This is to be carried out during clouded-out observing session(s). Your observing TA will make note of which teams have completed the prep work and Dr. Rengstorf will review your report.

Pre-Observing Prep:

Neatly write-up a list of calibration images and an outline of how you will proceed in your observing notebook. ***This should be done before the next time you submit your observing notebooks.***

Upon Arrival:

Follow the standard 'Upon Arrival' directions, with the following exceptions:

- The dome shutter doesn't need to be open.
- The aperture cover doesn't need to be removed.
- The chip doesn't need to be cooled (yet).
- The focuser doesn't need to be turned on.

Bias Level Characterization:

Are bias levels really constant? How constant are they? Since a bias frame has an exposure time of 0.0 seconds, all we can vary is the chip temperature:

- Starting at 3 degrees below the current ambient temperature, take 5 bias images.
- Reduce the temperature by 3 degrees and repeat until you reach our standard operating temperature. Make sure to allow time for temperature to stabilize before taking more data.
- A sensible data-collection strategy can combine bias level collection with some of the dark current collection - read this whole thing before finalizing your plan.

Dark Current Characterization:

Is the dark current really linear with time? How does temperature affect dark current? We now have two variable parameters: exposure time and chip temperature.

Time dependence:

Take series of dark frames at a variety of exposure times. Under the initial hypothesis that a warmer CCD chip has more dark current, this step will go quicker if we work on a warm chip and it will be more precise if we work at a constant temperature. As with the bias-level characterization, set the temperature to 3 degrees below ambient temperature - just enough cooling to keep the temperature stable.

- Starting with an exposure time of 5 seconds, take 5 dark images.
- Keep doubling the exposure time until pixel counts are ~10^4.
- But use common sense - I don't expect you to take hour-long exposures. The key will be to get enough range in counts to reliably confirm/deny a linear trend. (Don't forget to subtract the bias level from your darks ***before*** determining dark-current pixel counts.)

Temperature dependence:

Take a series of dark frames at a variety of temperatures. Since you're now testing for temperature, you need to keep exposure time constant. Since you're starting warm, use an exposure time that gives you lots of pixel counts, since our initial assumptions suggest that the dark current will get shorter as you go colder. (Pro-tip: You already have your first data series for this part when you were testing for time dependence. Bonus!)

- Use the longest exposure time from the dark-current time test as your initial data set for the temp. test.
- Starting at 3 degrees below the current ambient temperature, take 5 dark images.
- Decrease temp by 3 degrees and take 5 dark images with the same exposure time.
- Repeat until you reach standard operating temperature.

Monitor the chip temperature in the CCDSoft window and wait for the new temperature to stabilize before taking a new data set. This will also give you a sense of *how* stable the temperature regulation is - are you stable to within 1.0 degree? 0.5 degree? 0.1 degree? Be sure to make a note of this and report it along with your findings.

Write-up:

Your observing team should submit a word-processed report ***to which all team members contributed***. The following is a (not necessarily complete) list of things which I will be looking for:

- data-collection strategy and methodology
- what results you expect to see given initial assumptions
- a coherent and organized presentation of results
- plots of your data:
    - pixel count vs. temperature for the biases
    - pixel count vs. time @ constant temp for the darks
    - pixel count/sec vs. temperature for the darks
- analysis of your data (see below)
- a brief discussion and conclusion, discussing whether your initial assumptions were justified

This is essentially a lab report template you may have used for high-school lab experiments. Keep effective communication in your mind as you think about what you want to write. If you haven't had the chance to do anything like this in the past, the TAs, Dr. Andersen, & myself will be more than happy to give you some pointers on experimental technique.

This work will also be included as a section of your final report, so the more thought you put into it now, the less work it will be at the end of the program.

Data Analysis:

Avoid any edge effects by trimming 20 pixels off the edges of all images before proceeding.

The signal (bias-subtracted signal for the dark images!) is straightforward - the signal will be the average value of the pixel counts. Even after trimming 20 pixels off the edges, there's still over 3 million pixel in every image. Those are good statistics.

The uncertainty of the signal (i.e., the noise) is a bit more nuanced. Here, we don't particularly care about the standard deviation of the signal. That would tell us much the pixel counts spread out about the mean value. What we *do* care about here is the variation of a pixel from one image to the next. Standard error propagation tells us that the standard deviation for two data points is

$$\sigma = \frac{|x_2 - x_1|}{\sqrt{2}}$$

With 5 images, we can make 4 noise images. Perform the above calculation, pixel by pixel, comparing images 1 & 2, 2 & 3, 3 & 4, and 4 & 5. The noise value we're interested in will then be the average value of every pixel in all 4 of those noise images.

Bias frames

You are essentially validating/refuting the hypothesis that bias frames do not depend on temperature. You can test this by performing a best-line fit to the data. If they are temp-independent, then the slope will be closer to zero than the uncertainty on the slope. (Note to determine this, you need to determine the error on the slope!) There are numerous references for how to determine a best-line fit, but see chapter 6 of Bevington's text [1] for the treatment with the official Rengstorf seal of approval - Accept no substitutes. As seen on TV!

Dark frames - time

This is a repeat of the bias analysis, except here the starting assumption is that the slope is non-zero. Certainly give the slope and its uncertainty, but some thought is required here. A slope can be calculated for *any* data, even if the data set is obviously non-linear. This is where a simple visual inspection of the plot is essential. Is there an obvious curve to the trend? Is there a function other than y = mx+b that might better fit the data?

Dark frames - temperature

Try to model the dependence of dark-count rate on temperature. How well does your dark current agree with the Arrhenius law? [Note that an exponential relation such as Arrhenius can be analyzed via a best-line fit if you let y = log(dark current) and x = 1/temp.] Estimate the exponential prefactor and the activation energy for the CCD chip.

Following the treatment in Widenhorn [2], each pixel on the chip is seen to have its own prefactor and activation energy. If each pixel is studied individually, it is possible to determine the chip's isokinetic temperature.

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[1] Bevington & Robinson, *Data Reduction and Error Analysis for the Physical Sciences*, 3rd ed., McGraw-Hill, (2003)

[2] Widenhorn, R. et al, "Temperature dependence of dark current in a CCD," Proc. SPIE 4669, 193-201 (2002).