD, and do so at high \( S/N \geq 1000 \).

1. **Visually inspect all dome flat frames, add filter name, and convert to 32-bit format**
2. **Interpolate over the bad pixels/columns we defined earlier**
3. **Subtract the MASTERBIAS frame to correct for structure in the bias (optional)**
4. **Subtract the level measured in the overscan strip and trim the image (cut off the overscan and other bad/non-illuminated pixels)**
5. **Model shutter shading correction using frames with exposures shorter than \( \sim 3 \) sec**
6. **Median average the dome flats together, scaling by the average signal level**
7. **Fit a low-order surface to the combined flat, and divide by the fit to produce a normalized response frame, containing only the high-order structure (i.e., the pixel-to-pixel sensitivity variations)**

- Visually inspect all dome flat frames and remove any flats with problems (e.g., overexposed/saturated frames, anomalous gradients, filter wheel problems, etc...):

```plaintext
cl> imexamine @flat.lis 1 allframes nframes=1
```

Add a proper (human readable) filter name to the image headers — at the VATT, only the position of each filter wheel is recorded. The observing log files (see § 8.2) give us the following translations:

Apr 2005: \( R = "1 2 1 0" \) (and \( B = "2 1 1 0" \), but no \( B \) flats were taken)

Sep 2005: \( R = "2 1 1 0" \) and \( B = "1 3 1 0" \)

```plaintext
cl> hselect @flat.lis $I 'telfilte="1 2 1 0"' > _flatR.lis
cl> hselect @flat.lis $I 'telfilte="2 1 1 0"' >> _flatR.lis
cl> hselect @flat.lis $I 'telfilte="1 3 1 0"' > _flatB.lis
cl> hedit.add=yes ; hedit.verify=no ; hedit.show=no
cl> hedit @_flatR.lis filter "R"
cl> hedit @_flatB.lis filter "B"
cl> delete _flat?.lis yes verify-
```

Convert all dome flats from 16-bit integer to 32-bit floating-point format:

```plaintext
cl> chpixtype @flat.lis @flat.lis "real" oldpixtype="all" verbose+
cl> !sed 's:%:flat:g' hdrlog_init.tem > hdrlog_init.cl
cl> cl < hdrlog_init.cl
```
• Interpolate over the bad pixels/columns + warm pixels identified earlier:

```
cl> fixpix (@flat.lis", "badpix.ccd26", verbose+, >> "ccdproc.log")
```

```
cl> !sed 's:%:flat:g' hdrlog_fpx.tem >hdrlog_fpx.cl
```

```
cl> cl <hdrlog_fpx.cl
```

• It is not necessary to correct (dome- and twilight-) flat frames for either structure in the bias level, or for dark current. Flat field frames (should) have high signal levels and are normalized to 1. Hence the maximum error one would make would be:

\[ 100\% \times \text{few ADU} / \text{several tens of thousands of ADU} \approx 0.1\% \]

Furthermore, flat field exposures tend to be short exposures (generally, less than a minute), and the dark rate is very much less than the photon rate.

• Subtract the bias level as measured in the virtual overscan strip. First, we’ll measure that level and record it in a temporary log file:

```
cl> !sed ’s/\[[1032:1044,1:1000]\]/g’ flat.lis >_flat.lis
cl> imstat (@_flat.lis", fields="image,midpt", lower=INDEF, upper=INDEF,
>>> nclip=3, lsigma=3., usigma=3., format-, cache-, >> "overscan.dat")
cl> delete _flat.lis yes verify-
```

Now, fit and remove the overscan level from all dome flats using colbias:

```
cl> colbias (@_flat.lis", "@flat.lis", bias="[1032:1044,1:1000]", median+
>>> trim="[16:1015,1:1000]", interactive-, function="legendre", order=1,
>>> low_reject=3., high_reject=3., niterate=3, logfiles="ccdproc.log")
```

```
cl> !sed ’s:%:flat:g’ hdrlog_ovsc.tem >hdrlog_ovsc.cl
cl> cl <hdrlog_ovsc.cl
```

• Model any shutter shading features and correct the short dome flat exposures. For the VATT CCD camera, shutter shading effects become progressively serious for exposure times shorter than \(~3\text{sec.}\)

The basic approach to construct a pixel-to-pixel response frame is to combine the dome flat frames and fit out any low-order gradients, which are presumed to reflect the illumination pattern of the CCD.

Constructing the pixel-to-pixel response frame using a surface fit can create artifacts when there is a relatively high-order feature present in the flats (such as the shutter
shading feature). To fit that feature out may require a surface fit of high enough order, that genuine features (e.g., dust particles) will be (partially) fit out. Hence, a two-step approach is required: (1) divide the combined flats for the shorter exposure times by a response frame constructed from flats with much longer exposure times to produce an image of the shutter shading pattern, and (2) fit a surface to that image (which may be a high-order fit, because all genuine variations dropped out already). Lastly, normalize the combined flat by dividing by that fit.

First, let’s see what exposure times we have per filter:

```
cl> hselect @flat.lis exptime,filter yes | sort numeric+ | unique
0.1  R  short; Sep 29 2005
0.4  R  short; ""
0.8  R  short; ""
1.2  R  short; ""
2.0  R  short; ""
5.0  R  long; ""
12.  R  long; Apr 4-8 2005
14.  R  long; ""
15.  R  long; ""
30.  B  long; Sep 29 2005
```

Create lists per exposure time and observing run:

```
# Apr 4-8 2005:
cl> hselect @flat.lis $I 'filter=="R"&&exptime>5.0' > flatR_long.lis
cl> hselect @flat.lis $I 'filter=="R"&&exptime==0.1' > flatR_0.1s.lis
cl> hselect @flat.lis $I 'filter=="R"&&exptime==0.4' > flatR_0.4s.lis
cl> hselect @flat.lis $I 'filter=="R"&&exptime==0.8' > flatR_0.8s.lis
cl> hselect @flat.lis $I 'filter=="R"&&exptime==1.2' > flatR_1.2s.lis
cl> hselect @flat.lis $I 'filter=="R"&&exptime==2.0' > flatR_2.0s.lis
cl> hselect @flat.lis $I 'filter=="R"&&exptime==5.0' > flatR_5.0s.lis
cl> hselect @flat.lis $I 'filter=="B"' > flatB_long.lis
```

Combine flats per observing run or night, per filter, and per exposure time. Scale by the mean signal level:

```
# Apr 4-8 2005:
cl> imcombine (@flatR_long.lis, output="FLATapr_R.fits", combine="average",
    logfile="ccdproc.log", reject="avsigclip", outtype="real",
    scale="mean", zero="none", weight="none", statsec="[1:1000,101:1000]",
    lthreshold=INDEF, hthreshold=64000., nkeep=1, mclip=yes, lsigma=3.,
    hsigma=3., sigscale=0.1, grow=1.0)
```
Normalize the combined flat. Note, that for the normalization of the flats with “long” exposures, we can use a low-order 2-D fit. In the fitting, all higher-order features are rejected iteratively. The ratio of flat and fit is then a response frame, containing only the pixel-to-pixel (small-scale) sensitivity variations. Task \texttt{imsurfit} performs both fitting and computing this ratio when \texttt{type\_output="response"} is selected:

```python
cl> unlearn imsurfit
cl> imsurfit ("FLATapr.R.fits", "RESPapr.R.fits", xorder=9, yorder=9,
          >>> type\_output="response", function="spline3", cross\_terms=yes,
          >>> lower=3., upper=3., ngrow=1, niter=5, div\_min=0.2)
cl> imstat RESPapr.R.fits fields="image,mean,midpt,stddev,min,max" nclip=X
#    IMAGE MEAN MIDPT STDDEV MIN MAX
nclip=0: RESPapr.R.fits 0.9966 0.9994 0.01568 0.2119 1.131
nclip=5: RESPapr.R.fits 0.9992 0.9999 0.005335 0.9824 1.016
```

# Sep 29 2005:

```python
cl> imcombine ("@flatB_long.lis", output="FLATsep_B.fits", combine="average",
         >>> logfile=ccdproc.log", reject="avsigclip", outtype="real",
         >>> scale="mean", zero="none", weight="none", statsec="[1:1000,101:1000]",
         >>> lthreshold=INDEF, hthreshold=64000., nkeep=1, mclip=yes, lsigma=3.,
         >>> hsigma=3., sigscale=0.1, grow=1.0)
```

Normalize the combined flat:

```python
cl> unlearn imsurfit
cl> imsurfit ("FLATsep_B.fits", "RESPsep_B.fits", xorder=9, yorder=9,
          >>> type\_output="response", function="spline3", cross\_terms=yes,
          >>> lower=3., upper=3., ngrow=1, niter=5, div\_min=0.2)
cl> imstat RESPsep_B.fits fields="image,mean,midpt,stddev,min,max" nclip=X
#    IMAGE MEAN MIDPT STDDEV MIN MAX
nclip=0: RESPsep_B.fits 0.9989 0.9995 0.008119 0.2493 1.058
nclip=5: RESPsep_B.fits 0.9998 0.9999 0.003079 0.9905 1.009
```

Next, combine the various short and 5.0 s long $R$-filter flats (all from Apr 4–8 2005) per exposure time:

```python
cl> unlearn imcombine
cl> imcombine logfile="ccdproc.log" ; imcombine.combine="average",
cl> imcombine.reject="avsigclip" ; imcombine.outtype="real"
cl> imcombine.scale="mean" ; imcombine.zero="none" ; imcombine.weight="none"
cl> imcombine.statsec="[1:1000,101:1000]" ; imcombine.lthreshold=INDEF
cl> imcombine.hthreshold=64000. ; imcombine.nkeep=1 ; imcombine.mclip=yes
```
cl> imcombine.sigscale=0.1 ; imcombine.lsigma=3. ; imcombine.hsigma=3.
cl> imcombine.grow=1.0
cl> imcombine (@flatR_0.1s.lis, output="FLATR_0.1s.fits")
cl> imcombine (@flatR_0.4s.lis, output="FLATR_0.4s.fits")
cl> imcombine (@flatR_0.8s.lis, output="FLATR_0.8s.fits")
cl> imcombine (@flatR_1.2s.lis, output="FLATR_1.2s.fits")
cl> imcombine (@flatR_2.0s.lis, output="FLATR_2.0s.fits")
cl> imcombine (@flatR_5.0s.lis, output="FLATR_5.0s.fits")

Normalize the combined flat for the long 5.0 sec exposure (where shutter shading should be negligible) into a response frame:

cl> unlearn imsurfit
cl> imsurfit (@FLATR_5.0s.fits, @RESPR_5.0s.fits, xorder=5, yorder=5, output="response", function="spline3", cross=terms=yes, lower=3., upper=3., ngrow=1, niter=5, div.min=0.2)
cl> imstat RESPR_5.0s.fits fields="image,mean,midpt,stddev,min,max" nclip=5

# IMAGE MEAN MIDPT STDDEV MIN MAX
nclip=0: RESPR_5.0s.fits 0.9991 0.9993 0.006432 0.2157 1.056
nclip=5: RESPR_5.0s.fits 0.9999 1.0000 0.002864 0.9912 1.008

Construct the response frames for the shorter exposures using the 2-step approach. Since we will have many repeated commands, it’s best to write a little template script:

cl> type shadnorm.tem
imarith (@FLATR_%s.fits, "/", @RESPR_%s.fits, @SHUTR_%s.fits, divzero=0., pixtype="real", calctype="real", noact=)
imsurfit(@SHUTR_%s.fits, @SHUTR_%s.fits, xorder=15, yorder=15, output="fit", function="spline3", cross=terms=yes, lower=3., upper=3., ngrow=1, niter=5)
imarith (@FLATR_%s.fits, "/", @RESPR_%s.fits, output="real", calctype="real", noact=)
imstat RESPR_%s.fits fields="image,mean,midpt,stddev,min,max" nclip=5

cl> !sed 's:%:0.1:g' shadnorm.tem > shadnorm.cl
cl> cl < shadnorm.cl

# IMAGE MEAN MIDPT STDDEV MIN MAX
RESPR_0.1s.fits 0.9999 1.0000 0.003033 0.9907 1.009

cl> !sed 's:%:0.4:g' shadnorm.tem > shadnorm.cl
cl> cl < shadnorm.cl

# IMAGE MEAN MIDPT STDDEV MIN MAX
RESPR_0.4s.fits 0.9998 0.9999 0.003294 0.9899 1.010
Figure 9: (a) Combined frame constructed from the 0.1 s dome flats in $R$. The hexagonal shutter shading pattern (see Fig. 1) is obvious. (b) Combined frame constructed from the 1.2 s dome flats. A central “bright spot” due to shutter shading is still apparent, but other low-order structures (e.g., a gradient from lower right to upper left) become important too. Gradients seen in dome flats need not be identical to those (if any) observed in the night-sky background.

```
c> !sed 's:%:0.8:g' shadnorm.tem > shadnorm.cl
c> cl < shadnorm.cl
 # IMAGE    MEAN    MIDPT   STDDEV    MIN    MAX
RESPR_0.8s.fits  0.9999  1.0000    0.002773  0.9915  1.008

c> !sed 's:%:1.2:g' shadnorm.tem > shadnorm.cl
c> cl < shadnorm.cl
 # IMAGE    MEAN    MIDPT   STDDEV    MIN    MAX
RESPR_1.2s.fits  0.9998  0.9999    0.003050  0.9906  1.009

c> !sed 's:%:2.0:g' shadnorm.tem > shadnorm.cl
c> cl < shadnorm.cl
 # IMAGE    MEAN    MIDPT   STDDEV    MIN    MAX
RESPR_2.0s.fits  0.9998  1.0000    0.003050  0.9910  1.009
```

Lastly, average the pixel-to-pixel response frames thus constructed together into a final high-$S/N$ response frame:

```
c> !ls -1 RESPR_*.fits > respsep.lis

c> unlearn imcombine
```
Figure 10: The final high-S/N $R$-filter response frame for the 2005 Sep 29 data, constructed from all dome flats taken during that night. The response frame shows only the pixel-to-pixel (small-scale) variations in the effective sensitivity of CCD images. Such variations can be intrinsic (pixel-to-pixel Quantum Efficiency variations) or extrinsic (e.g., the many semi-transparent dust and pollen particles) to the CCD. Note, that since we opted to interpolate over bad pixel columns as one of our first processing steps, they are absent from the above response frame (only the very wide column at upper right shows through).

```bash
c1> imcombine (@resp_sep_lis.lis, output="RESPsepR.fits", combine="average",
>>> logfile="ccdproc.log", reject="avsigclip", outtype="real",
>>> scale="mean", zero="none", weight="none", statsec="[1:1000,101:1000]",
>>> lthreshold=INDEF, hthreshold=64000., nkeep=1, mclip=yes, lsigma=3.,
>>> hsigma=3., sigscale=0.1, grow=1.0)
```

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Fig. 9 illustrates why we couldn’t just average all individual dome flat frames together to create a high-S/N response frame. Fig. 10 shows what our resulting response frame, “RESPsepR.fits”, looks like.

Now, did we indeed reach our goal of 1,000,000 $e^-$ per pixel?

# Sep 29 2005 (see § 8.2):

<table>
<thead>
<tr>
<th>Time</th>
<th>Color</th>
<th>Averge Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1 s</td>
<td>$R$</td>
<td>5 × 28,886</td>
</tr>
<tr>
<td>0.4 s</td>
<td>$R$</td>
<td>5 × 19,355</td>
</tr>
<tr>
<td>0.8 s</td>
<td>$R$</td>
<td>5 × 37,313</td>
</tr>
<tr>
<td>1.2 s</td>
<td>$R$</td>
<td>5 × 25,280</td>
</tr>
<tr>
<td>2.0 s</td>
<td>$R$</td>
<td>5 × 30,059</td>
</tr>
<tr>
<td>5.0 s</td>
<td>$R$</td>
<td>8 × 19,516</td>
</tr>
</tbody>
</table>

$\sum 860,593. \text{ADU} = 1,680,738 \, e^- \rightarrow \text{OK!}$

<table>
<thead>
<tr>
<th>Time</th>
<th>Color</th>
<th>Averge Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>30. s</td>
<td>$B$</td>
<td>10 × 15,895</td>
</tr>
</tbody>
</table>

$\sum 158,950. \text{ADU} = 310,429 \, e^- \rightarrow \sim \frac{1}{3}$

# Apr 4-8 2005:

<table>
<thead>
<tr>
<th>Time</th>
<th>Color</th>
<th>Averge Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>12,14,15</td>
<td>$R$</td>
<td>19 × 28,356</td>
</tr>
</tbody>
</table>

$\sum 538,764. \text{ADU} = 1,052,206 \, e^- \rightarrow \text{OK}$
8.5.4 Twilight flat frames

Our goal is to construct a reference frame for each filter, that records the wavelength-dependent illumination pattern (large-scale variations) of the CCD.

1. visually inspect all twilight flat frames, add filter name, and convert to 32-bpp
2. interpolate over the bad pixels/columns we defined earlier
3. subtract the MASTERBIAS frame to correct for structure in the bias (optional)
4. subtract the level measured in the overscan strip and trim the image (cut off the overscan and other bad/non-illuminated pixels)
5. correct frames with very short exposure times for shutter shading
6. if the $S/N \ll 1000$, then fit a low-order 2-D surface (illumination pattern) to the combined flat; if $S/N \gtrsim 1000$, use the normalized combined twilight flat directly for correction of both pixel-to-pixel sensitivity variations and illumination. If the $S/N$ is intermediate and if the $S/N$ of the response frame constructed from the dome flats is $<1000$, then the illumination pattern should be fit, but illumination-corrected dome flats and twilight flats may be combined to increase the $S/N$ of the final response frame.

- Visually inspect all twilight sky flat frames and remove any flats with problems (e.g., overexposed/saturated frames, anomalous gradients, filter wheel problems, etc...):

```bash
cl> imexamine @sky.lis 1 allframes- nframes=1
```

△ Removed frame “050929/b0151.fits” from file “sky.lis”: it is saturated!

Add a proper (human readable) filter name to the FITS headers. The translations from wheel positions to filter names are as for the dome flats. Note, that wheel-position string "2 1 1 0" corresponds to the $B$ filter in Apr 2005, while it denotes $R$ in Sep 2005:

Apr 2005: $R = "1 2 1 0"$ and $B = "2 1 1 0"$
Sep 2005: $R = "2 1 1 0"$ and $B = "1 3 1 0"

```bash
cl> match "0504" "sky.lis" > sky.apr.lis
cl> match "0509" "sky.lis" > sky.sep.lis
cl> hselect @sky.apr.lis $I 'telfilte="1 2 1 0"' > sky.aprR.lis
cl> hselect @sky.apr.lis $I 'telfilte="2 1 1 0"' > sky.aprB.lis
cl> hselect @sky.sep.lis $I 'telfilte="2 1 1 0"' > sky.sepR.lis
cl> hselect @sky.sep.lis $I 'telfilte="1 3 1 0"' > sky.sepB.lis
```
Convert all twilight flats from 16-bit integer to 32-bit floating-point format:

\[ \texttt{cl> chpixtype @sky.lis @sky.lis "real" oldpixtype="all" verbose+} \]

\[ \texttt{cl> !sed 's:%:sky:g' hdrlog_init.tem > hdrlog_init.cl} \]
\[ \texttt{cl> cl < hdrlog_init.cl} \]

- Interpolate over the bad pixels/columns + warm pixels identified earlier:
  \[ \texttt{cl> fixpix (@sky.lis, "badpix.ccd26", verbose+, >> "ccdproc.log")} \]
  \[ \texttt{cl> !sed 's:%:sky:g' hdrlog_fpx.tem > hdrlog_fpx.cl} \]
  \[ \texttt{cl> cl < hdrlog_fpx.cl} \]

- It is not necessary to correct the sky flat frames for either structure in the bias level, or for dark current.

- Subtract the bias level as measured in the virtual overscan strip. First, we'll measure that level and record it in a temporary log file:
  \[ \texttt{cl> !sed 's/$/[1032:1044,1:1000]/g' sky.lis > _sky.lis} \]
  \[ \texttt{cl> imstat (@_sky.lis, fields="image,midpt", lower=INDEF, upper=INDEF,} \]
  \[ \texttt{>>> nclip=3, lsigma=3., usigma=3., format-, cache-, >> "overscan.dat")} \]
  \[ \texttt{cl> delete _sky.lis yes verify-} \]

Now, fit and remove the overscan level from all twilight flats using \texttt{colbias}:

\[ \texttt{cl> colbias (@_sky.lis, @_sky.lis, bias="[1032:1044,1:1000]", median+,} \]
\[ \texttt{>>> trim="[16:1015,1:1000]", interactive-, function="legendre", order=1,} \]
\[ \texttt{>>> low_reject=3., high_reject=3., niterate=3, logfiles="ccdproc.log"} \]
• Correct the short twilight sky flat exposures for shutter shading effects.

We already produced images of the shutter shading pattern, when we processed the short dome flat exposures. The one corresponding to the very shortest exposure, “SHUTR 0.1s.fits”, has the highest fidelity (in the exposures longer than ~1 sec, the non-uniform illumination starts to contribute, as well).

First, let’s find an appropriate normalization of frame “SHUTR 0.1s.fits”, such that the center of the shutter feature, measured to be near pixel (496, 485), will have a value of exactly 1, and the edges of the CCD a value of \( I_{\text{border}} / I_{\text{center}} \):

So, in a 0.1 sec exposure, the exposure time for pixels on the optical axis of the shutter is \( 33522 / 27656.68 = 1.212076 \) times larger than the exposure time for pixels along the outer edge of the CCD.

Repeating the measurements of the relative exposure times of center and border for the other exposure times, we find the following:

<table>
<thead>
<tr>
<th>Exposure time, ( t )</th>
<th>( I_{\text{center}} )</th>
<th>( I_{\text{border}} )</th>
<th>Relative strength, ( S(t) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1 s</td>
<td>33522. ADU</td>
<td>27656.68 ADU</td>
<td>1.212076</td>
</tr>
<tr>
<td>0.4 s</td>
<td>20281. ADU</td>
<td>19134.28 ADU</td>
<td>1.059930</td>
</tr>
<tr>
<td>0.8 s</td>
<td>38218. ADU</td>
<td>37088.87 ADU</td>
<td>1.030444</td>
</tr>
<tr>
<td>1.2 s</td>
<td>25627. ADU</td>
<td>25212.62 ADU</td>
<td>1.016435</td>
</tr>
<tr>
<td>2.0 s</td>
<td>30313. ADU</td>
<td>30028.83 ADU</td>
<td>1.009463</td>
</tr>
<tr>
<td>5.0 s</td>
<td>19456. ADU</td>
<td>19462.09 ADU</td>
<td>0.999687</td>
</tr>
</tbody>
</table>

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Figure 11: Relative shutter shading strength versus exposure time for the Sep 2005 run. Adopting strength $S(t)$ from the fit in this graph (green), we can scale frame “SHUTSHAD.0.1s.fits” and correct the twilight flats with any $0.1 < t < 5.0$.

Having determined the shape of the shutter shading pattern and the normalization as a function of exposure time, we can correct the twilight flats with short exposures, should the $S/N$ in the combined longer exposures not suffice.
Average the twilight flats together per run (or night) and per filter, scaling by the mean signal level, and fit the illumination pattern.

Create lists per observing run and filter for the longer twilight flat exposures:

# Apr 4–8 2005:
    cl> hselect @sky_apr.lis $I 'filter="R"&exptime>=3.0' > skyR_apr.long.lis
    cl> hselect @sky_apr.lis $I 'filter="B"&exptime>=3.0' > skyB_apr.long.lis

# Sep 29 2005:
    cl> hselect @sky_sep.lis $I 'filter="R"&exptime>=3.0' > skyR_sep.long.lis
    cl> hselect @sky_sep.lis $I 'filter="B"&exptime>=3.0' > skyB_sep.long.lis

Combine the sky flats per run and per filter:

    cl> type ftcomb.tem
    imcombine (@sky%$long.lis, output="SKY%$.fits", combine="average",
               logfile="ccdproc.log", reject="avsigclip", outtype="real",
               scale="mean", zero="none", weight="none", statsec="[1:1000,101:1000]",
               lthreshold=INDEF, hthreshold=64000., nkeep=1, mclip=yes, lsigma=3.,
               hsigma=3., sigscale=0.1, grow=1.0)

    cl> unlearn imcombine
    cl> !sed 's:%:R:g' ftcomb.tem | sed 's:$:apr:g' > ftcomb.cl
    cl> cl < ftcomb.cl

    cl> !sed 's:%:B:g' ftcomb.tem | sed 's:$:apr:g' > ftcomb.cl
    cl> cl < ftcomb.cl

    cl> !sed 's:%:R:g' ftcomb.tem | sed 's:$:sep:g' > ftcomb.cl
    cl> cl < ftcomb.cl

    cl> !sed 's:%:B:g' ftcomb.tem | sed 's:$:sep:g' > ftcomb.cl
    cl> cl < ftcomb.cl

Normalize the combined twilight flats. Since there are no $B$-filter dome flats, the Apr 2005 twilight flats in $B$ will serve both to correct for pixel-to-pixel (small-scale) sensitivity variations and to correct for the illumination pattern. That frame will therefore merely be normalized to a mean level of 1. The $R$-filter twilight flats of both Apr and Sep 2005 will be used only to fit the illumination pattern. And the Sep 2005 $B$-filter twilight flat will be used both to correct for the illumination pattern and to increase the $S/N$ in the response frame constructed from the dome flats.
# Apr 2005, $B$-filter twilight flat:

```
c> imstat SKYapr_B.fits nclip=0
# IMAGE MEAN MIDPT STDDEV MIN MAX
   SKYapr_B.fits 46359. 46465. 1599. 5780. 53316.
```

```
c> imarith ("SKYapr_B.fits", "/", "46359.", "RESPILLUMapr_B.fits",
            divzero=0., hparams="", pixtype="real", calctype="real",
            title="RESP+ILLUMapr_B", verbose+, noact-, >> "ccdproc.log")
```

```
c> imstat RESPILLUMapr_B.fits nclip=0
# IMAGE MEAN MIDPT STDDEV MIN MAX
   RESPILLUMapr_B.fits 1. 1.002 0.0345 0.1247 1.15
```

# Apr and Sep 2005, $R$-filter; and Sep 2005, $B$-filter, twilight flats:

```
c> type mkillum.tem
imarith ("SKY$%.fits", "/", "RESP$%.fits", "_ILLUM$%.fits",
pixtype="real", calctype="real")
imsurf(x) ("_ILLUM$%.fits", "ILLUM$%.fits", xorder=9, yorder=9,
type_output="fit", function="spline3", cross_terms=yes,
lower=3., upper=3., ngrow=1, niter=5)
imstat ("ILLUM$%.fits", fields="mean", format-) | scan(s1)
imarith ("ILLUM$%.fits", "/", s1, "ILLUM$%.fits",
title="ILLUM$%.", pixtype="real", calctype="real")
```

```
c> unlearn imarith
cl> !sed 's:%:R:g' mkillum.tem | sed 's:$.apr:g' > mkillum.cl
cl> cl < mkillum.cl
cl> imstat ILLUMapr_R.fits nclip=0
```

```
c> !sed 's:%:R:g' mkillum.tem | sed 's:$.sep:g' > mkillum.cl
cl> cl < mkillum.cl
cl> imstat ILLUMapr_R.fits nclip=0
```

```
c> !sed 's:%:B:g' mkillum.tem | sed 's:$.sep:g' > mkillum.cl
cl> cl < mkillum.cl
cl> imstat ILLUMapr_B.fits nclip=0
```
8.6 Processing of the science frames

(0) visually inspect all science frames, add filter name, and convert to 32-bpp
(1) interpolate over the bad pixels/columns we defined earlier
(2) subtract the MASTERBIAS frame to correct for structure in the bias
(3) subtract the level measured in the overscan strip and trim the image (cut off the
overscan and other bad/non-illuminated pixels)
(4) subtract any bulk dark signal (if significant; possibly optional)
(5) correct for shutter shading (if significant; it likely won’t be)
(6) correct for the pixel-to-pixel (small-scale) variations in effective sensitivity
(7) correct for the illumination pattern (large-scale variations)

- Visually inspect all science frames and remove any that have uncorrectable prob-
lems (e.g., overexposed/saturated frames, filter wheel problems, etc...):

```
c> imexamine @sci.lis 1 allframes- nframes=1
```

\(\triangle\) Removed frame “050929/b0147.fits” from file “sci.lis”: it is near saturation (\(~60,000
ADU\)). Also removed “050929/b0089.fits”, because the secondary jumped.

Add a proper (human readable) filter name to the FITS headers. The translations
from wheel positions to filter names are as for the dome and twilight flats:

Apr 2005: \(R = "1 2 1 0"\) and \(B = "2 1 1 0"\)
Sep 2005: \(R = "2 1 1 0"\) and \(B = "1 3 1 0"\)

```
c> match "0504" "sci.lis" > sciapr.lis
cl> match "0509" "sci.lis" > sci sep.lis
cl> hselect @sciapr.lis $I 'telfilte="1 2 1 0"' > sciR.lis
cl> hselect @sciapr.lis $I 'telfilte="2 1 1 0"' > sciB.lis
cl> hselect @scisep.lis $I 'telfilte="2 1 1 0"' >> sciR.lis
cl> hselect @scisep.lis $I 'telfilte="1 3 1 0"' >> sciB.lis
cl> count sci.lis
73 73 1314 sci.lis
cl> count sci*.lis
27 27 486 sci_B.lis
46 46 828 sky_R.lis
73 73 1314 Total
cl> hedit.add=yes ; hedit.verify=no ; hedit.show=no
cl> hedit @sciR.lis filter "R"
cl> hedit @sciB.lis filter "B"
cl> delete sci*.lis yes verify-

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Convert all science frames from 16-bit integer to 32-bit floating-point format:

```sh
chpixtype @sci.lis @sci.lis "real" oldpixtype="all" verbose+
```

Add a line to the image headers, indicating the start of the processing log entries, and add an entry logging the pixel data type conversion:

```sh
!sed 's:%:sci:g' hdrlog_init.tem > hdrlog_init.cl
c> cl < hdrlog_init.cl
```

- Interpolate over the bad pixels/columns + warm pixels identified earlier:

```sh
fixpix (@sci.lis", "badpix.ccd26", verbose+, >> "ccdproc.log")
!sed 's:%:sci:g' hdrlog_fpx.tem > hdrlog_fpx.cl
c> cl < hdrlog_fpx.cl
```

- Correct for the structure in the bias level, and for the small offset of that level between the image region and the overscan strip, by subtracting the MASTER-BIAS frame:

```sh
imarith (@sci.lis", "-", "MASTERBIAS.fits", @sci.lis", divzero=0.,
>>> hparams="", pixtype="real", calctype="real", title="", verbose+,
>>> noact-, >> "ccdproc.log")
!sed 's:%:sci:g' hdrlog_zrcr.tem > hdrlog_zrcr.cl
c> cl < hdrlog_zrcr.cl
```

- Subtract the bias level as measured in the virtual overscan strip. First, we’ll measure that level and record it in a temporary log file, then we’ll remove it and trim the images using task colbias:

```sh
!sed 's/[@32:1044,1:1000]/g' sci.lis > _sci.lis
imstat (@sci.lis", fields="image,midpt", lower=INDEF, upper=INDEF,
>>> nclip=3, lsigma=3., usigma=3., format-, cache-, >> "overscan.dat")
delete _sci.lis yes verify-
colbias (@sci.lis", @sci.lis", bias="[1032:1044,1:1000]",
>>> trim=[16:1015,1:1000], median+, interactive-, function="legendre",
>>> order=1, low_reject=3, high_reject=3, niterate=3, logfiles="ccdproc.log")
!sed 's:%:sci:g' hdrlog_ovsc.tem > hdrlog_ovsc.cl
cl < hdrlog_ovsc.cl
```
• Subtract any bulk dark signal, if significant:

We found that the bulk dark rate is very low, $\sim 1\ e^-/\text{pix}/\text{hr}$. Our longest science exposure is 600s (image "050929/b0044.fits"; see § 8.2), corresponding to a bulk dark signal of $(600/3600) \times 1 \simeq 0.17\ e^-$ or $\sim 0.1\ \text{ADU}$. Most science exposures are much shorter. We will, therefore, omit any correction for dark signal.

• Correct short science exposures for shutter shading, if significant:

The shortest science exposures are 10s and, hence, no correction for shutter shading is required.

• Correct for pixel-to-pixel (small-scale) variations in sensitivity:

We need to process the science frames per observing run and per filter — the small-scale variations, particularly those due to dust and pollen particles, vary per run and possibly even from night to night.

c1> hselect @sci_apr.lis $I 'filter=="R"' > sci_apr_R.lis

c1> hselect @sci_apr.lis $I 'filter=="B"' > sci_apr_B.lis

c1> hselect @sci_sep.lis $I 'filter=="R"' > sci_sep_R.lis

c1> hselect @sci_sep.lis $I 'filter=="B"' > sci_sep_B.lis

c1> type hdrlog_ftcr.tem
gdate()
hedit ("@%.lis", "FLATCOR", "COMPLETE")
hedit ("@%.lis", "FTCRIMAG", "/data1/raj/ast598/$.fits")
hedit ("@%.lis", "FTCRDATE", gdate.fdate)
c1> type hdrlog_ilcr.tem
gdate()
hedit ("@%.lis", "ILLUMCOR", "COMPLETE")
hedit ("@%.lis", "ILCRIMAG", "/data1/raj/ast598/$.fits")
hedit ("@%.lis", "ILCRDATE", gdate.fdate)

# Apr 2005, B-filter science frames:

c1> imarith (@sci_apr_B.lis, "/", "RESPILLUMapr_B.fits", @sci_apr_B.lis",
>>> title="", divzero=0., hparams="", pixtype="real", calctype="real",
>>> verbose+, noact-, >> "ccdproc.log")

c1> !sed 's:%:sci_apr_B:g' hdrlog_ftcr.tem | sed 's:\$:RESPILLUMapr_B:g'

>> grep -w "ccdproc.log"

c1> cl < hdrlog_ftcr.cl
c1> !sed 's:%:sci_apr_B:g' hdrlog_ilcr.tem | sed 's:\$:RESPILLUMapr_B:g'

>> grep -w "ccdproc.log"

c1> cl < hdrlog_ilcr.cl

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# Apr 2005, \textit{R}-filter science frames:

\begin{verbatim}
cl> imarith("@sci\_apr\_R.lis", "/", "RESPapr\_R.fits", "@sci\_apr\_R.lis",
>>> \quad title="", divzero=0., hparams="", pixtype="real", calctype="real",
>>> \quad verbose+, noact-, >> ccdproc.log numerically)
cl> imarith("@sci\_apr\_R.lis", "/", "ILLU\_Map\_R.fits", "@sci\_apr\_R.lis",
>>> \quad title="", divzero=0., hparams="", pixtype="real", calctype="real",
>>> \quad verbose+, noact-, >> ccdproc.log numerically)
cl> !\text{sed} 's:%sci\_apr\_R:g' hdrlog\_ftcr.tem | sed 's:$RESPapr\_R:g' \\
>>> \quad > hdrlog\_ftcr.cl
cl> cl < hdrlog\_ftcr.cl
cl> !\text{sed} 's:%sci\_apr\_R:g' hdrlog\_ilcr.tem | sed 's:$ILLU\_Map\_R:g' \\
>>> \quad > hdrlog\_ilcr.cl
cl> cl < hdrlog\_ilcr.cl
\end{verbatim}

# Sep 2005, \textit{B}-filter science frames:

\begin{verbatim}
cl> imarith("@sci\_sep\_B.lis", "/", "RESPsep\_B.fits", "@sci\_sep\_B.lis",
>>> \quad title="", divzero=0., hparams="", pixtype="real", calctype="real",
>>> \quad verbose+, noact-, >> ccdproc.log numerically)
cl> imarith("@sci\_sep\_B.lis", "/", "ILLUMsep\_B.fits", "@sci\_sep\_B.lis",
>>> \quad title="", divzero=0., hparams="", pixtype="real", calctype="real",
>>> \quad verbose+, noact-, >> ccdproc.log numerically)
cl> !\text{sed} 's:%sci\_sep\_B:g' hdrlog\_ftcr.tem | sed 's:$RESPsep\_B:g' \\
>>> \quad > hdrlog\_ftcr.cl
cl> cl < hdrlog\_ftcr.cl
cl> !\text{sed} 's:%sci\_sep\_B:g' hdrlog\_ilcr.tem | sed 's:$ILLUMsep\_B:g' \\
>>> \quad > hdrlog\_ilcr.cl
cl> cl < hdrlog\_ilcr.cl
\end{verbatim}

# Sep 2005, \textit{R}-filter science frames:

\begin{verbatim}
cl> imarith("@sci\_sep\_R.lis", "/", "RESPsep\_R.fits", "@sci\_sep\_R.lis",
>>> \quad title="", divzero=0., hparams="", pixtype="real", calctype="real",
>>> \quad verbose+, noact-, >> ccdproc.log numerically)
cl> imarith("@sci\_sep\_R.lis", "/", "ILLUMsep\_R.fits", "@sci\_sep\_R.lis",
>>> \quad title="", divzero=0., hparams="", pixtype="real", calctype="real",
>>> \quad verbose+, noact-, >> ccdproc.log numerically)
cl> !\text{sed} 's:%sci\_sep\_R:g' hdrlog\_ftcr.tem | sed 's:$RESPsep\_R:g' \\
>>> \quad > hdrlog\_ftcr.cl
cl> cl < hdrlog\_ftcr.cl
cl> !\text{sed} 's:%sci\_sep\_R:g' hdrlog\_ilcr.tem | sed 's:$ILLUMsep\_R:g' \\
>>> \quad > hdrlog\_ilcr.cl
cl> cl < hdrlog\_ilcr.cl
\end{verbatim}
To test whether the quality of the flat fielding meets our goals (i.e., residual large-scale variations in the background level of no more than a few tenths of a percent), we can examine one or more representative frames with a non-negligible background level:

```
c> implot 050408/i0153.fits
:l 1 100  ← plot the average of the lower 100 lines
:l 250 500 ← plot the average of lines 250–500
:l 1 1000 ← plot the average of all 1000 lines
:y 4095 4120 ← change the vertical plot limits to 4095–4120 ADU
:c 1 1000 ← plot the average of the 1000 columns
```

Some of the resulting graphs are shown in Fig. 12. The residual variations in the background level on scales of ~100 pixels appear to be less than ~25 ADU (peak-to-valley) on an average level of ~4102 ADU, corresponding to $\leq 0.61\%$. The residual variations on larger scales are less (~0.25%).

![Figure 12: Graph of the average of all columns (top) and rows (bottom) in a flatfielded image (050408/i0153.fits) produced with task implot. The spikes correspond to genuine astronomical objects (mostly stars) in the image. The residual variations in the image background on scales of ~100 pixels are less than ~25 ADU (peak-to-valley) on an average level of ~4102 ADU, i.e., $\leq 0.61\%$. When averaging 1000 lines or columns, the variations are less than ~0.25%.](image-url)
Figure 13: Processed (bias- and overscan-subtracted, flatfielded) $R$-filter science image of photometric standard star field Rubin 149 ("050405/f0057.fits"). Some additional bad column-sections are visible that were not visible in the flat images (whether or not a charge trap rears its ugly head can depend on the signal level!). If many frames display these columns, they should be added to the bad pixel list and all frames reprocessed. There are also a few patches visible, where the flat fielding is imperfect: dust particles moved, disappeared or were newly deposited at these locations. "Delta" flats may be constructed from dome or twilight flats taken before and after such a particle (dis)appeared/moved to correct for them.
8.7 Photometric calibration of the science frames

- Load digital photometry packages:

  ```
  cl> digiphot
  cl> apphot
  cl> photcal
  ```

- Create lists of standard star images for both April and September 2005 runs:

  ```
  cl> hselect @sci.lis $I,object yes | match "MarkA" | fields "-" 1 > tmp.lis
  cl> hselect @sci.lis $I,object yes | match "PG" | fields "-" 1 >> tmp.lis
  cl> hselect @sci.lis $I,object yes | match "Rubin" | fields "-" 1 >> tmp.lis
  cl> sort tmp.lis | match "0504" | sed 's:.fits::g' > standards_apr.lis
  cl> sort tmp.lis | match "0509" | sed 's:.fits::g' > standards_sep.lis
  cl> delete tmp.lis yes verify-
  cl> hselect @standards_apr.lis object yes > std_apr.lis
  cl> hselect @standards_sep.lis object yes > std_sep.lis
  ```

- Using task `markstds`, create files `*.stdcoo` listing the pixel coordinates of each photometric standard star within the observed Landolt fields. First, we need to know what number of pixels corresponds to a radius of 7” (the aperture Landolt used). The pixel size of the VATT camera was found (through astrometric matching to 2MASS fields) to be 0".3746, so 7” ~ 18.7 pixels. The choice of inner radius of the sky annulus is fairly arbitrary, but should be well away from the outer edge of the measurement aperture. The width of the annulus should be chosen such that at least a thousand pixels or so fall within the annulus.

  ```
  cl> type getstdcoo.tem
  print ("\nLandolt field $2 ...")
  markstds ("$1.fits", radstr="18.7,40,50", refstar="$2")
  ctrcoo ("$1.stdcoo", "$1.stdcoo", "$1.fits",
      cntrbox=7, redispl-, verbose-)
  ```

# Apr 2005 standards:

  ```
  cl> !narg getstdcoo.tem standards_apr.lis '1 std_apr.lis '2 > getstdcoo.cl
  cl> type getstdcoo.cl
  print ("\nLandolt field Rubin149 ...")
  markstds ("050405/f0047.fits", radstr="18.7,40,50", refstar="Rubin149")
  ctrcoo ("050405/f0047.stdcoo", "050405/f0047.stdcoo", "050405/f0047.fits",
      cntrbox=7, redispl-, verbose-)
  print ("\nLandolt field Rubin149 ...")
  ```

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Have the finding charts of each observed standard star field ready (e.g., Fig. 15). Then, in each image, mark the individual photometric standard stars. In each field, start with the naming (reference) star of that field, then star “A”, “B”, “C”, etc. Note, that you may have to invert the x- and/or y-axis in ds9 (using the Zoom menu) to get the same image orientation as your finding chart (N up, E to the left):

c1> unlearn markstds
cl> cl < getstdcoo.cl
Landolt field Rubin149 ...
MARKSTDS: NOAO/IRAF2.12.2 raj@andromeda Nov 16 01:06:17 2006
image = 050405/f0047.fits [1000 x 1000]
Wait for the cursor cross to appear in the image display area, then mark all (standard) stars in the image using the ‘c’ key. Hit ‘q’ to quit. Note: start with the main (i.e., naming or reference) star in the field.

MARKSTDS: Finished.
Landolt field Rubin149 ...
MARKSTDS: NOAO/IRAF2.12.2 raj@andromeda Nov 16 01:07:03 2006
...

RUBIN149

Figure 14: Display with graphical overlay after marking each of the 8 individual photometric standard stars in the field of Rubin 149 using task markstds on frame “050405/f0049.fits”.

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Figure 15: Finding charts for several Landolt (1992) fields with R.A. < 12h. Only fields that contain multiple photometric standard stars were observed (see also § 8.2). Each field is named after the primary or reference star in the field. A convenient web-accessible list of Landolt standards and finding charts can be found at www.noao.edu/wiyn/obsprog/images/atlasinfo.html.
Figure 15: (cont’d) Finding charts for several Landolt standard star fields with R.A. $> 12^h$. 

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# Sep 2005 standards:

```
c1> !narg getstdcoo.tem standards sep.lis 'S1' _std sep.lis 'S2' > getstdcoo.cl
c1> cl < getstdcoo.cl
```

- Using task **qphot**, perform aperture photometry to measure instrument magnitudes for all standard stars in each field. Note, that an arbitrary zero-point magnitude needs to be chosen. For no particular reason, I will use 26 mag throughout (any value in the 25–30 mag range would be fine, *as long as you stick with just one value throughout*).

In order to correctly compute the uncertainties on the aperture magnitudes, **qphot** also needs to know the CCD gain (which we computed in § 8.4):

```
c1> type getstdphot.tem
qphot ("%.fits", cbox=5, annulus=40., dannulus=11., apertures="18.7",
        coords="%.stdcoo", output="%.stdmag", zmag=26.,
        exposure="exptime", airmass="airmass", filter="filter", obstime="ut",
        epadu=1.953, interactive-, verbose+)
```

```
c1> unlearn apphot ; unlearn qphot
c1> !narg getstdphot.tem standards apr.lis '%' > getstdphot.cl
c1> type getstdphot.cl
qphot ("050405/f0047.fits", cbox=5, annulus=40., dannulus=11., aperture="18.7",
        coords="050405/f0047.stdcoo", output="050405/f0047.stdmag", zmag=26.,
        exposure="exptime", airmass="airmass", filter="filter", obstime="ut",
        epadu=1.953, interactive-, verbose+)
```

```
c1> cl < getstdphot.cl
```

```
f0047.fits 447.55  674.77  40.86908  16.024 ok  ← Rubin 149 (RU149)
f0047.fits 401.74  645.45  40.06779  16.492 ok  ← star RU149A
f0047.fits 575.56  680.00  40.06578  14.409 ok  ← star RU149B
f0047.fits 564.94  572.19  39.77685  16.432 ok  ← star RU149C
f0047.fits 487.72  631.16  40.70958  13.563 ok  [etc.]
f0047.fits 608.18  392.49  40.38199  15.529 ok
f0047.fits 434.98  446.69  40.06924  15.037 ok
f0047.fits 349.10  499.03  40.25653  14.631 ok
f0048.fits 445.50  674.39  119.3431  16.031 ok  ← star RU149
f0048.fits 398.76  645.15  118.1907  16.476 ok  ← star RU149A
f0048.fits 573.51  679.53  118.1061  14.423 ok  [etc.]
f0048.fits 562.87  571.56  117.7270  16.445 ok
```

```
c1> !narg getstdphot.tem standards sep.lis '%' > getstdphot.cl
c1> cl < getstdphot.cl
```
In what follows, we will use the tasks in the photcal package to simultaneously and interactively solve for the absolute photometric zeropoints, atmospheric extinction and color terms, in order to reduce our instrument magnitudes onto the Landolt photometric system. Since the syntax is rather cryptic, and since the steps required to prepare for these tasks leave little room for error, you might also want to read the package help file (help pcintro), the help files on the individual tasks used in the following, and Phil Massey’s tutorial ("Stellar CCD Photometry using IRAF", p.22-35) for additional examples.

- Prepare matched input and configuration files. First, get an inventory of the standard star images per run, per field, and per filter:

```bash
# Apr 2005 standards:
cl> hselect @standards_apr.lis $I 'object=="Rubin149"&filter=="R"'
  050405/f0047 050405/f0048 050405/f0057 050408/10034 050408/10035 050408/10044
cl> hselect @standards_apr.lis $I 'object=="Rubin149"&filter=="B"'
  050405/f0049 050408/10036 050408/10037
cl> hselect @standards_apr.lis $I 'object=="PG0918-029"&filter=="R"'
  050405/10045 050408/10050
cl> hselect @standards_apr.lis $I 'object=="PG0918-029"&filter=="B"'
  050408/10046
cl> hselect @standards_apr.lis $I 'object=="PG1047+003"&filter=="R"'
  050405/f0058 050405/f0068 050405/f0122 050405/f0123 050405/f0132 050408/10028
  050408/10033 050408/10105 050408/10110
cl> hselect @standards_apr.lis $I 'object=="PG1047+003"&filter=="B"'
  050405/f0060 050405/f0061 050405/f0124 050405/f0125 050408/10029 050408/10106
cl> hselect @standards_apr.lis $I 'object=="PG1323-086"&filter=="R"'
  050408/10111 050408/10116
cl> hselect @standards_apr.lis $I 'object=="PG1323-086"&filter=="B"'
  050408/10112
cl> hselect @standards_apr.lis $I 'object=="PG1528+062"&filter=="R"'
  050405/f0175 050405/f0180 050408/10117 050408/10122
cl> hselect @standards_apr.lis $I 'object=="PG1528+062"&filter=="B"'
  050405/f0176 050408/10118
cl> hselect @standards_apr.lis $I 'object=="PG1633+099"&filter=="R"'
  050405/f0181 050405/f0186 050408/10157
cl> hselect @standards_apr.lis $I 'object=="PG1633+099"&filter=="B"'
  050405/f0182 050408/10158
cl> hselect @standards_apr.lis $I 'object=="MarkA"&filter=="R"'
  050408/10152
cl> hselect @standards_apr.lis $I 'object=="MarkA"&filter=="B"'
  050408/10153
```

And similarly for the Sep 2005 standards (use the field names from “_std_sep.lis”).

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Next, create (using your favorite ASCII text editor) a file that lists per night the
matched sets of images of the same field, one $R$ and one $B$ filter image per line,
preceded by the field identifier. “Matched” means taken during the same sequence of
exposures at the same pointing (give or take a few pixels) and at very similar UT and
Airmass. If no matched observation is available in $B$, then INDEF should be specified.
The spaces before and after the colon following the standard star field identifier are
mandatory. The files, should be formatted as shown below. If you specified the image
extension “.fits” as part of the image names to qphot, then they also need to be
specified here, or mkobsfile will complain.

# Apr 2005 standards:

```bash
cl> type 050405/standards.sets
Rubin149 : f0048.fits f0049.fits
Rubin149 : f0047.fits INDEF
Rubin149 : f0057.fits INDEF
PG1047+003 : f0058.fits f0060.fits
PG1047+003 : f0068.fits f0061.fits
PG1047+003 : f0122.fits f0124.fits
PG1047+003 : f0123.fits f0125.fits
PG1047+003 : f0132.fits INDEF
PG1528+062 : f0175.fits f0176.fits
PG1528+062 : f0180.fits INDEF
PG1633+099 : f0181.fits f0182.fits
PG1633+099 : f0186.fits INDEF
```

Note, that if we had made observations in more filters, the above file would have
listed matched images in each of the observed filters, not just $R$ and $B$.

```bash
cl> type 050408/standards.sets
Rubin149 : i0034.fits i0036.fits
Rubin149 : i0035.fits i0037.fits
Rubin149 : i0044.fits INDEF
PG0918-029 : i0045.fits i0046.fits
PG0918-029 : i0050.fits INDEF
PG1047+003 : i0028.fits i0029.fits
PG1047+003 : i0033.fits INDEF
PG1047+003 : i0105.fits i0106.fits
PG1047+003 : i0110.fits INDEF
PG1323-086 : i0111.fits i0112.fits
PG1323-086 : i0116.fits INDEF
PG1528+062 : i0117.fits i0118.fits
PG1528+062 : i0122.fits INDEF
PG1633+099 : i0157.fits i0158.fits
MarkA : i0152.fits i0153.fits
```
Now, create an observations file using task \texttt{mkobsfile}, which collects and tabulates the measured instrument magnitudes for each star in each of the photometric standard star images as well as associated information extracted from the image headers (filter, UT, Airmass at the middle of the exposure). If this information is not (or incorrectly) recorded in the image headers, then the headers need to be fixed before running \texttt{mkobsfile} \textit{(before running \texttt{qphot}, actually)}. The default tolerance for shifts between matched images is 5 pixels. If the distances between stars in the images are relatively large, we can get away with larger shifts by selecting a larger value of the \texttt{tolerance} parameter (set here to 20 pixels). If larger shifts occurs, or if the fields are relatively crowded, one would first have to construct a shifts file, in which the pixel shifts between each set of matched images is given.
Check that the reported number of stars matches the number of standard stars within the field of view. If a larger number is reported, the shifts between matched images is larger than the specified tolerance.

\[
c\> \text{cd ../050408/}
\]
\[
c\> \text{mkobsfile ("*.stdmag", "R,B", "standards.obs", imsets="standards.sets",}
\]
\[
>>> \text{minmagerr=0.001, shifts="", apercors="", tolerance=20., verbose+)}
\]

△ There are three matched sets, where there is a large shift between the exposures: “i0106” is shifted \((-105.4, -53.9)\) pixels with respect to “i0105”, “i0153” \((0.4, 344.8)\) pixels with respect to “i0152”, and “i0158” \((-106.3, 0.6)\) pixels with respect to “i0157”. We have to take these sets out of the “standards.sets” file and handle them seperately:

\[
c\> !\text{egrep -ve \(\{i0106|i0153|i0158\}\) standards.sets > standards.sets}
\]
\[
c\> !\text{egrep -e \(\{i0106|i0153|i0158\}\) standards.sets > standards1.sets}
\]
\[
c\> !\text{mv _standards.sets standards.sets}
\]
\[
c\> \text{delete standards.obs,fstandards.obs.dat yes}
\]
\[
c\> \text{mkobsfile ("*.stdmag", "R,B", "standards.obs", imsets="standards.sets",}
\]
\[
>>> \text{minmagerr=0.001, shifts="", apercors="", tolerance=20., verbose+)}
\]
\[
c\> \text{type standards1.shifts}
\]
\[
i0105.fits 0.0 0.0
i0106.fits 105.4 53.9
i0152.fits 0.0 0.0
i0153.fits -0.4 -344.8
i0157.fits 0.0 0.0
i0158.fits 106.3 -0.6
\]
\[
c\> \text{mkobsfile ("*.stdmag", "R,B", "standards1.obs", imsets="standards1.sets",}
\]
\[
>>> \text{minmagerr=0.001, shifts="standards1.shifts", apercors="", tolerance=5.)}
\]

Observations file: standards1.obs
  Image set: PG1047+003 4 stars written to the observations file
  Image set: PG1633+099 5 stars written to the observations file
  Image set: MarkA 4 stars written to the observations file

And merge the two observations tables (omit the 3 header lines):

\[
c\> !\text{tail +4 standards1.obs >> standards.obs}
\]

And for the Sep 2005 standards:

\[
c\> \text{cd ../050929/}
\]
\[
c\> \text{mkobsfile ("*.stdmag", "R,B", "standards.obs", imsets="standards.sets",}
\]
\[
>>> \text{minmagerr=0.001, shifts="", apercors="", tolerance=20., verbose+)}
\]

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Along with the “standards.obs” files, `mkobsfile` also outputs files “fstandards.obs.dat” that describe the format of the former. The files “standards.obs” for each night need to be edited, such that they list the proper identification for each individual star as published in Landolt (1992; his Table 2), or as included within IRAF's `photcal` catalogs directory in file: `noao$digiphot/photcal/catalogs/nlandolt.dat`.

If you intend to use standard stars from other sources/fields or for near-IR filters, be sure to read: `noao$digiphot/photcal/catalogs/README`

```bash
cl> cd ../050405/
cl> copy standards.obs standards.obs.orig
```

Before editing:

```bash
cl> type standards.obs.orig
```

<table>
<thead>
<tr>
<th>#</th>
<th>FIELD</th>
<th>FILTER</th>
<th>OTIME</th>
<th>AIRMASS</th>
<th>XCENTER</th>
<th>YCENTER</th>
<th>MAG</th>
<th>MERR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rubin149-1</td>
<td>R</td>
<td>2:58:21.0</td>
<td>1.256</td>
<td>445.502</td>
<td>674.385</td>
<td>16.031</td>
<td>0.002</td>
</tr>
<tr>
<td>2</td>
<td>B</td>
<td></td>
<td>2:59:47.0</td>
<td>1.256</td>
<td>398.765</td>
<td>645.148</td>
<td>16.476</td>
<td>0.003</td>
</tr>
<tr>
<td>3</td>
<td>Rubin149-2</td>
<td>R</td>
<td>2:59:47.0</td>
<td>1.256</td>
<td>398.765</td>
<td>645.148</td>
<td>16.476</td>
<td>0.003</td>
</tr>
<tr>
<td>4</td>
<td>B</td>
<td></td>
<td>2:59:47.0</td>
<td>1.256</td>
<td>398.765</td>
<td>645.148</td>
<td>16.476</td>
<td>0.003</td>
</tr>
</tbody>
</table>

After editing:

```bash
cl> type standards.obs
```

<table>
<thead>
<tr>
<th>#</th>
<th>FIELD</th>
<th>FILTER</th>
<th>OTIME</th>
<th>AIRMASS</th>
<th>XCENTER</th>
<th>YCENTER</th>
<th>MAG</th>
<th>MERR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rubin149-1</td>
<td>R</td>
<td>2:58:21.0</td>
<td>1.256</td>
<td>445.502</td>
<td>674.385</td>
<td>16.031</td>
<td>0.002</td>
</tr>
<tr>
<td>2</td>
<td>B</td>
<td></td>
<td>2:59:47.0</td>
<td>1.256</td>
<td>398.765</td>
<td>645.148</td>
<td>16.476</td>
<td>0.003</td>
</tr>
<tr>
<td>3</td>
<td>Rubin149-2</td>
<td>R</td>
<td>2:59:47.0</td>
<td>1.256</td>
<td>398.765</td>
<td>645.148</td>
<td>16.476</td>
<td>0.003</td>
</tr>
<tr>
<td>4</td>
<td>B</td>
<td></td>
<td>2:59:47.0</td>
<td>1.256</td>
<td>398.765</td>
<td>645.148</td>
<td>16.476</td>
<td>0.003</td>
</tr>
</tbody>
</table>

Remove any standards stars of which the images (perhaps only the stellar cores!) are saturated from file “standards.obs”. Also weed out stars with cosmic ray hits within the measurement aperture (if you have relatively long standard star exposures), which

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may require visual inspection:

```bash
cl> type standards.stat.tem
imexamine ("%.fits", 1, "", logfile="standards.stat", keeplog*,
   defkey="a", allframes=--, nframes=1, ncstat=27, nlstat=27,
   imagecur="%.stdcoo")
cl> !\ls -1 *.stdcoo | sed 's:.stdcoo::g' > standards.stat.lis
cl> !narg standards.stat.tem standards.stat.lis '%' > standards.stat.cl
cl> type standards.stat
# [1] f0047.fits - Rubin149
# COL LINE COORDINATES R MAG FLUX SKY PEAK E PA
447.68 674.81 447.68 674.81 16.92 12.53 97314. 40.90 1995. 0.02 -65
401.36 645.43 401.36 645.43 17.95 13.00 63112. 40.12 1150. 0.22 22
575.69 679.98 575.69 679.98 16.69 10.93 425754. 44.12 8743. 0.04 -63
564.97 572.08 564.97 572.08 16.90 12.95 65834. 40.81 1357. 0.04 -58
487.78 631.07 487.78 631.07 17.09 10.08 929397. 49.58 18752. 0.04 -62
608.10 392.42 608.10 392.42 16.22 12.05 151762. 41.66 3236. 0.04 -57
435.00 446.71 435.00 446.71 17.74 11.56 237520. 43.13 4981. 0.06 -53
349.08 499.01 349.08 499.01 16.40 11.16 344955. 44.96 7090. 0.08 -5
# [1] f0048.fits - Rubin149
# COL LINE COORDINATES R MAG FLUX SKY PEAK E PA
445.51 674.22 445.51 674.22 20.70 11.35 289461. 122.6 3822. 0.01 56
398.96 644.99 398.96 644.99 20.93 11.77 195043. 119.8 2420. 0.21 27
... ... ... ... ... ... ... ... ... ... ... ... ... ...
```

In output table “standards.stat”, check the column containing the peak intensities (PEAK) for values above ~62,000 ADU or so, and remove any found from the observations file.

- Create, edit and verify a configurations file using task `mkconfig`. The resulting configuration file should list the proper transformation equations, which (in our case) should be in terms of $B-R$ colors (instead of $B-V$ and $V-R$). Note, that `mkconfig` dumps you into a `vi` text editor. Delete the transformation equations for $U$, $V$ and $I$, and edit the default ones for $B$ and $R$ to look like shown below. To exit, hit `ESQ` (if you’re in ‘insert’ mode) and :wq:

  ```bash
  cl> unlearn mkconfig
  cl> mkconfig ("standards.cfg", "nlandolt", "standards.obs", "nlandolt",
      >>> verbose+)
  ```
# Declare the new Landolt UBVRI standards catalog variables

catalog

V 4     # the V magnitude
BV 5    # the (B-V) color
UB 6    # the (U-B) color
VR 7    # the (V-R) color
RI 8    # the (R-I) color
VI 9    # the (V-I) color

error(V) 12  # the V magnitude error
error(BV) 13  # the (B-V) color error
error(UB) 14  # the (U-B) color error
error(VR) 15  # the (V-R) color error
error(RI) 16  # the (R-I) color error
error(VI) 17  # the (V-I) color error

# Declare the observations file variables

observations

TR 3     # time of observation in filter R
XR 4     # airmass in filter R
xR 5     # x coordinate in filter R
yR 6     # y coordinate in filter R
mR 7     # instrumental magnitude in filter R
error(mR) 8  # magnitude error in filter R

TB 10    # time of observation in filter B
XB 11    # airmass in filter B
xB 12    # x coordinate in filter B
yB 13    # y coordinate in filter B
mB 14    # instrumental magnitude in filter B
error(mB) 15  # magnitude error in filter B

# Customized transformation section to reduce our mags onto the Landolt system

transformation

fit  b1=0.0, b2=0.35, b3=0.000
    const b4=0.0
    BFIT : mB = (BV + V) + b1 + b2 * XB + b3 * (BV + VR) + b4 * (BV + VR) * XB

fit  r1=0.0, r2=0.08, r3=0.000
    const r4=0.0
    RFIT : mR = (V - VR) + r1 + r2 * XR + r3 * (BV + VR) + r4 * (BV + VR) * XR

<ESQ>
:wq
"standards.cfg" 46L, 1554C written

** Beginning of compilation **

** End of compilation **

CATALOG VARIABLES, COLUMNS, AND ERROR COLUMNS:

1 V 4 12
2 BV 5 13
3 UB 6 14
4 VR 7 15
5 RI 8 16
6 VI 9 17

OBSERVATIONAL VARIABLES, COLUMNS, AND ERROR COLUMNS:

1 TR 3 INDEF
2 XR 4 INDEF
3 xR 5 INDEF
4 yR 6 INDEF
5 mR 7 8
6 TB 10 INDEF
7 XB 11 INDEF
8 xB 12 INDEF
9 yB 13 INDEF
10 mB 14 15

FIT AND CONSTANT PARAMETER VALUES:

1 b1 0.
2 b2 0.35
3 b3 0.
4 b4 0. (constant)
5 r1 0.
6 r2 0.08
7 r3 0.
8 r4 0. (constant)

TRANSFORMATION EQUATIONS:

1 BFIT: mB = (BV+V)+b1+b2*XB+b3*(BV+VR)+b4*(BV+VR)*XB
delta(BFIT, b1) = 0.1
delta(BFIT, b2) = 0.1
delta(BFIT, b3) = 0.1
delta(BFIT, b4) = 0.1
error = , min = , max =
weight = , min = , max =
plot x = , y =

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RFIT: \( m_R = (V-VR)+r_1+r_2*XR+r_3*(BV+VR)+r_4*(BV+VR)*XR \)

\[ \text{delta(RFIT, } r_1) = 0.1 \]
\[ \text{delta(RFIT, } r_2) = 0.1 \]
\[ \text{delta(RFIT, } r_3) = 0.1 \]
\[ \text{delta(RFIT, } r_4) = 0.1 \]

\[ \text{error = , min = , max =} \]
\[ \text{weight = , min = , max =} \]
\[ \text{plot x = , y =} \]

Catalog input variables = 12
First catalog column = 4
Last catalog column = 17

Observational input variables = 12
First observational column = 3
Last observational column = 15

Fitting parameters = 6
Constant parameters = 2

Auxiliary (set) equations = 0
Transformation equations = 2

Warnings = 0
Errors = 0

\text{standards.cfg}

\text{Run task fitparams to interactively solve (fit) the transformation equations listed in standards.cfg, one at a time. Check that solutions indeed converge. On photometric nights, the RMS scatter should be no more than } \sim 0.03 \text{mag after rejection of outliers, and the reduced } \chi^2 \text{ should be close to 1.}

\text{c1> unlearn fitparams}
\text{c1> fitparams ("standards.obs", "nlandolt", "standards.cfg", "standards.sol",}
\text{>>> weighting="photometric", nreject=5, logfile="photcal.log",}
\text{>>> log_fit+, log_results+)}

\text{:tolerance 1e-2} \quad \text{make fit less restrictive; allow poor fit to converge}
\text{h} \quad \text{plot function (observed B mag + mean offset) against fit (B mag)}
\text{t} \quad \text{toggle overlay with indication of fit (open boxes)}
\text{l} \quad \text{plot residuals with respect to the fit versus function}
\text{=} \quad \text{hardcopy of screen to default print device (optional)}
\text{d} \quad \text{delete some of the most pronounced outliers}
\text{f} \quad \text{refit}
\text{:tolerance 1e-3} \quad \text{reduce tolerance somewhat to see if fit still converges}

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yes, it does

plot the residuals versus time of observation, UT (denoted by ‘TB’)

redefine the ‘j’ key to plot:
XB,residuals ← residuals versus Airmass (symbolically denoted by ‘XB’)

redefine the ‘j’ key to plot:
BV,residuals ← residuals versus $B-V$ color

delete some additional outliers

refit; RMS is down to 0.0??? mag

redefine the ‘j’ key to plot:
er(mB),residuals ← residuals vs. error in instrumental $B$ magnitude

:errors ← print an overview of the errors and fitted parameters

#Wed 01:32:41 06-Dec-2006

#mB = (BV+V)+b1+b2*XB+b3*(BV+VR)+b4*(BV+VR)*XB

#Solution converged

low_reject 3.
high_reject 3.
mreject 5
grow 0.
tol 0.001
maxiter 15

niterations 10
total_points ??
rejected ??
deleted ??
standard deviation 0.0??????????
reduced chi 1.??????????
average error 0.0??????????
average scatter 0.0??????????
RMS 0.0??????????

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
<th>error</th>
</tr>
</thead>
<tbody>
<tr>
<td>b1</td>
<td>.??????</td>
<td>0.0??????? (fit)</td>
</tr>
<tr>
<td>b2</td>
<td>0.??????</td>
<td>0.00??????? (fit)</td>
</tr>
<tr>
<td>b3</td>
<td>0.0??????</td>
<td>0.00??????? (fit)</td>
</tr>
<tr>
<td>b4</td>
<td>0.000000</td>
<td>0.000000 (constant)</td>
</tr>
</tbody>
</table>
Since the reduced $\chi^2 \sim 1$ and the RMS $< 0.03$ mag, and since the fitted values appear to make sense (errors on fit $< 10\%$ of the fitted values), let's accept this fit as a valid solution and move on to the next filter:

```
q
yes
next
```

And similar key-command sequences for the $R$ filters, but with TR instead of TB, and XR instead of XB.

→ standards.sol and photcal.log

Check in file `photcal.log’ that nothing is listed under the header “#UNMATCHED OBJECT” (i.e., all stellar indentifications were indeed found in the ‘landolt’ standard table. Check under the header “#RESULTS: BFIT” and “#RESULTS: RFIT” whether there are any stars that are consistently bad and, hence, rejected from the fit (values of INDEF in each column).

cl> type standards.sol

The fitted photometric transformation coefficients, $p_z$, $p_e$ and $p_c$, (and errors thereon) are (1) the photometric zeropoint offsets with respect to the assumed zeropoint of the instrument magnitudes of 26.0 mag (see qphot above), (2) the atmospheric extinction coefficient in magnitudes per airmass, and (3) the first-order color term, $\Delta(B-R)$ per 1 magnitude of $B-R$, which reflects the difference between the natural system of your telescope, instrument and detector, and that of the Landolt system.

If the system throughput in the $B$ and $R$ filters are reasonably similar to those of Landolt, then higher-order color terms are probably not required (besides, we here consider only two filters, so a fit of such higher-order terms will likely be uncertain or not converge at all).

Note, that the absolute zeropoint magnitude that places our instrument magnitudes on the Landolt photometric system is $(26 - \text{offset})$ mag (i.e., we subtract, not add, the fitted zeropoint offset from our assumed instrument zeropoint).

To photometrically calibrate any instrument magnitude measured during the given night, simply compute:

$$m = (m_{\text{instr}} - 26) + (26 - p_z) + p_e \cdot \text{airmass} + p_c \cdot \text{color}$$

where color is $B - R$ in our case, and $p_z$ the zeropoint offset. This equation must be applied iteratively, since the correct color is not known a priori (only the difference between the two instrument magnitudes, i.e., the color on the instrument’s natural system, is known). Alternatively, to avoid loss of precision or introduction of additional correlated errors, one would follow the procedure given in Appendix B of Jansen et al. 2000, ApJS 126, 271.
8.8 Image analysis: differential photometry of SN 2005bk

**Figure 16:** Finding chart with the discovery images of SN 2005bk in CGCG 223−029 (A16006+4302).