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Testing an e2v CCD230-42 Sensor for Dark Current Performance at Ambient Temperatures

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Abstract

The design of the Guidance Focus and Alignment (GFA) system for the Dark Energy Spectroscopic Instrument (DESI) project calls for a set of charge-coupled devices (CCDs) which operate at ambient temperature. Here we assess the performance of these CCDs under such conditions. Data was collected from $-21^o C$ to $28^o C$ and used to determine the effect of temperature on the effectiveness of dark current subtraction. Comparing the dark current uncertainty to our expected signal has shown that the DESI design specifications will be met without need for significant changes.

I. INTRODUCTION

The Dark Energy Spectroscopic Instrument (DESI) is a Stage IV Dark Energy Task Force project being constructed for use on the Mayall telescope at Kitt Peak National Observatory. DESI will measure the spectrum for tens of millions of galaxies in the night sky and use this data to build a three dimensional map of the universe[1]. It will accomplish this with an array of 5000 robotically actuated optical fibers. Each fiber will be pointed at an individual galaxy, feeding its light into a spectrograph. After measuring the spectra of this light it can be compared to the spectra it was emitted at giving the cosmological redshift. The cosmological redshift can then be converted into a distance to the galaxy.

Due to the size of the optical fibers and their targets, DESI must determine its pointing with high precision. This high precision requirement will be met by the Guidance, Focus and Alignment system (GFA). The GFA consists of an array of 10 cameras with charge-coupled devices (CCDs). Six of the ten cameras are used for the guidance component of the GFA, which serves the purpose of determining where in the sky the instrument as a whole is pointing. It

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accomplishes this by use of existing sky catalogues in concert with the stars visible during an exposure. The remaining four cameras are to be used in the focus and alignment component of the GFA, which serves the purpose of aiding the alignment of the optical fibers as well as keeping the image in focus[2]. Both components of the GFA are designed to operate in the same manner as those used in the Dark Energy Camera (DECam), whose scientists are supporting the development of this system.

The design for the GFA requires that these CCDs operate at ambient temperature. This is problematic because all CCDs suffer from an issue known as 'dark current'. Dark current is the thermal noise that affects the readout of a CCD, negatively impacting the signal to noise ratio. In most cases the solution is to cool the CCD to the point where dark current is negligible. Since this is not an option for DESI an alternative method for dark current correction is needed. The method chosen is dark frame subtraction, wherein dark exposures are collected and subtracted from image exposures. The question we seek to answer is whether or not this method is sufficient to meet the signal to noise ratio requirement while operating at ambient temperature.

II. METHODS AND INSTRUMENTATION

A. CCD230-42-1-143

In order to ensure the GFA would meet specifications a CCD matching those which would be used on DESI was obtained and tested. The MicroLine ML23042 manufactured by Finger Lakes Instruments was chosen, inside was the e2v CCD230-42-1-143 sensor, which is to be used on the DESI instrument. This sensor was chosen for its alleged dark current performance, which would later be proven erroneous[3], but the sensor would be kept for its 4-channel readout and ability to still perform within specifications.

B. Image Processing

There are several sources which contribute to the values that a CCD reports after each exposure. Here we briefly describe each source:

1) Bias and Overscan: All CCDs include a bias value that is added to each pixel. The bias is an arbitrary and approximately constant (for a given temperature) value added to the exposure during digitization. To get an idea of what this value is a 0.0 second exposure is used. By reading out the pixels as quickly as possible the CCD does not allow any current to accumulate. As a result the values being read out reflect only the bias and readout noise inherent to the electronics. These values can be reported in one of two ways: a bias frame, or the overscan region.

A bias frame is a 0.0 second dark exposure of the entire CCD. Bias frames are taken shortly before or after the image exposure, as a number of factors can cause the bias value to change gradually over time. Several bias frames are averaged together, in order to reduce potential problems with the readout noise. The resulting frame is then subtracted from the image exposure in a process known as ’bias subtraction’.

Alternatively one can use the overscan region. If a detector is set to return an overscan region it will report extra pixels attached to each image. These pixels do not correspond to any physical pixel on the detector but instead represent a collection of values obtained by reading from the amplifier without shifting in any new pixels. The overscan is used by averaging a row of these overscan pixels together and then subtracting that value from the corresponding row of image pixels.

2) Dark Current: All CCDs suffer from an effect known as dark current. It originates from the thermal motions of the silicon in the detector, which are strong enough to knock electrons free. Since the electronics are incapable of distinguishing between these thermally emitted electrons and the photoelectrons both sources end up contributing to the reported signal. As a result of this when we perform dark current subtraction we reduce the ratio of our signal to noise (SNR). To see this we refer to our definition of SNR:

$$SNR = \frac{N_{e-}}{\sqrt{N_{e-} + \sigma_{sky}^2 + \sigma_{read\ out}^2 + N_{Dark\ Current}}} \tag{1}$$

It is important to note that the N_{e-} value which appears in the denominator refers only to the image electrons. In other words the signal that we use is only that which remains after bias subtracting and dark frame subtracting our exposure. The noise contribution of these removed counts remains, reducing our SNR value. σ_{sky}^2 is the noise which originates from the sky background, the sky signal itself is subtracted out during image processing.

3) Image: The object being imaged is the final source that contributes to a CCD’s readout. It consists solely of the electrons that are emitted by the photoelectric effect. The bias and dark current corrections discussed above are meant to leave nothing but the image behind, allowing for further processing.

C. Data Collection

The MicroLine camera was disassembled in order to test it in a form closer to how it will be placed on DESI. However, in order to continue collecting data over a range of temperatures the cooling system was needed and the camera had to be reassembled. Issues were encountered during this process with making a good thermal contact between the CCD and the peltier cooler which controls its temperature. To solve this issue several squares of foil were cut out and stacked together to replace the thermal paste which had been lost during previous disassembly. Wires that had been cut were fixed with connectors in order to simplify future reassembly.

With the camera operational again data collection resumed. New data was collected over the temperature range $10°C$ to $25°C$. The lower limit of this range was chosen to avert potential condensation on the CCD and the upper is hard coded in the firmware of the camera. Exposures were taken in alternating sets of 10 starting with a set of bias frames, followed by a set of some exposure length. Chosen exposure lengths were (in seconds) 0.5, 1.0, 2.0, 4.0, 8.0, 15.0, 30.0, and 60.0. The temperature of the CCD was monitored throughout the data collection to ensure its stability and preliminary analysis shows the same behavior as older data sets.

D. Dark Frame Subtraction

Dark frame subtraction takes advantage of the fact that for any given temperature the rate at which dark current accumulates is approximately constant. Thus two exposures taken at the same temperature and for the same length of time should have equal amounts of dark current build up. If one of the two exposures is an image and the other a dark exposure, then subtracting the two frames will leave only the image electrons. However, during testing the data that was used consisted only of dark exposures and as result the final image we expect to see after dark current correction should be blank. This meant that to test effectiveness of the dark frame subtraction we would look for a mean value of $0\,e^-$ for each quadrant. The values measured also had an associated uncertainty which would ideally be $\approx 20\,e^-$ as this is the readout noise of the electronics.

The dark frame used in the subtraction process is an average over all of the exposures that have the same temperature and exposure length. To account for differences in when the exposures were taken, and the resulting effects on the bias, the exposures are bias corrected before being averaged together. As a result the frame generated is a thermal frame, which represents only the dark current in the detector. To subtract from a raw exposure the raw must first be bias corrected. These subtractions are done repeatedly across the range of temperatures for which data exists allowing us to plot dark current and uncertainty as functions of temperature.

It is impractical to store a dark frame for every possible temperature that an exposure will potentially be at. Additionally, taking a dark exposure for each image exposure both doubles the operating time of the instrument and does not allow for the use of averaged dark frames. The solution to this is the use of interpolation. Dark frames are created at set temperatures and these frames are interpolated to create a dark frame of the appropriate temperature. Proposed interpolation methods are: taking an average of the two nearest temperatures, weighting that average, and fitting a function for the temperature dependence of dark current.

III. RESULTS

A. Quadrants of the CCD

As mentioned in Section II-A, the CCD has a 4-channel readout. Because of this most of the data presented in this paper is divided by quadrant. This is to account for the fact that each quadrant has its own independent gain, bias and temperature that are independent of the others. The subplots on each figure correspond to the physical location on the CCD, i.e. the upper left subplot is plotting information from the upper left quadrant of the CCD.

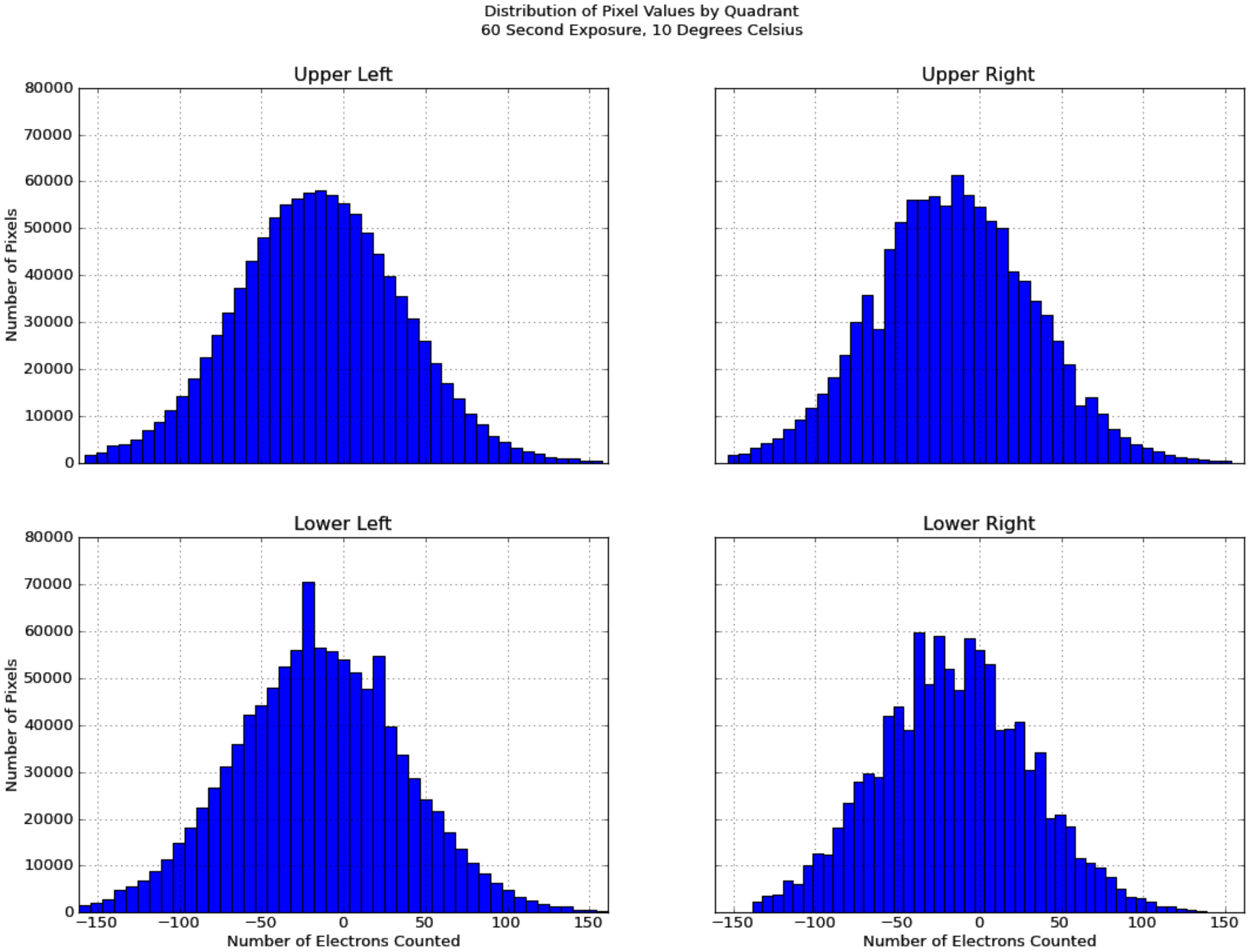

Fig. 1: A histogram of the number of electrons counted by each pixel. This data has been bias subtracted as well as dark frame subtracted. As such it represents a zero signal with all of the associated noise.

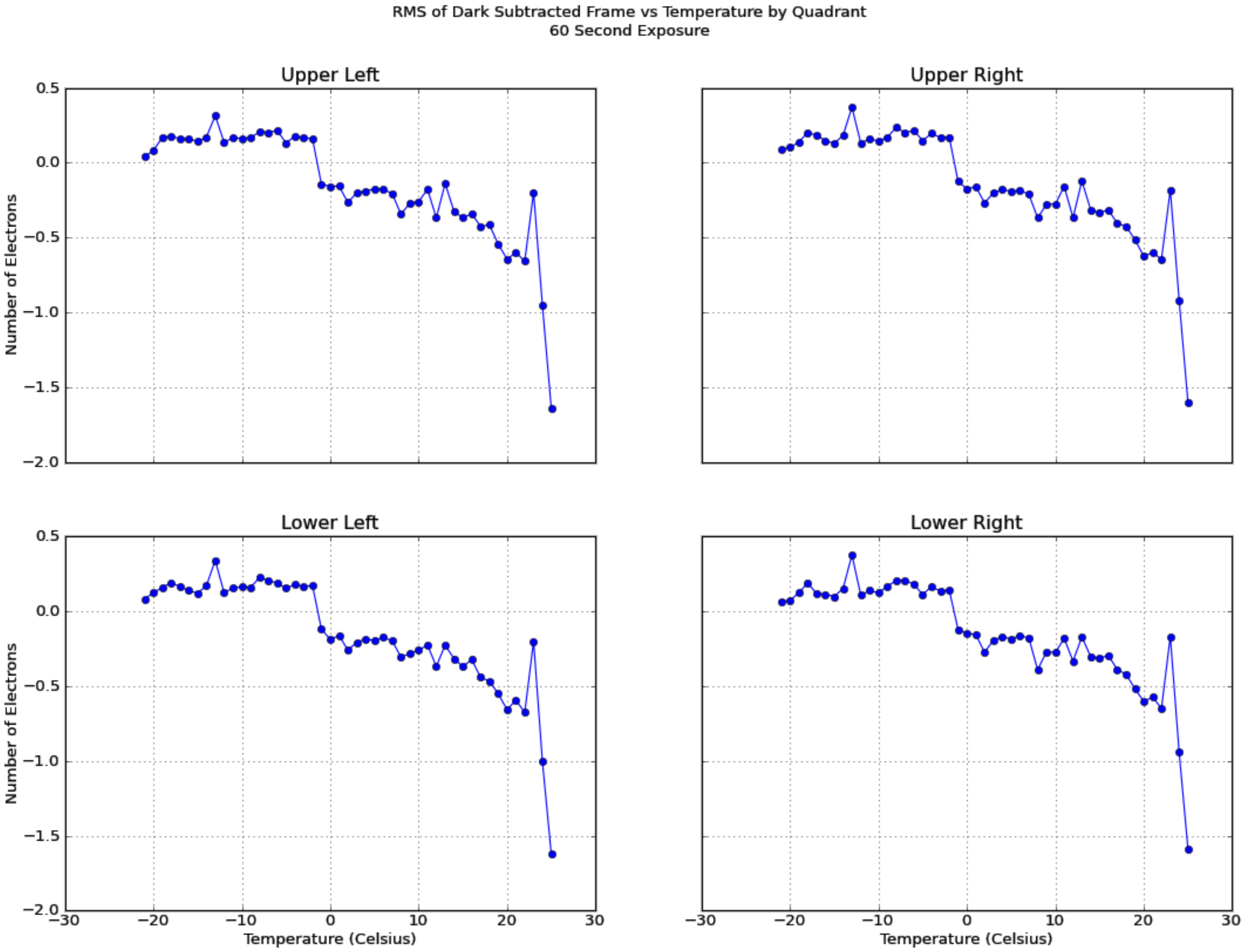

Fig. 2: A plot of the mean value of each quadrant versus temperature. Note that this data is dark subtracted and as such we expect it to be zero. The data plotted has no uncertainty bars due to the scale necessary to resolve the important features. The uncertainty is instead plotted as a function of temperature in Fig. 3. We note that although the mean is not zero it is well within the associated uncertainties for each point.

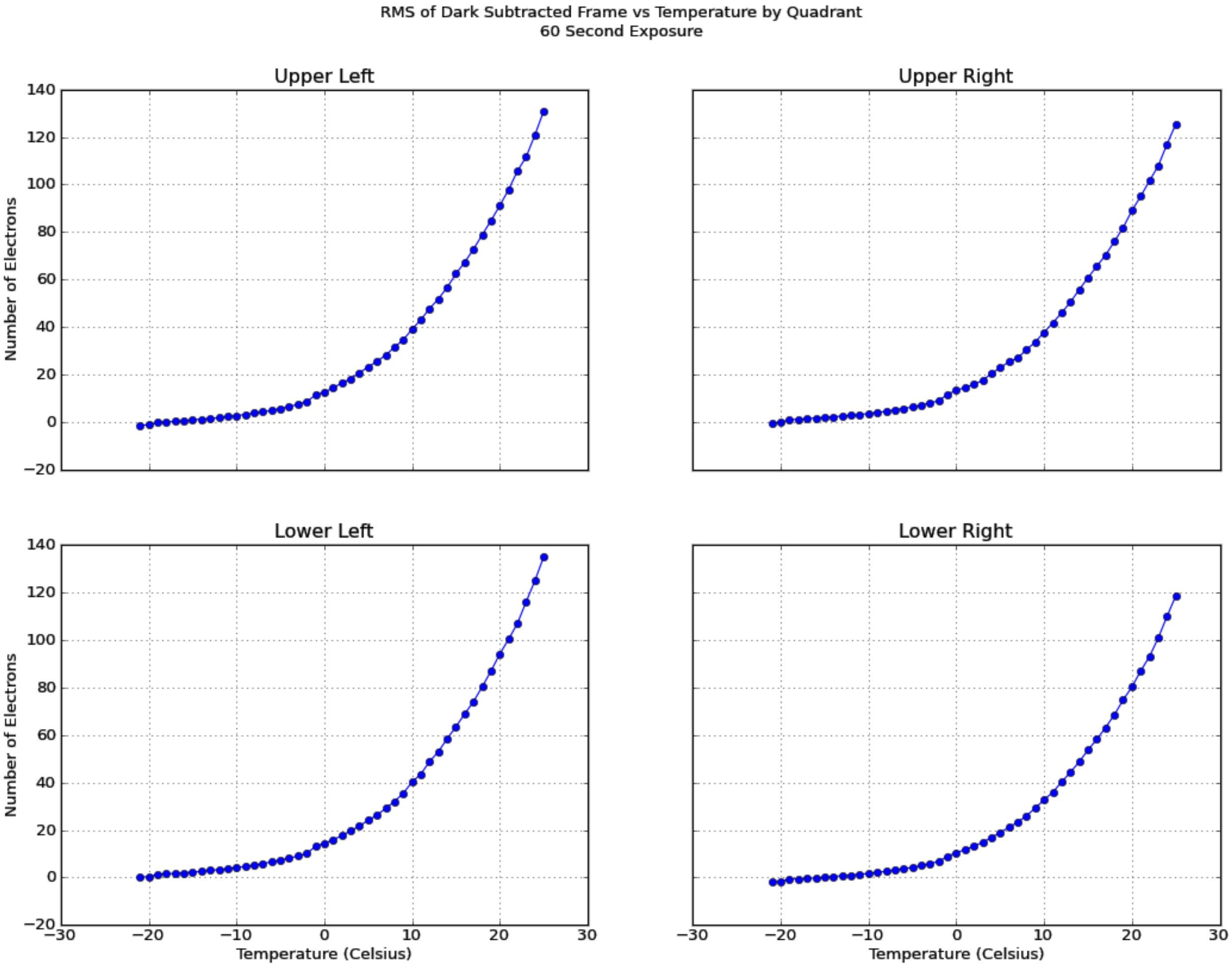

Fig. 3: A plot of the uncertainty associated with each mean value in their respective quadrants. Note that these values reach upwards of $120\ e^{-}$, hence the need to plot this separately from the means.

IV. PREDICTED SIGNALS

We can use a combination of collected and simulated data to obtain example values of the SNR (Eq. 1). These example values can then be used to determine whether or not the CCD will meet DESI specifications for precision. For these predicted signals the worst conditions are assumed for sky signal and dark current, and the SNR is calculated for several different magnitudes of brightness. We will show that even the dimmest guide star that would be used meets the DESI specifications and thus the system performs as needed even in ambient conditions. To begin we reuse Eq. 1, substituting known and measured values:

TABLE I: A table of Averaged Dark Current Values taken from 60 second exposures.

Brightness of Star $[Magnitude]$	Number of Electrons $[N_{e-}]$	Expected SNR
18^{th}	1200	10
17^{th}	3000	23
16^{th}	7600	52
15^{th}	19000	106

$$SNR = \frac{N_{e-}}{\sqrt{N_{e-} + 16 \times [(6.6\ e^{-})^2 + (20\ e^{-})^2 + 400(e^{-})^2]}} \tag{2}$$

Here the value $(6.6\ e^{-})^2$ is the sky noise, $(20\ e^{-})^2$ is the readout noise, and $400(e^{-})^2$ is the dark current for $28°C$. Note that each of these values is multiplied by a factor of 16, this originates from the fact that these values are per pixel and a guiding star is expected to illuminate a 4x4 set of pixels on the CCD. We can then calculate the expected SNR value for stars of different brightnesses, these calculations are outlined in Table I.

These SNR values can then be used to determine if they match the precision requirement for DESI using the equation:

$$\sigma_{centroid} = \frac{\sigma_{seeing}}{SNR} \tag{3}$$

The DESI specifications state that the maximum value for $\sigma_{centroid}$ is $0.1''$. Since a typical value of $1''$ is expected for σ_{seeing} we can see that even a single guide star of the weakest magnitude will meet the requirements. However, we note that at minimum 10 guide stars will be used, improving our $\sigma_{centroid}$ value by a factor of approximately $\frac{1}{3}$.

V. CONCLUSIONS

A. Design Changes

In Fig. 1 the upper left quadrant has noticeably better behaved data than the other quadrants. This was consistent across a wide number of exposures, leading us to believe that this quadrant was the one with the thermometer attached to it. As such its temperature was more stable than the other three quadrants, giving it better performance. Because of this we believe that the DESI system could benefit from adding a thermometer to each of the remaining quadrants, giving higher fidelity in the temperature data.

B. Mean Value Post Dark Current Subtraction

In Fig. 2 the mean value of each dark current corrected quadrant was plotted versus temperature. All the values plotted are easily within their respective uncertainties of the $0\ e^-$ objective. However, there is a downward trend with increasing temperature. While still well within the uncertainty bounds, it is indicative that something is happening, and as such this will be a subject of future investigation.

C. Uncertainty versus Temperature

In Fig. 3 the uncertainty growth is exactly as expected. The uncertainty associated with these exposures is sourced from the readout noise and counting statistics. The values that are plotted have had the readout noise of $20\ e^-$ subtracted out, leaving only the dark current noise. The behavior we see is as we would expect. At lower temperatures with little to no dark current we see little to no additional noise, but as the dark current grows the uncertainty on our values grows with it.

D. Future Work

Due to time constraints on finishing the project a number of objectives were not achieved. The most important of these incomplete objectives is to test the multiple types of interpolation methods against each other. The fitted function would most likely provide the best results, in which case the question is whether or not the gain in accuracy is worth the extra computation.

REFERENCES

[1] M. Levi et al. *The DESI Experiment, a whitepaper for Snowmass 2013* (arXiv:1308.0847, 2013).

[2] DESI Collaboration *DESI Technical Design Report Part II: Instrument Design* (DESI-DOC 1125, 2015), Section 3.

[3] DESI Collaboration *DESI Technical Design Report Part II: Instrument Design* (DESI-DOC 1125, 2015), Section 3.4.

[4] B. Flaughler et al. *The Dark Energy Camera* (arXiv:1504.02900v1, 2015).

TABLE II: A table of Averaged Dark Current Values taken from 60 second exposures.

Temperature $[C^\circ]$	Dark Current $[e^-/s]$	Temperature $[C^\circ]$	Dark Current $[e^-/s]$
-21.0	< 1	5.0	17.2
-20.0	< 1	6.0	19.7
-19.0	< 1	7.0	22.6
-18.0	< 1	8.0	26.1
-17.0	< 1	9.0	30.0
-16.0	< 1	10.0	34.9
-15.0	1.1	11.0	39.9
-14.0	1.3	12.0	45.6
-13.0	1.5	13.0	52.8
-12.0	1.6	14.0	60.7
-11.0	1.9	15.0	70.3
-10.0	2.2	16.0	80.1
-9.0	2.5	17.0	91.5
-8.0	3.0	18.0	105.1
-7.0	3.4	19.0	120.9
-6.0	3.9	20.0	139.9
-5.0	4.3	21.0	158.9
-4.0	5.1	22.0	181.1
-3.0	5.8	23.0	207.4
-2.0	6.6	24.0	237.1
-1.0	7.2	25.0	274.0
0.0	8.4	26.0	310.8
1.0	9.6	27.0	350.2
2.0	10.9	28.0	387.5
3.0	12.7		
4.0	14.8		