CCD Laboratory Evaluation - Revised

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Objectives

The objectives of this lab were to characterize the CCD so that future ostensible observations using this device can be properly corrected for read noise, dark current, and linearity, and so that measurements can be converted between ADUs and actual electron counts.

Setup

The CCD used was an SBIG CCD, controlled by the rhojec display and interface. The intentional light source was light from a computer monitor reflected from the wall for read noise, dark current, and gain, and a covered smartphone screen for linearity. Lack of perfect stability in these light sources may have influenced the results below.

Read Noise

The objective of this section is to characterize the read noise of this CCD. In order to do so, we took nine 0.1-second dark exposures and calculated the root mean square (RMS) for each pixel across the resulting nine fits files, placing the calculation for each pixel into its corresponding position on a 2D array. The median read noise was found to be 25.087 +/- 0.009 ADU (the mean read noise is 25.390 +/- 0.009 ADU, which is expected as it is pulled slightly higher by outlier values). The statistical spread of the average read noise, the "RMS of the RMS", is 6.583 +/- 0.002 ADU. Here and in what follows, uncertainties were calculated by dividing by the square root of the number of pixels because we assume a Poisson process.

Alternatively, we made a histogram of the RMS array and fit a Gaussian distribution over it (Figure 1). The mean from the Gaussian is 24.435 +/- 0.008 ADU, and its statistical spread is 6.503 +/- 0.002 ADU. The mean and RMS of the Gaussian fit are quite close to that calculated in the first method, with difference in mean of about 1 ADU and difference in RMS of less than 0.1 ADU. The deviation in mean could have come from error in the fit or the incorrect assumption that we collected statistically "perfect" samples with no deviations from systematics.

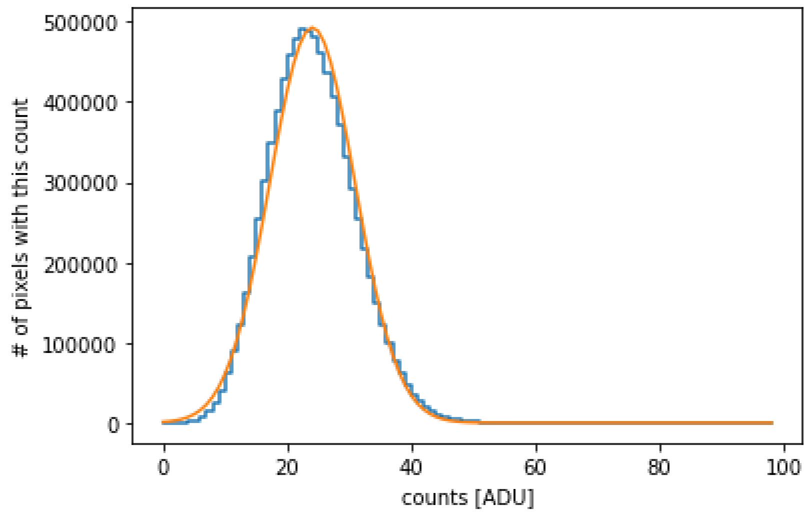

Figure 1

At the longer exposure times of 1s and 10s, read noise becomes smaller - with median read noises of 18.833 +/- 0.006 ADU and 18.928 +/- 0.006 ADU, respectively; mean read noises of 20.083 +/- 0.007 ADU and 20.184 +/- 0.007 ADU, respectively; and statistical spreads of 10.952 +/- 0.004 ADU and 10.657 +/- 0.004 ADU, respectively. Using Gaussian fits as above, we get mean and statistical spreads of 17.388 +/- 0.006 ADU and 10.982 +/- 0.004 ADU, respectively, for the 1s exposure, and 17.475 +/- 0.006 ADU and 11.035 +/- 0.004 ADU, respectively, for the 10s exposure. Their fits are shown in Figures 2 and 3, respectively.

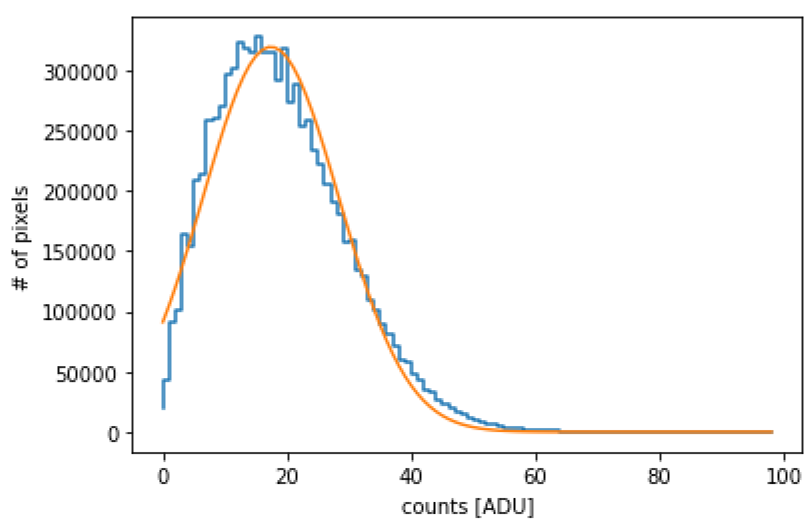

Figure 2

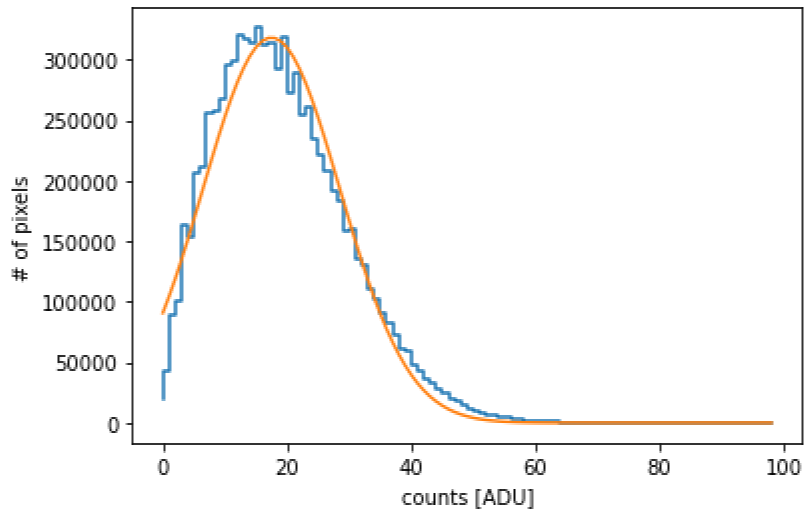

Figure 3

The significant reduction in median read noise is puzzling, and might be attributable to a change in the light source intensity during the longer exposures, as well as there being fewer exposures (9 0.1s exposures, versus 3 1s and 3 10s exposures), leading to larger uncertainty and a more Poisson-shaped distribution. Important values for this section are summarized below in Table 1.

Table 1: Read Noise (values in ADU)

	Median	Median Uncertainty	Mean	Mean Uncertainty	Standard Deviation	Standard Deviation Uncertainty
2D array median (0.1s)	25.087	0.009	25.390	0.009	6.583	0.002
Gaussian fit (0.1s)			24.435	0.008	6.503	0.002
2D array median (1s)	18.833	0.006	20.083	0.007	10.952	0.004
Gaussian fit (1s)			17.388	0.006	10.982	0.004

2D array median (10s)	18.928	0.006	20.184	0.007	10.657	0.004
Gaussian fit (10s)			17.475	0.006	11.035	0.004

We can tell if there is a light leak by plotting the median-combined signal on the 2D array of the CCD and visually inspecting it. There appears to be no light leak in this device, from Figure 4 below (more figures like Figure 4 in the Jupyter notebook attached).

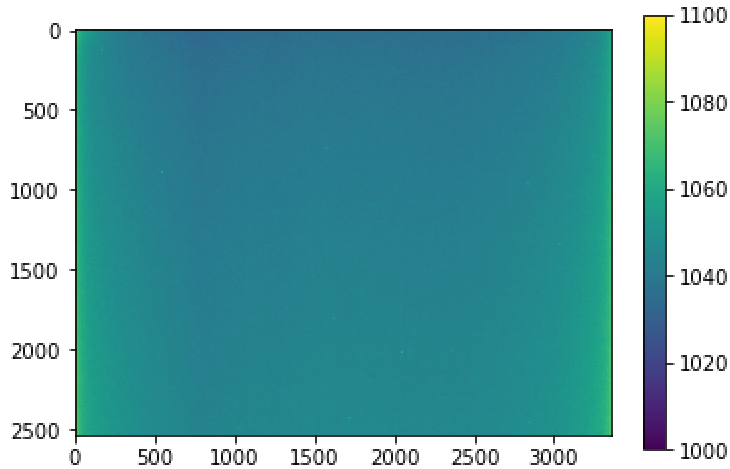

Figure 4: median-combined signal for the 9 0.1s exposures

Dark Current

The objective of this section is to characterize the dark current of the CCD, which is a key systematic error to account for when doing actual measurements. In order to do this, we took 1s, 5s, 25s, 125s, and 500s dark exposures, sandwiched between 0.1s bias exposures. The temperature at which the dark current is measured is 0℃.

We begin by simply taking the median of each exposure and plotting it against exposure time, as shown in Figure 5. At a CCD temperature of 0℃, the slope of the line, and therefore the dark current, is 0.079 +/- 0.004 ADU/s, where the uncertainty is one standard error.

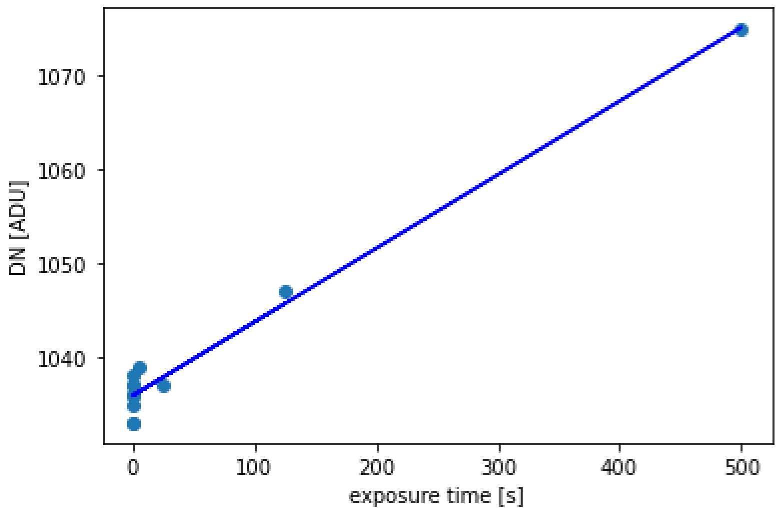

Figure 5

Alternatively, we take the median of each exposure and fit a Gaussian over it before plotting each exposure's Gaussian-fitted mean and standard deviation as a function of exposure time. We plot the DN/dt mean and standard deviation in Figures 6 and 7. The slope of the line in Figure 6, and therefore the dark current, closely agrees with that calculated by the former method: 0.078 +/- 0.003 ADU/s. Similarly, using the slope of the (considerably worse) linear fit in Figure 7, the standard deviation of the dark current is -0.06 +/- 0.06 ADU/s. Again, uncertainties here are the standard errors of each fit.

For each of these three fits, we calculated the reduced chi-squared value, finding very high values for all three but particularly that of the standard deviation. The sigma used for the calculations was the standard error of each fit, and the degrees of freedom were the number of observations, subtracted by two (one for the slope and one for the y-intercept). The reduced chi-squared values are 743 for the median-method fit, 742 for the Gaussian mean fit, and 233072 for the Gaussian standard deviation fit. The drastic increase for the latter model agrees with the eye test and the standard errors of the fits, but the high values across the board may be attributable to choosing the wrong sigma in calculating reduced chi-squared.

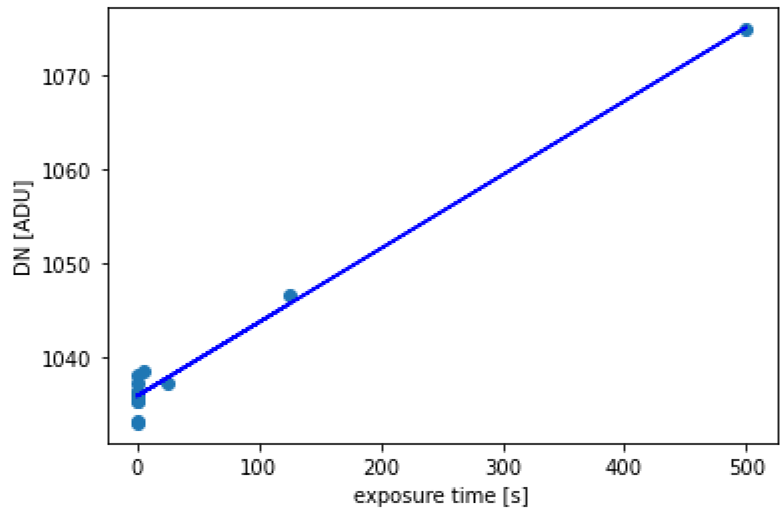

Figure 6

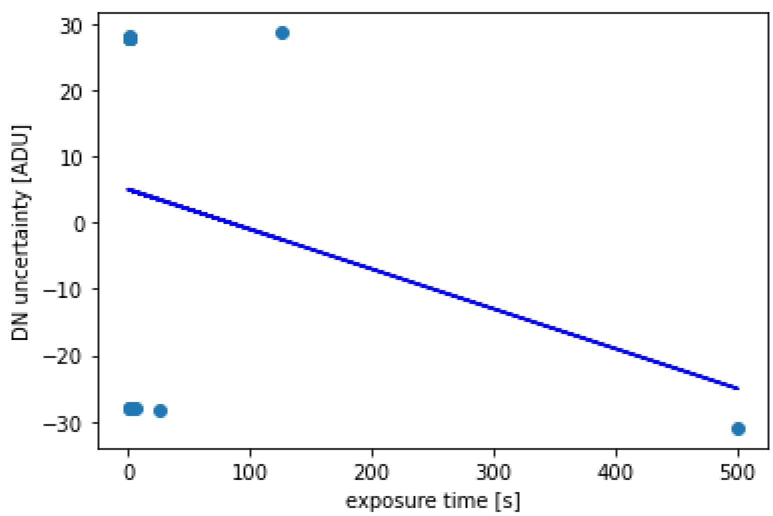

Figure 7

Important values for this section are summarized below in Table 2.

Table 2: Dark Current (values in ADU/s)

	Slope	Slope uncertainty
Median method	0.079	0.004
Gaussian fit of mean	0.078	0.003
Gaussian fit of std	-0.06	0.06

Gain
The objective of this section is to characterize the gain of this CCD so that future measurements can be converted between ADU and electron counts. In order to characterize gain, we took three images each with the following exposure times: 0.1s, 1s, 5s, 20s, 45s, 60s, 80s, and 100s. For each of the eight exposure times, we pixelwise-median-combined the three images, then took the median of that single 2D array to get the signal. We also took the standard deviation of each pixelwise-combined array, and then took the median of that to get the noise per exposure time. Squaring that value yields the variance, which we then plotted against the signal in logspace, in order to determine which points to cut out when drawing a best-fit line to get the gain (Figure 8).

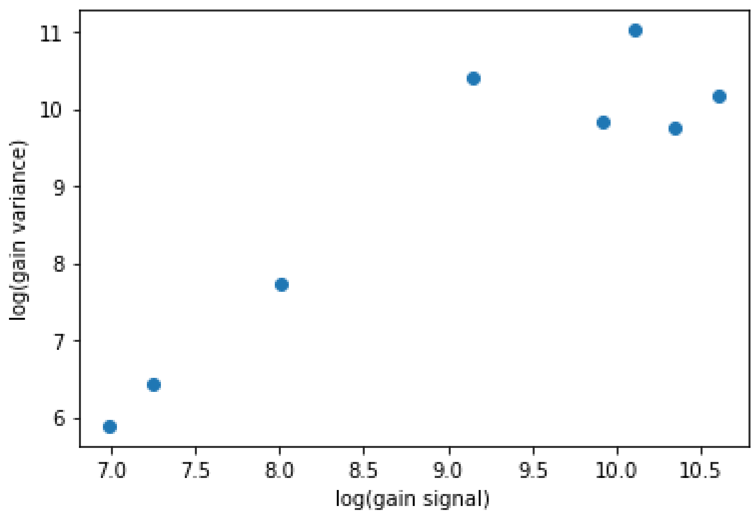

Figure 8

Judging from Figure 8 and the fact that the variance starts wavering down and up after the fourth set of exposures, a conservative decision was made to fit a line through only the first four points. This likely excluded sets where the pixels were not saturated enough to the point of decreasing variance, but where systematic effects or other external factors (such as a faulty USB connection that occurred during measurement for this section and linearity) may have come into play. The result is shown in Figure 9 below, where the slope, and therefore the gain, was 4.1 ADU/e-, with an uncertainty of 0.5 ADU/e-.

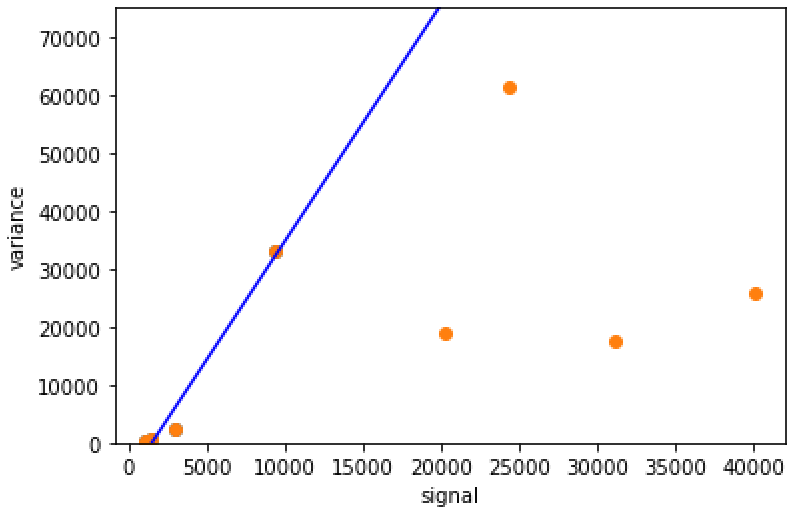

Figure 9

Including the first six (rather than four) sets of exposures would yield a slope of 2.0 ADU/e- and uncertainty of 0.6 ADU/e-. In measuring the gain, flatfield frames used to were not calibrated, meaning bias frames were not subtracted out. As a result, read noise and dark current may have contributed to a skew in the gain and its uncertainty.

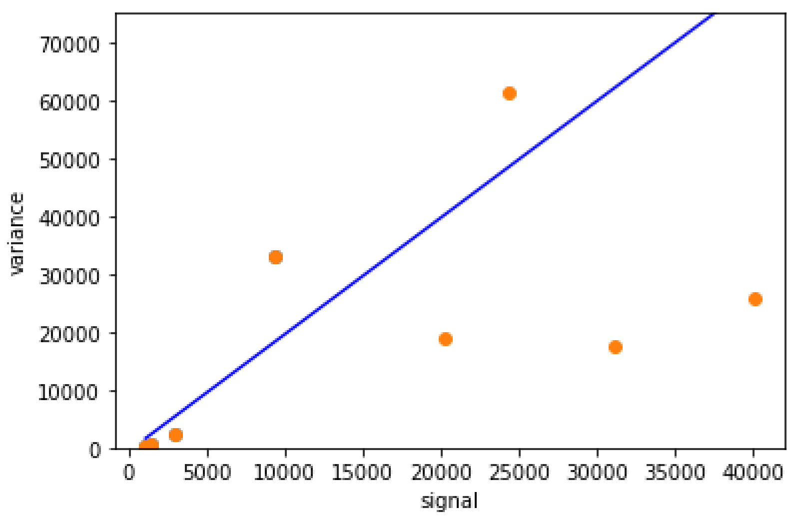

Figure 10

Table 3: Gain (values in ADU/e-)

	Slope	Slope uncertainty
4 first exposure sets	4.1	0.5

6 first exposure sets	2.0	0.6

Linearity

The objective of this section is to characterize the linearity of the CCD in order to capture any drift in behavior at longer and longer exposure times. In order to do this, we took faint and bright exposures for each of the following exposure times: 1s, 3s, 10s, 30s, 60s, 100s, and 200s. To fill in gaps in the collection with the time constraints we had, we also took a 150s bright exposure and a 300s faint exposure. Here, the light source was the screen from a smartphone, covered to varying degrees for faintness and brightness. The median difference between bright and faint exposures was 3656 ADU.

We plot the signal against exposure time length in Figures 11 (bright) and 12 (faint). We find that linearity holds more strongly with faint exposures, with R value within a ten-thousandth of 1.0 and standard error of 0.5 ADU. Bright exposures, as shown in Figure 11, exhibit less linearity, with R value within six hundredths of 1.0 and standard error of 44 ADU. Some possible causes for the larger drift in linearity for brighter exposures could be a lack of stability in the light source being exacerbated at brighter exposures, discrepancies in longer exposure times used between the two samples, and the USB connection issue we experienced during the night of gain and linearity data collection.

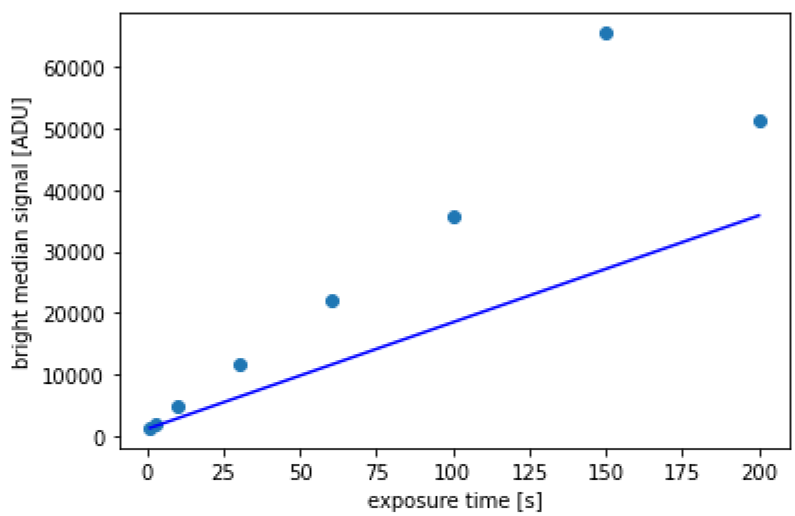

Figure 11

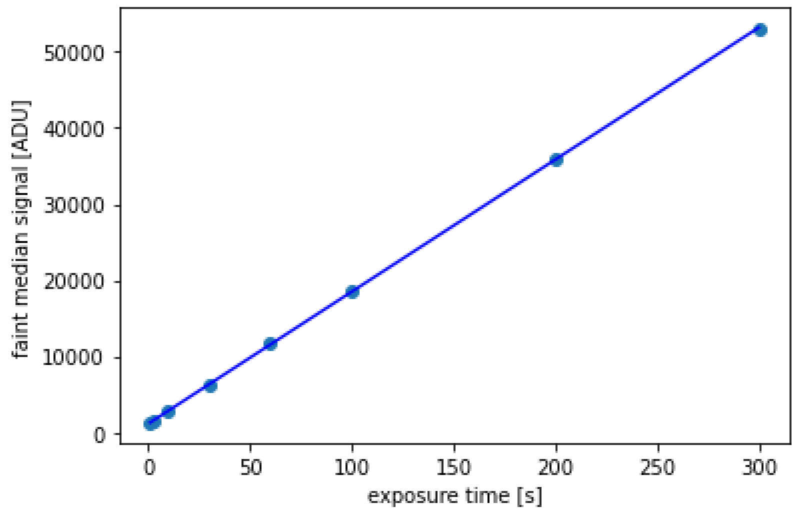

Figure 12

Table 4: Linearity

	R value	Linear fit standard error (ADU)
Bright exposures	0.94	44
Faint exposures	1.00	0.5

Conclusion
Our work has shown greater linearity for faint exposures than for brighter exposures. We find that gain is, conservatively, 4.1 +/- 0.5 ADU/e-. We find dark current to be 0.079 +/- 0.004 ADU/s. Going by the Gaussian fits, we find read noise to be 24.435 +/- 0.008 ADU for 0.1s exposures; (surprisingly) 17.388 +/- 0.006 ADU for 1s exposures; and (also surprisingly) 17.475 +/- 0.006 ADU for 10s exposures.

Systematics such as dark current and read noise, as well as external factors such as light source instability and the USB connection issue during collection for gain and linearity may have contributed to less than ideal linearity for bright exposures, as well as skew in the measured gain. The most unexpected result, however, is the significant reduction in median read noise at the 1s and 10s exposures. Short of external factors like a change in the light source intensity during these exposures but not the 0.1s exposures, we are unable to explain this behavior. With more exposures (9 rather than 3), we may have been able to characterize the median read noise at these longer times.