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**Properties of CCD cameras**

# 1. Introduction

In this lab, you will measure characteristic properties of the observing equipment used at Mt. Stony Brook. You will gather sets of calibration data for both imaging and spectroscopic observations, and develop the strategy of how to calibrate science data. *Your data is always only as good as your calibration!*

## 1.1. CCD cameras

Charge-coupled devices (CCDs) are the sensors of choice for optical, infrared, and X-ray astronomy. At its heart, a CCD detector converts incoming photons to electrons. 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:

$$N_{\mathrm{electons}} \propto \mathrm{flux} \times \Delta t \qquad , \tag{1}$$

where $\Delta t$ is the exposure time. (In comparison, photographic plates have an approximately logarithmic response.) These electrons are read out and digitized into "counts" using an analog-to-digital converter (ADC). 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.

The following properties of CCD cameras are important for understanding the calibration steps:

**Gain:**

The *gain*, which is set by the electronics of the camera, expresses the conversion of electrons into counts by the ADC:

$$\mathrm{gain} = \frac{N_{\mathrm{electons}}}{N_{\mathrm{counts}}} \qquad . \tag{2}$$

Its unit is electrons per count. Typical values for the gain are $\sim 2-3$.

**Quantum efficiency:**

Ideally, every photon striking the CCD would free an electron. However, this is not the case, and the *quantum efficiency* (QE) of a CCD expresses the ratio of electrons to photons. QE is a function of wavelength. Modern CCDs reach QE$<$90% in the optical. However, other components of the equipment further reduce the number of photons that reach the CCD: the reflectivity of the mirrors, transmission of lenses and filters, as well as the transmission of the atmosphere. The product of all of these is the total sensivity, which again is a function of wavelength.

We will not measure QE or total sensivitiy in this lab, but we will investigate the variation of the total sensitivity as function of position on the CCD. The total sensitivity can vary between pixels because of intrinsic QE variations, as well as varying fractions of incoming photons: e.g. because of vignetting (the further away from the optical axis, the less light is received), or dust grains blocking the light.

**Bias level:**

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 current:**

In cameras that are not cooled to $\lesssim -100°$ C, electrons can spontaneously tunnel into the conduction band even when there is no incoming light, mimicking a signal. The number of electrons is proportional to the time over which the data is integrated, i.e. the exposure time. The dark current is measured in units of electrons/pixel/second.

**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.

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 $0$.

**Read noise:**

The process of measuring the number of electrons in a pixel and converting them to counts is not perfect, it generates random noise. Read noise is measured in $\mathrm{e}^{-}/\mathrm{px}$.

### 1.2. Spectrographs

CCDs are also used as sensors in spectrographs, so very similar concepts apply. In addition, the following properties are important:

**(Spectral) resolution:**

The smallest wavelength difference $\Delta\lambda$ that can be distinguished at wavelength $\lambda$. This is determined by the instrumental set-up, in particular the grating, as well as the width of the entrance slit. It can be limited by the atmospheric seeing or the size of the pixels. Spectral resolution is expressed as:

$$R = \frac{\lambda}{\Delta\lambda} \quad . \tag{3}$$

**Dispersion:**

The length $\Delta\lambda'$ of the spectrum over a single pixel, i.e. in units of [Å/px].

### 1.3. Calibration data for imaging

**Bias frames:**

A *bias frame* is an exposure of 0 seconds duration (and a closed shutter). They are used to measure the bias level of every pixel.

**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. They are used to measure the dark current of each pixel, and to identify hot pixels.

**Flat fields:**

Exposures of evenly illuminated surfaces, such as the twilight sky (*sky flats*) or illuminated parts of the dome (*dome flats*). Flat fields are used to measure, and correct for, the relative sensitivity of the CCD pixels to each other.

**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).

### 1.4. 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.

### 1.5. This lab

In this lab, we will measure the following properties of the CCD camera we use for imaging:

- Read noise at different temperatures
- Fraction of hot and dead pixels at different temperatures
- Bias level
- Dark current at different temperatures
- The Flat-field and variation in sensitivity

For the spectrograph, we will measure the following:

- Dispersion
- The Flat-field and variation in sensitivity

As part of the lab report, you will be asked to discuss how the different calibration steps need to be applied to the scientific data you will take in future labs.

## 2. Equipment

- STL1001 CCD camera (camera used for imaging)
- ST402ME CCD camera (camera used for spectroscopy)
- DADOS spectrograph with 900 lines/mm grating ("high-resolution")
- Neon arc lamp for spectrograph
- plot of Neon emission spectrum
- laptop with CCDSoft

## 3. Data acquisiton

### 3.1. Set up the imaging camera

Follow the "CCDSoft step-by-step instructions" to set up the STL-1001 camera and connect it to the control software `CCDSoft`. **Cool the camera to $0°$C.** Note that the camera takes a while to completely cool at the center, so start cooling as soon as possible. When you're ready to take your data, 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. **Make sure to use 1x1 binning.**

### 3.2. 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.

1. Take a series of 10 bias frames at a CCD temperature of $0°$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 $\sim 5$ min.
3. Take a series of 10 dark frames at a typical exposure time ($\sim 30$ sec).
4. Take a bias frame, and a dark with your longest exposure time, at a different CCD temperature (difference of at least $\pm10°$C).

### 3.3. 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 ("auto-dark" will take a dark frame of the same exposure time and automatically subtract it from the image as a first order correction for the dark current).

4. Take a series of 10 dome flats, with counts at $\sim 30\%$ of the detector's saturation threshold. To do so, slew dome and/or the telescope (by using the arrow keys on the hand controller) so that the telescope points 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.

### 3.4. 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, exchange 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 flat-field by turning the dome lights back on. Make sure you get enough counts above the bias level over the entire spectrum. **Keep the dome shutter and doors closed to avoid contaminating your flat-field with the Sun's spectrum.**

## 4. Data analysis

The following is best done in python. The spectroscopy analysis can be done in pyraf.

### 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. Compare the bias frame taken at the different temperature setting. Does the fraction of "outlier" pixels change? Does the read noise change?

### 4.2. Dark frames

1. Make a median combine of the series of 10 dark frames with the same exposure time. This is your *master dark frame*. Plot a histogram of the count values (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. What fraction of 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. What fraction of the pixels are hot?

2. Compare the master dark frame to one of its input frames. Does the fraction of outlier pixels change? Does the standard deviation change? In both cases, explain why / why not.

3. Subtract the master bias from each dark exposure. The counts in each pixel now measure only the dark current. Determine the cuts so that a Gaussian distribution (mean and standard deviation) is a good description of the data.

4. Plot the mean counts against the exposure time for your dark frames taken at $0°$C. Make sure to include error bars that indicate the uncertainty on the mean. Perform a linear regression. What is the dark current in electrons per pixel per second?

5. Estimate the dark current for the other temperature at which you took bias / dark frames. Explain why or why not it changes.

### 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. Make a plot of the typical (relative) sensitivity as function of distance from the center of the image. If you placed the same star first into the center of the image, and then close to one the corners, how would its "observed" magnitude change?
5. If you forgot to take flat-fields on the night of your observations, can you re-take them later?

### 4.4. Bad pixel map

1. Make a bad pixel map that rejects hot pixels and dead pixels.
2. How would you use a bad pixel map in a subsequent analysis?

### 4.5. Spectroscopic calibration

For reducing spectroscopic data, you can use `python` (in particular the `numpy` and `scipy` packages, or `pyraf`.

1. The spectrograph has 3 slits, with widths 25, 35 and 50 $\mu$m. Open your master flat-field in ds9. You should see 3 spectra - which of them corresponds to the $50\mu\text{m}$ slit?
2. In the following, you will work with the spectrum taken with the $50\mu\text{m}$ slit. Cut out the images to keep only the data from your target slit. Make a plot of the flat-field values against the pixel positions along the dispersion axis.
3. Recall that the variation in flat-field counts with wavelength can be due to either a change in sensitivity, or the intrinsic spectrum of the lamps used to take the flat-field. Since we cannot tell the difference at this point, we will first "normalize" the flat-field along the dispersion axis to vary around 1. Variations between neighboring pixels thus reflect true differences in sensitivity, but we do not draw conclusions about variations between pixels on large pixels (which may be dominated by the lamp spectrum). To normalize the flat-field, first fit a low-order polynomial to the observed flat-field spectrum[1]. Divide the flat-field by the fit. Plot the normalized flat-field.
4. Apply the normalized flat field to the arc lamp spectrum (make sure to specify the rows over which the spectrum extends).
5. Derive the wavelength calibration from the arc lamp spectrum. To do so, identify the emission lines that you see. In `python`, make a table consisting of the pixel positions and wavelengths of the lines. Plot wavelength vs. pixel position and find the best-fit line (or polynomial) to compute wavelength from pixel position - this is the wavelength calibration.
6. What is the dispersion 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.

[1] Note that the "wiggles" with a period of $\sim 100$ pixels are variations in the spectrograph response. You can choose higher-order polynomials to fit these, but your data analysis will be more straightforward you don't.

### 4.6. Calibration strategies

Discuss how to apply the various calibration files. Which calibration exposures have to be taken with the same telescope + instrument set-up as the observations; which ones could you take on the next day, if necessary?

## 5. Lab report

The lab report will consist of two parts:

1. Prepare a `jupyter` notebook that documents your entire analysis for the lab. Make sure to make ample use of the "markdown" boxes, which can parse LaTeX, to explain your steps and conclusions - this is what we will read (we will only look at your code if we think you did something wrong). Once your notebook is finished, make sure to restart it and re-run all cells. Then choose "Download as PDF via LaTeX" to prepare a pdf.

2. Write a journal-paper style lab report about your measurements of the dark current of the imaging CCD. Make sure to include the relevant background, measurements and analysis steps in the appropriate sections.

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

+1 week: Complete the data analysis for imaging (Sect. 4.1-4.4) and check your results, and your current notebook, 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.