# AY105 Lab Experiment #5
# Telescope and CCD

## Purpose

CCD imaging is the most fundamental component of observational astronomy. In this week's lab, you will learn the basic concepts to operate a telescope, how an observation is conducted, how CCD exposures are calibrated and what the steps are needed to reduce CCD images. We will take a break from locking ourselves in the lab and do the experiments on the Cahill Rooftop Observatory.

## Background

**Before going up to the rooftop, make sure you have enough clothes with you. Also, bring enough snacks to keep up with the energy you lose during the night. NO KIDDING! Bring as much as you can. Even in summer, evenings in California can be challenging.**

Modern astronomy relies heavily on imaging through all wavelengths. By taking exposures, optical astronomers can measure the brightness (photometry), and position (astrometry) of astronomical sources.

A charge coupled device (CCD) is an array of millions of pixels each sensitive to photons. Photons enter the CCD and are absorbed by a silicon layer. This absorption excites an electron from the silicon's valence band to its conduction band in a process known as the photoelectric effect. These "photo-electrons" are then captured and stored by applying a positive voltage to the pixel to hold the electrons in a potential well. The varying number of electrons stored in each pixel produces different voltages across the pixel that is measured (by a fast voltmeter) and the voltage converted to a digital number (DN) that is presented as "counts" or ADUs (analog-to-digital units).

The ability to detect a signal depends on the relative strengths of the signal and overall noise present on the detector. For our purposes, noise will be quoted as the standard deviation of a signal. There are several types of noise in a CCD. Shot noise is noise that is associated with events that occur with constant arrival rates. (i.e. the photons collected by the telescope and the electrons detected by the CCD). Shot noise follows Poisson statistics, and it can be estimated by the signal in the units of the events recorded at the detector. Note that the events themselves are quantized in electrons (not ADU!). However, as discussed in lecture, the readout electronics that convert electrons detected at the CCD to digital numbers (DN or ADU) that are stored in the image by way of the gain present additional noise sources. Specifically, the read noise is the average error contributed to a pixel value by the amplifier used to measure the number of electrons contained in the pixel. Thus there is noise associated with the signal that arrives on the detector and noise associated with the detection of that signal. To make effective use of a CCD, its noise sources must be understood and calibrated.

Another set of calibration involves the setup of optics. Because of the existence of optical aberrations (Lab 7), there is always optical distortion and nonuniform illumination on the focal plane. To make the field uniform, one always need to take flat fields before observation. For precise astrometry and photometry (especially for wide field camera), one also need to fit the position of objects in the image with polynomials, and convert those information into World Coordinate System (WCS) and write them into header of the FITS file.

## Equipment

This week, we will use the equipments on Cahill Rooftop Observatory. Make sure you read the manual ([http://www.astro.caltech.edu/cro/index.html](http://www.astro.caltech.edu/cro/index.html)) before going. Here are the instrument we are going to use.

- Celestron 14-inch Schmidt-Cassegrain Telescope with finder/guider scope
- SBIG ST-9E Self Cooling CCD
- QHY5L-II(M) CMOS guider camera
- A computer with the following softwares installed:
  - MaxIm DL - our main controlling software
  - Stellarium - planetarium for you to get familiar with the celestial coordinates
- Eyepieces
- Power and signal cables

### Celestron 14-inch Schmidt-Cassegrain Telescope

Schmidt-Cassegrain telescopes are designed based on Cassegrain telescopes, where they put a Schmidt corrector plate around the secondary mirror to correct for spherical aberration caused by the primary and increase the field-of-view. Similar optical design was used in the 48-inch telescope on Palomar Observatory. A sketch of the light path is shown in Fig. 1.

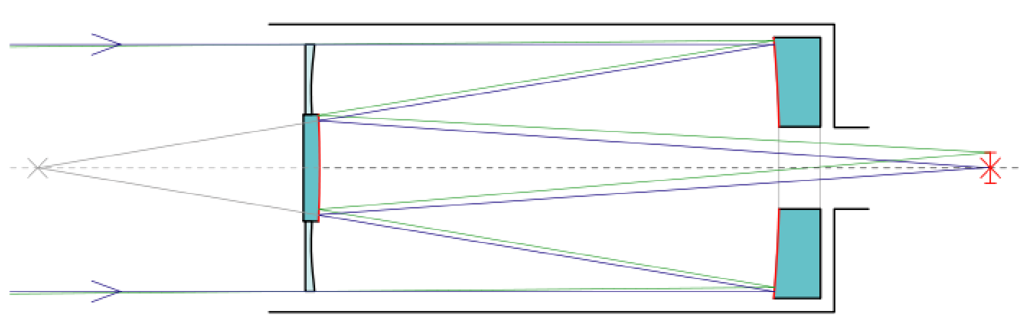

**Figure 1: Light path of a Schmidt-Cassegrain telescope. (Credit: Wikipedia)**

The Celestron 14-inch telescope is mounted on an equatorial mount. Such mounting system has axis aligned to the polar direction so that only one axis is need to track the motion of stars. Almost all of the older telescopes use similar mounts, e.g. the 200-inch telescope on Palomar Observatory. However, more recent telescopes, e.g. Keck Telescope, abandoned such design because they take huge amount of space. With such design, computerized system not only needs to control the two axis track the position, but also needs to control a "rotator" to track the rotation of the field (think about why).

## SBIG ST-9E CCD

This CCD is a self-cooling CCD manufactured by Santa Barbara Instrument Group. It contains a filter wheel with clear, Red, Green, Blue, and I-band filters installed. Its quantum efficiency is shown in Fig. 2. Modern CDDs for scientific usage can reach more than 95% quantum efficiency.

The CCD is mounted on the telescope with a f/6.3 focal reducer to increase the field-of-view, and a flip mirror to make it convenient to switch light path between CCD and eyepiece.

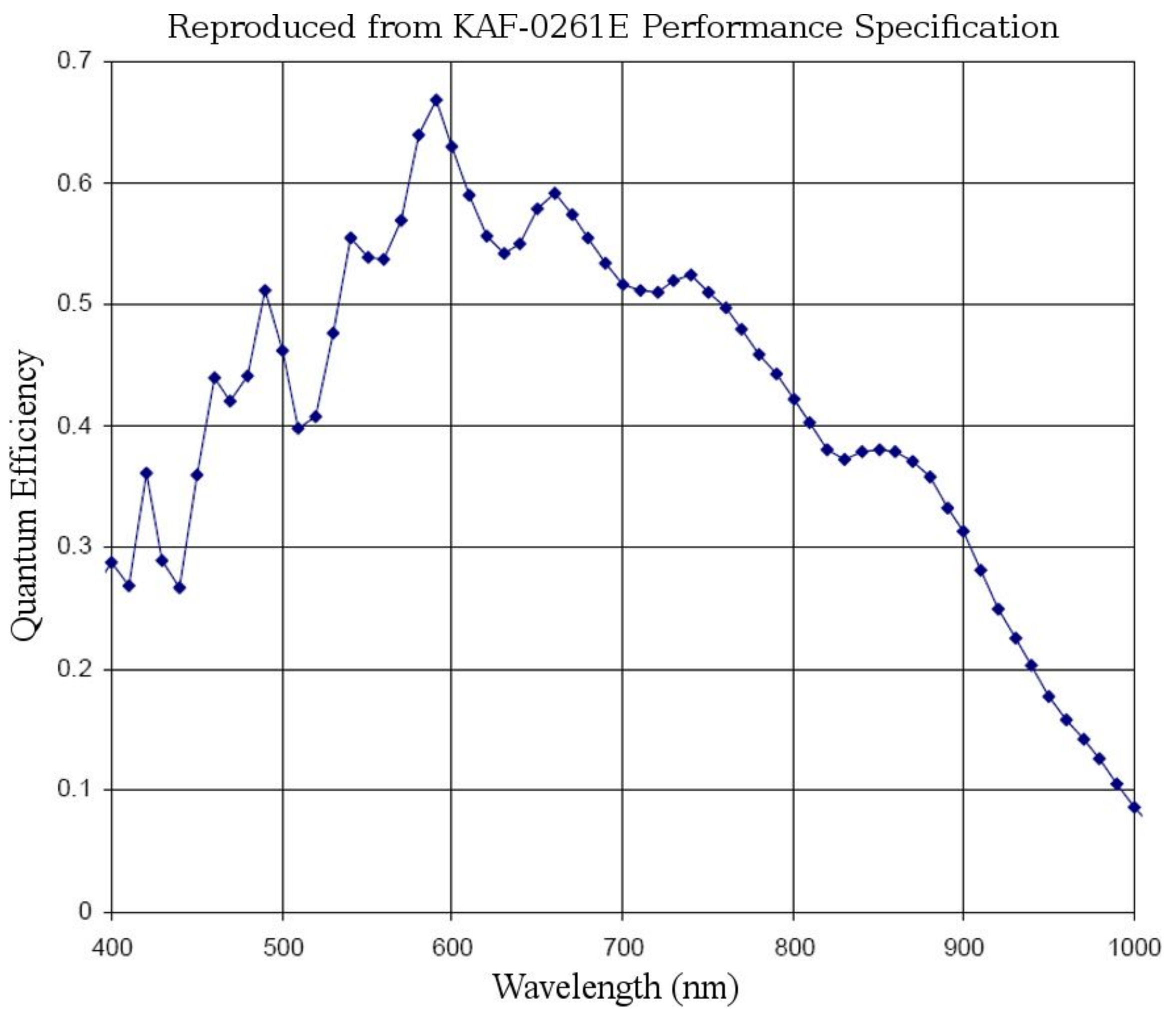


**Figure 2: Quantum efficiency curve of the SBIG ST-9E CCD.**

## QHY5L-II(M) CMOS

CMOS stands for Complementary Metal-Oxide Semiconductor, which has a very different architecture compared with CCDs. It tends to have higher read speed but lower signal-to-noise ratio, making it more optimal for video camera or guiders.

The QHY CMOS will be mounted on the finderscope. Its QE curve is shown in Fig. 3.

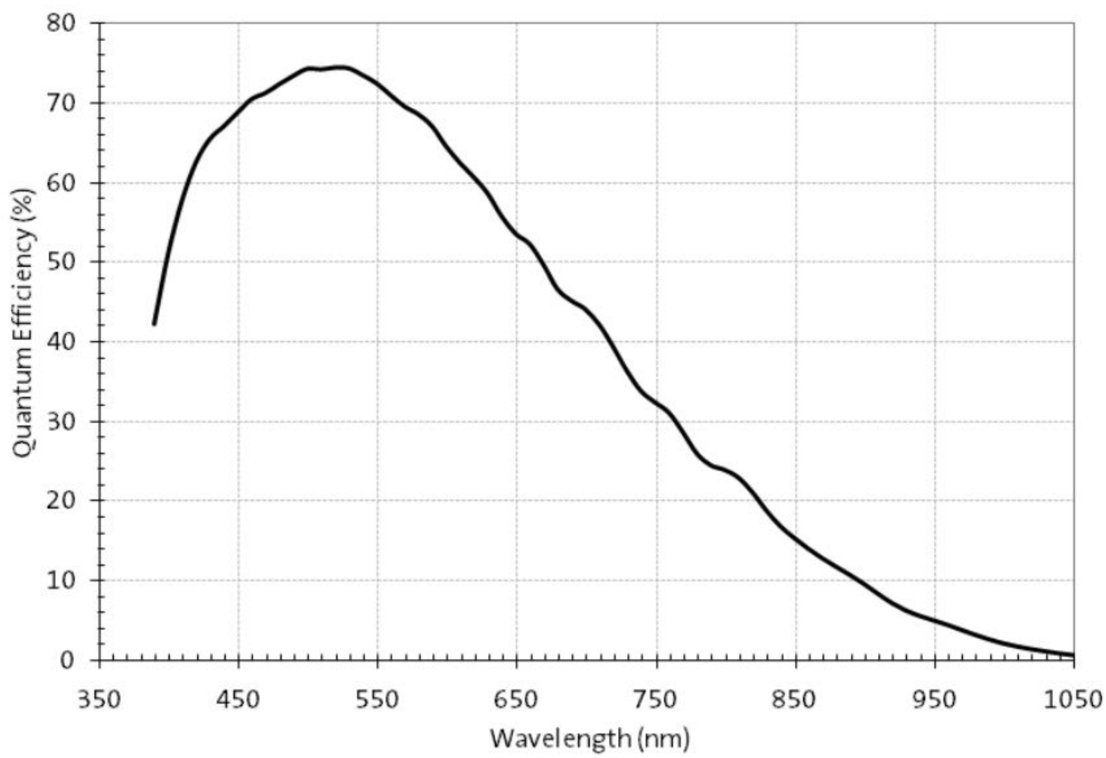


**Figure 3: The quantum efficiency as a function of wavelength for the QHY5L-II(M) CMOS.**

## MaxIm DL

MaxIm DL is our main controlling software. A typical setup looks like Fig. 4. It contains a widget for telescope controlling and another for CCD controlling. Two subwindows are for the images from the primary CCD and monitoring the guiding.

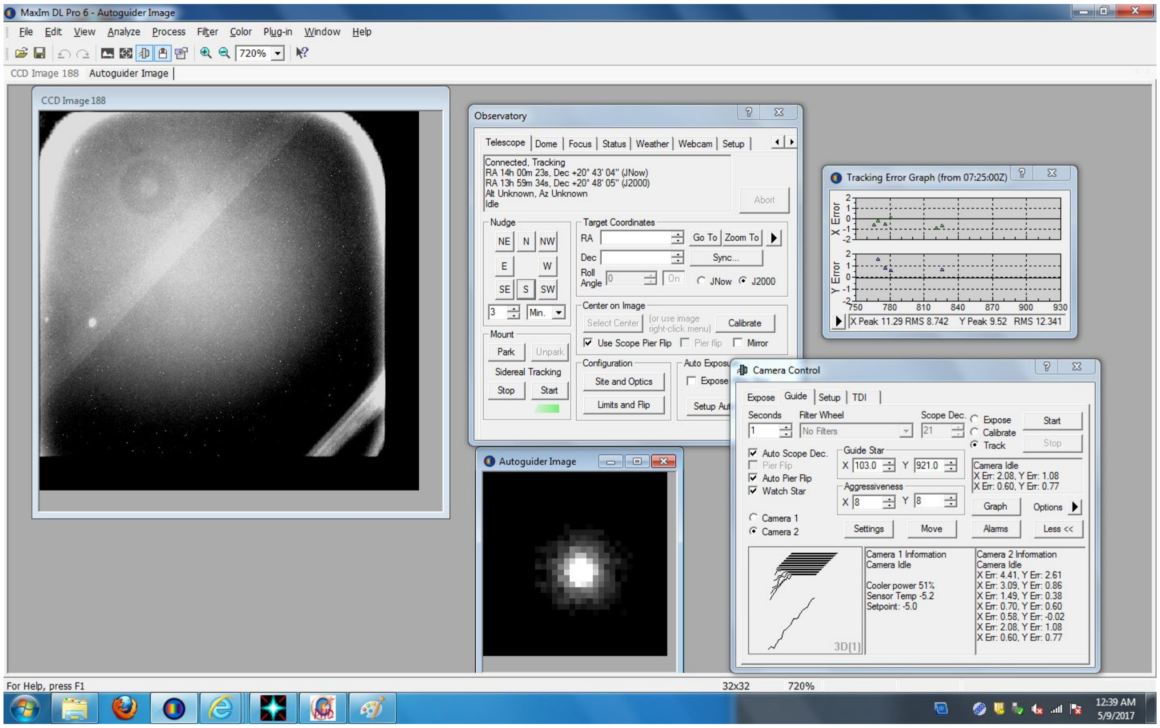


**Figure 4: A typical MaxIm DL setup.**

## Lab activities

The goal of this lab is to demonstrate the key steps for observation and data reduction by observing a galaxy called M104 (Sombrero Galaxy). Upon arrival, **READ ALL OF THE EQUIPMENTS BEFORE DOING ANYTHING! Don't ever try to adjust the angle of how the CCD is mounted.** It will ruin the flats taken in the afternoon, and you will be punished to take flats in the morning :-). **Get familiar with the position of the focus knob, the eyepiece, and the mirror flipper. Don't get stumbled by the wires on the ground. Use the log sheet at the end to keep track of your exposures.**

There are two optional parts: afternoon calibration and aperture photometry. You are required to do one of them, and leave the other part as the bonus.

### Part I: Afternoon Calibrations (Optional I)

This part can be done by your TA upon request, or you can ask data from your groupmate. If you choose to do this part, **arrive before sunset** (~7:45PM).

Connect CCD and the telescope to the computer. Don't forget to initiate the cooling system. Wait for a while until it is cooled and stabilized. While waiting, setup a directory in the option menu of the expose tab to save images.

Take flat fields at random position on sky with R, G, B and clear filters. Read histogram to make sure the exposure time is set to let the counts of most pixels not too large or too small. Saturation occurs when the count reaches 65535. Make sure you used $1 \times 1$ binning.

A dark exposure is not necessary for modern scientific CCDs, since they are normally cooled by liquid nitrogen which minimizes the dark current to near zero, and the only thing need to do will be taking biases (exptime=0). However, in our case, we do need to take dark exposures.

Take dark exposures with the exposure times used for flat field. Take more dark exposures with the possible exposure times that will be used during the night (30s, 1min, 2min, and 3min and 5min mostly). You can do this by using the "autosave" function in the CCD widget.

### Part II: Focusing

Telescopes need to be frequently focused because of thermal expansion, gravity, etc. Changing filter or dispersing element (for spectrograph) sometimes also requires refocus the telescope. (Fortunately, our filters are designed not to redo focus after changes.) The current instrument setup requires you to do that manually. First, move your telescope to a bright star. If it saturates in the CCD, use shorter exposure time or move to a fainter one. Starting focusing mode in the CCD widget. Take short exposures and use $2 \times 2$ binning to save time. Meanwhile, screw the focus knob until you are satisfied with the focus.

Repeat the same step for the guider. There is no focus knob on the finderscope, so you will need to move the position of the CMOS by hand.

## Part III: Calibrating the Guider

Move your telescope to your science target -- M104. Acquire an image in the guide tab. Click on a star to select it as the guiding star. You will notice the change of the pixel numbers on the widget. Change the mode to calibrate to start a calibration sequence. The program will move the telescope to totally 5 positions and the guiding star will form an "L" shape. Figure out with direction is S and take a note on your lab reports.

The calibration is automatically saved and unless you moved the CMOS during the observation, it is not necessary to recalibrate.

## Part IV: Acquiring Science Exposures

Take a test exposure with clear filter. If you can't spot the galaxy and you are certain that the exposure time is long enough (~30s). Use the PinPoint Astrometry function in the dropdown menus to figure out where you are really is. Figure out what is necessary move for the telescope. Center the galaxy.

Now, in principle, you can start a sequence of exposures and head off to rely on the computer. But I recommend to take one exposure at a time so that everyone can have some experience. Even taking single exposures, I still recommend you to use the Autosave function just to let the program save the files automatically.

Since we are living in Pasadena, the ambient scattering light comes from everywhere and highly variable and anisotropic. Thus, I recommend to use the NIR way of sampling the background. By doing that, you need to dither the telescope after each exposure, e.g. we can move the telescope by 3 arcmin to the south and then make 2 consecutive 3-armin moves to the north, and go back to the center. When taking single exposures, you can do that manually. And need to turn off the autoguiding before moving the telescope. If you set up an autosave sequence, there is a dropdown menu to set up the dithering patterns.

After enough exposures (at least 30min per band), make sure that you have all of the dark frames with corresponding exposure times. If not, take those darks before the shutdown.

Disconnect the CCDs and the telescope in MaxIm DL. Copy your data (or upload them to your Google Drive/Dropbox). Inform your TA to park the telescope. As a reward for staying up late, you can watch the M104, Jupiter and the moon through eyepiece!

## Part V: Data Reduction

From here on, you need to do the rest of the work at home. **If you have difficulty installing any of the following softwares, don't hesitate to contact your TA for help.** We can either help you set them up or let you use the department computers.

Data reduction is as important as data acquiring. In fact, it can take more time to reduce data than to observe. Proper data reduction can increase data quality and eliminate false positives. Modern astronomers use *Python, IRAF, IDL*, etc. to reduce data and do further analyses. Pick up one software from that list.

Your images are stored as FITS files (FITS stands for Flexible Image Transport System).

They consist of a header and data cube. The header contains informations on how the file is organized, and observing log,. Some FITS files contain multi-extensions, and each extension has one header and one data cube. FITS files can be quickly examined by using *DS9* (can be installed with *homebrew* or *AstroConda*). In *Python*, FITS files can be read with *astropy.io.fits* package; in IDL, you can use *mrdfits.pro* or *readfits.pro* from the IDL Astronomy User's Library to read them. *IRAF* can naturally handle FITS files.

If you choose to use *Python*, I strongly recommend you to install it through *AstroConda*. I will install all of the necessary packages and offers an easy way to control your *Python* version. I also recommend *Python* users to use *Jupyter*, as it creates a worksheet that is very similar to the *Mathematica* environment.

The data reduction contains the following steps:

1) Stack dark frames and subtract all of the other images with proper dark image.
2) Stack flats. Since the twilight decays rapidly, renormalize them beforehands.
3) Divide all of the science exposures by proper flat.
4) Extract sky background from the science images. Since the sky background also varies with the orientation, you may need to normalize the sky in each exposure too.
5) Subtract all science exposures by proper sky background.
6) Figure out the relative shifts among exposures, and shift them back. You can either pick a bright star and measure its position in different images or shift and differentiate two images to search for the minimum RMS. You may also do this by using the WCS information stored in FITS header. Getting familiar with WCS is painful, but once you are familiar, this process can be very easy.
7) Stack science images in each band. Adjust the background level and stretch the counts if necessary to form a true-color image. Aside from that, stack all of the three band images to form a composite image.

You final result should look like Fig. 5. Take notes on details of your reduction.

**Figure 5: M104 observed by Yuguang Chen on March 30, 2017, UT. Left panel is a true-color image formed by merging R, G, and B band images with 15min exposure for each band. Right panel is the stack of the three bands, forming a composite**

**exposure.**

## Part VI: Aperture Photometry (Optional II)

Aperture photometry is one of the ways to measure the magnitude of a given object. The idea is shown in Fig. 6. The flux of an object is integrated inside $R_{ap}$, which is set to be large enough to include all of the signals. The level of sky background and noise can be estimated from the annulus between $R_{in}$ and $R_{out}$. In this part, you can use the *photutils.aperture* package in *python* or *aper.pro* in *IDL*.

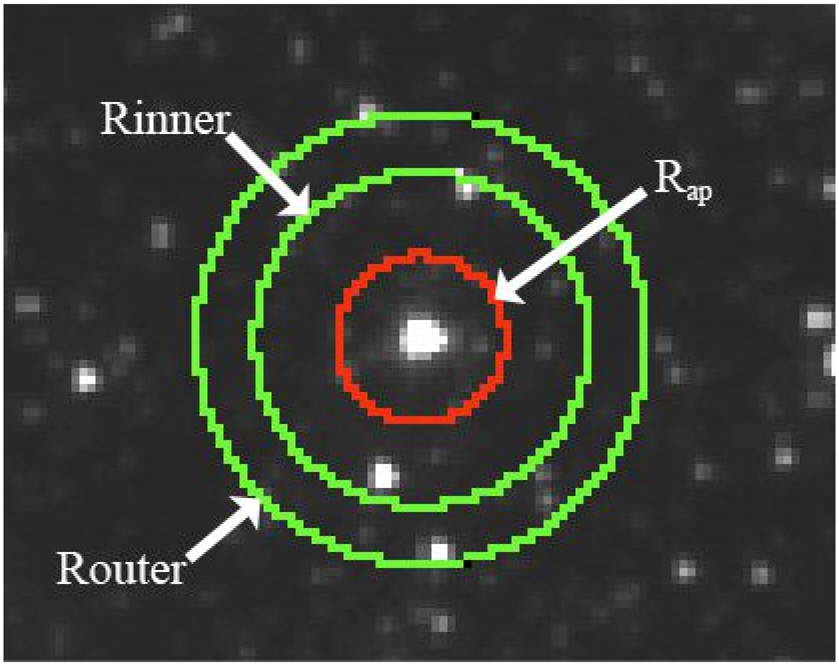


**Figure 5: Aperture Photometry. (Credit: http://wise2.ipac.caltech.edu/docs/release/prelim/expsup/sec4_3c.html)**

The star circled in red as shown in the right panel of Fig. 5 is called as HD110086. It has a V-band magnitude of 10.12. Given that, pick another star in the field, and measure its V-band magnitude. Compare your result with value from SIMBAD.

# Discussion

1) Download the CCD quantum efficiency curve and filter transmission curves from the Cahill Rooftop Observatory website. If the exposure times are the same on all of the RGB bands, and the images are stacked together, what is the total transmission curve for the composite image?
2) Based on the CCD properties from the Cahill Rooftop Observatory website, estimate the readout noise. Estimate the sky background from your images in the unit of electrons. Which one contributes most of the noise, readout noise or the shot noise from sky background?

## Log Sheet

Observer: Date: Condition:

| Object | File Prefix | File No. | Exp time | Filter | Time | Comment |
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