Properties of CCD cameras

1. Introduction

This lab serves two purposes: to learn about the properties of CCD cameras and the role of calibration data, and to acquaint yourselves with the equipment to be used for the optical labs.

At its heart, a CCD detector converts incoming photons to electrons. These electrons are read out and digitized into "counts" using an analog-to-digital converter (ADC). A big advantage of CCDs is that the response is nearly linear over most of the dynamic range, i.e. the ratio of electrons to incoming photons is nearly constant. The *gain*, which is set by the electronics of the camera, expresses this linear relationship in units of electrons per count:

$$\mathrm{gain} = \frac{N_{\mathrm{electons}}}{N_{\mathrm{counts}}} \tag{1}$$

Typical values for the gain are $\sim 2 - 3$.

To infer the flux of photons from the observed object from the measured counts requires a series of calibration steps. Most of these are based on additional calibration data which you need to acquire. Some of the calibration data can be taken during the day-time, a few types of calibration data have to be taken at night-time, under the same conditions as your science data. *Your data is only as good as your calibration!*

1.1. Calibration data for imaging

Bias frames: A *bias frame* is an exposure of 0 seconds duration (and a closed shutter). Every true CCD camera as an electronical offset level applied to it, the so-called *bias*. Hence, even if there is no signal, the counts measured in a bias frame are greater than 0.

Dark frames: Dark frames are taken with the same exposure time (and CCD temperature) as the science exposures, but with a closed shutter, i.e. no signal. Cameras such as ours have non-negligible dark current, which refers to electrons spontaneously tunneling into the conduction band even when there is no incoming light.

Flat fields: Pixels have varying sensitivity to the incoming flux from the sky. There are many possible reasons for this; some obvious effects are vignetting towards the edge of the field-of-view, dust grains on the CCD window and other surfaces, differences in the silicon doping, etc. By taking exposures of evenly illuminated surfaces, we can measure the relative sensitivity of the CCD pixels to each other. *Sky flats* are taken during twilight by imaging the not-yet-dark sky; *dome flats* are taken by imaging an evenly illuminated surface inside the dome; and *night-time flats* are assembled from the science exposures of the night by masking out detected objects and stacking the remaining sky background images.

Standard stars: If there are stars of known magnitude observed in the science images, we can use their measured fluxes to calibrate the fluxes of other objects in the image. If this is not the case, it is necessary to take separate exposures of *standard star fields*, ideally at the same airmass as the science exposure(s).

1.2. Calibration data for spectroscopy

Bias and/or dark frames need to be taken for spectroscopy, as well!

Flat fields: Flat fields for spectroscopy are taken in an identical fashion as for imaging. However, in this case, the response at different wavelengths does not only reflect variations in the pixel sensitivity, but also variations in the light output from the flat-field lamps. It is common to normalize the response as function of wavelength, e.g. by fitting a spline function the observed spectrum of the dome lamps, and dividing the flat-field by it. The flat-field thus serves to correct for small-scale pixel-to-pixel variations, as well as to determine the location of the spectra on the CCD.

Arc lamp spectra: Arc lamps are typically gas-discharge lamps of noble gases, with discrete emission line spectra. The wavelengths of these emission lines are well tabulated. By measuring the location of these lines on the CCD, one can relate position on the CCD to wavelength.

Spectrophotometric standard stars: Calibrating the measured flux across wavelengths requires the measurement of a source with a known spectrum. Similar to the standard stars used in photometry, spectrophotometric standard stars have well tabulated spectra.

1.3. Pixel artefacts

Dark frames and flat-fields are helpful in identifying and flagging broken pixels:

Dead pixels: Pixels without a response, i.e. even with large incoming photon flux, no electrons are transferred into the conduction band.

Hot pixels: Pixels with large dark current. These pixels will saturate even for short exposure times.

Warm pixels: Some pixels have a slightly higher dark current than most of the CCD, but are not quite “hot”. Whether these are usable depends on the specific application.

For dead pixels and hot pixels, the linear relation between counts and photons is broken. It is not possible to recover information from these pixels, and they should be removed from the analysis. This can be done with a *bad pixel map*, an image of the same dimensions as the CCD, where good pixels have a value of 1 and bad pixels have a value of 0.

2. Equipment

- STL1001 CCD camera (big camera used for imaging)
- ST402ME CCD camera (smaller camera used for spectroscopy)
- high-resolution DADOS spectrograph
- Neon arc lamp for spectrograph
- plot of Neon emission spectrum
- laptop with CCDSoft

3. Data acquisiton

Follow the "CCDSoft step-by-step instructions" to set up the STL-1001 camera and connect it to the control software `CCDSoft`. Take a bias exposure to flush the CCD, and discard it. Use the "File Defaults" menu to make sure that your subsequent exposures are automatically saved.

3.1. Bias and dark frames

For bias and dark frames, the camera does not have to be mounted on the telescope. Although the camera has an internal shutter, make sure that no light gets inside the camera. Keep the camera lid on (or the telescope lid).

1. Take a series of 10 bias frames at a CCD temperature of $-5°$C. Take note of the typical count levels in the images.

2. Take a series of dark frames with increasing exposure times, ranging from 10 s to ~ 5 min.

3. Take a series of 10 dark frames at a typical exposure time (~ 1 min).

4. Repeat the first two steps at a CCD temperature of $-10°$C.

3.2. Flat fields

For taking flat fields, the camera needs to be mounted on the telescope. The type of exposure has to be set to "light", and "auto-dark" should be selected.

4. Take a series of 10 dome flats, with counts at $\sim 30\%$ of the detector's saturation threshold. To do so, slew the telescope (by using the arrow keys on the hand controller) to point at a featureless, evenly illuminated part of the dome. Take a test exposure to estimate the count rate per second, and adjust your exposure time to reach the $\sim 30\%$ target. If necessary, use the dimmer to adjust the brightness of the dome lamps.

After taking these flat-fields, disconnect and disassemble the STL-1001 camera.

3.3. Spectroscopic calibration

Assemble the spectrograph with the 20mm eyepiece viewing the spectrum. Refer to the "Spectrograph step-by-step instructions" for guidance. Attach the Neon calibration lamp to the spectrograph entrance, and observe the lines through the eyepiece. Focus the spectrograph, and change the angle of the diffraction grating so that you can see the bright yellow Neon line at 5852.48Å (all other bright Neon lines are redder). Make sure to take turns with your lab partners.

Next, exchance the 20mm eyepiece for the ST-402 camera. Connect the camera to CCDSoft, and set up your data acquisition (temperature, auto-saving, etc.). Make sure that "auto-darks" are being taken. Take a bias frame to flush the CCD, and discard this frame. Focus the spectrograph by observing the lines from the arc lamp (use the CCDSoft Focus Tool to continuously read out images). Change the angle of the diffraction grating so that the Neon line at 5852.48Å is located towards the "blue" end of your spectrum, i.e. your spectral range is well sampled by this line and the redder lines.

Once the spectrograph is focused, attach it to the telescope. Be careful not to touch the focuser ring!

6. Take an arc lamp spectrum by shining the arc lamp into the telescope. The dome lights should be switched off for this step.

7. Take a series of 10 flat-fields by turning the dome lights back on. Make sure you get enough counts above the bias level over the entire spectrum.

4. Data analysis

The following is best done in python. The spectroscopy analysis requires pyraf in addition.

4.1. Bias frames

1. Open one of your bias frames in python and plot a histogram of the distribution of counts. Does it look Gaussian? Determine the mean, median, mode, and standard deviation. Overplot the Gaussian defined by the mean and the standard deviation. Define a cut that rejects pixels with count values the clearly deviate from the Gaussian distribution. What fraction of pixels get rejected?

2. The standard deviation of a bias frame is a measure of the read noise in units of counts. Look up the gain of the CCD camera in its header value, and convert your measurement of the read noise into units of electrons. Is it consistent with the manufacturer's description?

3. In order to counteract the read noise and determine the "true" bias image, we can combine multiple bias frames. Take the average of a series of 10 bias frames - this is called a *master bias frame*. Again, measure the mean and standard deviation. Verify that the standard deviation has decreased by a factor of $1/\sqrt{N_{\rm images}}$ compared to the single frame.

4. Repeat these steps for bias frames taken at the different temperature setting. Does the fraction of "outlier" pixels change? Does the read noise change?

4.2. Dark frames

1. Plot a histogram of your dark frame with the longest exposure time (make sure to adjust the ranges to show where most of the data are, rather than a few outliers). Does it look Gaussian? Determine the mean, median, mode, and standard deviation. Define a cut that selects pixels with count values consistent with a Gaussian distribution.[1] What fraction of

[1]To help automatize this step, you can use iterative sigma-clipping:
`https://docs.scipy.org/doc/scipy-0.14.0/reference/generated/scipy.stats.sigmaclip.html`
Use at least $\pm 5\sigma$ for the cuts.

pixels is included in this selection? Re-compute the mean, median, mode, and standard deviation. Which of these values change significantly after clipping? Decide how to identify hot pixels, and warm pixels. What fraction of the CCD does each category make up?

2. Subtract the master bias from each dark exposure. The counts in each pixel now measure only the dark current. Quantify the "typical" counts in each frame along with an uncertainty. For this step, you have to decide which metric to use (mean? median? mode?) and a way to assign an uncertainty. Justify your choices.

3. Plot the "typical" counts against the exposure time for your dark frames taken at $-5°$C. Perform a linear regression. What is the dark current in electrons per pixel per second?

4. Repeat this analysis for the dark frames taken at $-10°$C. How does the fraction of hot pixels change? How does the dark current change?

4.3. Imaging flat-fields

1. Take the average of your 10 flat-fields to reduce noise from photon-counting. Normalize it to its typical count level. This is your *master flat-field*.

2. Open the master flat-field in ds9. Note how some parts of the image receive less light than others. Identify regions of particularly low counts rates and quantify what fraction of light (compared to the brightest part of the flat-field) they receive. (To help quantify this number, you can use the "Pixel Table" in ds9 found under the "Analysis" tab, and/or a "Projection" region. To place a region, you first have to select "Region" under the "Edit" menu.)

3. Plot a histogram of the counts in your master flat-field. Can you identify any dead pixels?

4.4. Bad pixel map

1. Make a bad pixel map that rejects hot pixels and dead pixels.

4.5. Measuring the gain

The number of photons detected in each pixel is an example of a Poisson process. I.e. given an expectation value of N_{photons}, the measured values are subject to random stochastic fluctuations. In the limit of N_{photons} being a large number, the resulting distribution is a Gaussian with a mean of N_{photons} and a width of $\sigma = \sqrt{N_{\mathrm{photons}}}$. We can use this property to measure the gain of the CCD. In the following, assume that every pixel has perfect quantum efficieny.

1. Figure out how you can use a flat-field to measure the gain of the CCD. Make the measurement on one of your flat-fields, and compare it to the value of the header. If they do not agree, state possible reasons for the discrepancy.

4.6. Spectroscopic calibration

For reducing spectroscopic data, we will use `pyraf`. Refer to the *Guide for spectroscopic data reduction* on the wiki page for how to set up `pyraf`.

1. Combine your flat-fields into a master flat (this can be done in python).
2. Open your master flat-field in ds9. You should see 3 spectra - which of them corresponds to the $50\mu\text{m}$ slit?
3. Open your master flat-field in pyraf's implot routine. Identify which rows contain the spectrum from the $50\mu\text{m}$ slit.
4. Make a normalized flat-field (i.e. take out the flux variation with wavelength) for the $50\mu\text{m}$ slit.
5. Apply the normalized flat field to the arc lamp spectrum (make sure to specify the rows over which the spectrum extends).
6. Derive the wavelength calibration from the arc lamp spectrum. What is the disperson of the spectrograph? What is the length of the spectrum (in Å) that is covered by the spectrograph?
7. Write out the wavelength-calibrated spectrum to a text file. Plot the spectrum using python, labelling a few of the Neon emission lines.

5. Lab report

The timeline for the lab report, and intermediate check-ins is the following:

+1 week: Complete the data analysis for imaging (Sect. 4.1-4.5) and check your results with a TA / the instructor.

+2 weeks: Complete the data analysis for spectroscopic calibration and check your results with a TA / the instructor.

+3 weeks: Hand in your lab report. Make sure that your analysis codes are attached to your report, or available on github.