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Characterising the KL4040 sCMOS camera for use on the Boyden 1.5m Telescope

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sCMOS sensors are becoming increasingly popular for optical photometry due to the lower price and availability compared with CCDs, but also due to their fast readout speed and low read noise. However, the technology that sCMOS utilise is different from CCDs. Therefore, data processing must be performed differently for sCMOS sensors as compared to CCD data. In this proceedings we report on the testing of the bias and dark current behaviour of the Kepler KL4040 sCMOS camera from Finger Lake Instruments for use at the UFS-Boyden Observatory. Bias frames were analysed, and it was found that the mean bias counts increase by ~8.2% as the temperature increases from -15 to 10 degrees Celsius. The average standard deviation is only 5 counts, the maximum deviation being only 2.34 percent higher. The average dark current as a function of exposure time was investigated, ranging from 0.1 s to 300 s, at temperatures of -15, -10, -5°C and the Dark Signal Non-Uniformity (DSNU) was calculated for each series of dark frames. The rate of the Dark Noise increase clearly shows linear trends for all the temperatures.

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1. Introduction

Complimentary Metal-Oxide Semiconductor (CMOS) are common nowadays in consumer devices like cellphones and DSLR cameras, but are not commonly used on telescopes due to limitations compared to Charged-Coupled Devices (CCDs). CCDs offers low dark signals and uniform gain, which are crucial for astronomical observations. CMOS have struggled to match the performance of CCDs in these areas. In recent years science grade CMOS, commonly referred to as scientific Complimentary Metal-Oxide Semiconductor (sCMOS) cameras, have been developed for research applications. sCMOS can now replace CCDs in some cases and at a much lower price.

1.1 Differences in technologies

The fundamental process of image capturing stays the same for sCMOSs compared to CCDs,, where a photosensitive substrate converts incoming photons into photoelectrons which are then converted into digital data for computers to store or manipulate. The photon to electron conversion efficiency is referred to as the quantum efficiency (QE) and is wavelength dependent. The differences between sCMOSs and CCDs stems from the imaging sensors' technological operation after the incoming photons are converted into electrons. CCDs consists of pixels that are charge-coupled in parallel rows to the next pixel. There is only a single charge to voltage amplifier which converts the pixels' charges to voltages sequentially and then a single Analog-To-Digital Converter (ADC), which converts all of the pixels' voltages to digital units or ADUs, one pixel at a time, until all rows have been readout in sequential order from the serial readout register. sCMOSs, however, have charge to voltage converters on each pixel, so the accumulated electrons on each pixel can be converted to voltages simultaneously after an exposure. After the conversion from electrons to voltages, the voltages are readout to column amplifiers and ADCs where the voltages are converted to digital units. The pixel data is then transferred row by row to the final readout register. The differences have a remarkable influence on the final images and the origin of the most prevalent noise sources of an image. Dark current, which is the thermally generated build-up of electrons in pixels over the exposure time of a frame, rises quicker for sCMOS than for CCDs. This is due to the sCMOS having more transistors and converters on-board of the sensor chip itself, which heats up during exposures and introduces thermal electrons that are accumulated in the pixels, whereas CCDs have less electronic components on the chip that can introduce electrons of thermal noise. This means that it will be better to observe for shorter exposure lengths with an sCMOS to minimise the dark current build-up in frames.

CCDs also have a uniform gain over all pixels as all accumulated charges in all pixels are converted by a single charge to voltage amplifier and high quality ADC, which means that any error introduced by these components will be the same for all of the pixels. For an sCMOS this is not the case, since each pixel has its own charge to voltage converter, which will introduce a different error for each pixel, and each row has its own ADC, which will introduce a different error for each row of pixel voltages that is readout. This leads to sCMOS not having uniform gain over the sensor. Certain pixels might have a slight offset which causes the pixel to appear brighter or fainter than the surrounding pixels. The idea that each electronic component generally still introduces the same offset from one frame to the next frame, means that a fixed error pattern will form in images taken with the same sensor. This is called fixed pattern noise (FPN) and is generally more prevalent at

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long exposures. FPN can be removed by creating a master dark frame and subtracting it from the science frame.[1]

The read noise is introduced when converting the accumulated charge in a pixel to a voltage. The read noise is higher for CCDs than for sCMOSs, because in CCDs the electrons accumulated in each pixel are shifted multiple times, before being converted to a voltage. With sCMOSs, the conversion from electron charge to voltage happens on the pixel itself. Due to the generally lower read noise, sCMOS sensors are capable of detecting faint light sources that would typically be within the readnoise level of CCDs.

The sCMOS being tested in this study has a 12-bit ADC, compared to the usual 16 bit for a CCD. The difference results in CCDs with 16-bit ADCs having a higher dynamic range. One way that sCMOS can deal with this is by reading out a single image twice. Because sCMOSs converts charge to voltage on a pixel level, the sensor can be readout more than once. To create a 16-bit high dynamic range frame, a frame is readout with a low gain and the same frame is readout again, but with a high gain. Then the two frames are merged. The merging is determined by a threshold value. If pixels on the high gain image falls under a certain threshold, the pixels are replaced by the corresponding low gain frame pixels, which are scaled as to make sure that there is no discontinuity in the photo response of the camera. This architecture is also briefly discussed in Qiu et al [2]. and also described in the Kepler manual under 'Merge Settings - Threshold' [1].

1.2 Data processing and reduction

Processing data from both camera technologies follows the standard procedure of taking bias frames, dark frames and flat field frames. Bias frames are frames taken at 0 exposure time (or as close as possible) that records the base electronic current present in the image sensor when recording a frame. Dark frames are frames that captures the accumulation of the dark current over the exposure time of an image, where the dark current is due to thermal build-up of electrons in pixels. The higher the sensor temperature the quicker the dark current will rise. The flat field frames are exposures of a uniform intensity over the sensor, where all pixels on the sensor are meant to receive the same amount of light. Any non-uniformities in the sensor or illumination are captured in the flat frames.

The specific camera that is being tested is the KL4040 by Finger Lake Instruments (FLI). The KL4040 has a 4k x 4k sensor and has a peak QE of 74% at 600 nm. This is quite a high QE considering the sCMOS has a front illuminated sensor. The Andor ikon-M series have front illuminated CCDs with QE of up to 60% [3], and the Apogee Alta F16 up to 70% QE.[4] The typical read noise of the KL4040 is 3.7 e^-. More information can be viewed on the FLI website.[1] The KL4040 is currently being tested for use as a photometer on the UFS Boyden 1.5-m telescope. A reduction pipeline will also be built to reduce the data when the camera is commissioned on the telescope. This paper only focuses on the bias and dark current response and initial characterization.

[1]https://www.flicamera.com/downloads/KeplerManual.pdf

2. Experimental Setup

2.1 Test Environment

The experimental setup for testing the KL4040 camera is as follows: A box was built that would block any light from reaching the sensor of the camera. This box was made up of foam board and a single panel of wood on one side of the box, onto which the camera was mounted. Two layers of 1 mm vinyl was added to the foam layers, one layer on the interior and one layer on the exterior of the box. The box was then covered with cardboard as to eliminate the possibility of light leaking at the joined corners of the foam. The box was also covered with eight layers of dark curtain. At the top of the box a 2 cm × 2cm hole was made to later let in light from a solar simulator to test the camera's photo response curve, but for the bias and dark frames the hole was closed using a layer of vinyl and 8 layers of dark curtain fabric. The camera and the box was kept in a temperature controlled room at 20° C and images were recorded while the lights were off. Maxim DL astronomical imaging software was used to record the frames for this experiment [5].

2.2 Bias Frames

For analysing the bias frames, the camera was attached to the dark box. Three bias frames were taken for each absolute temperature from -15 to 10° C. The bias frames were taken at the minimum possible time which is 0.001 s. For each temperature the three bias frames were averaged using the PYTHON package CCDPROC [6] to create a master bias frame for each temperature.

2.3 Dark Frames

For taking the dark frames, the camera was attached to the dark box once again. Twenty bias frames were taken and averaged together using ccdproc python library [6], to create a master bias frame. Twenty dark frames were then taken at exposure lengths of: 10, 50, 100, 500 ms; 1 s to 60 s in 5 s increments and from 60 s to 300 s in 60 s increments. These exposures were taken at three temperatures: -15, -10 and -5° C. The twenty dark frames were then bias subtracted and averaged to create master dark frames for each exposure length at each temperature. The mean counts of each master dark frame were then calculated and plotted as a function of exposure length. The Dark Singal Non-Uniformity (DSNU) was also measured for each master dark frame. The DSNU is the standard deviation in counts across the image [7].

3. Results

Fig. 1 shows the mean counts of the master bias frames as a function of the absolute temperatures. There is a clear linear increase in the average bias as the temperature increases ($R^2 = 0.996$). This increase is, however, only increasing slowly by ≈ 8.25% from -15 to 10° C. The average Standard Deviation for the mean counts (for the master bias frames) was 5 counts with a maximum deviation from the average of 2.34 percent.

Fig. 2 shows the mean dark current as a function of exposure time, as measured at three different temperatures. The dark current shows a linear increase with exposure time at all three temperatures, as well as an average decrease at lower temperatures. The statistics of the linear fits

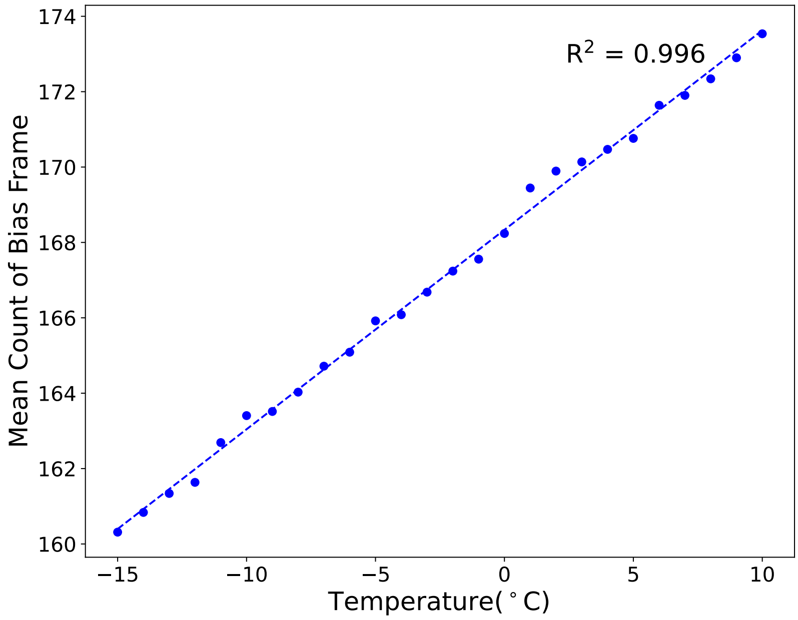

Figure 1: The mean counts of the master bias frames as a function temperatures of -15 to 10 °C

Temperature (°C)	Linear Fit	R^2	DSNU
-5	0.308t - 0.292	0.998	27.11
-10	0.152t + 0.488	0.883	14.39
-15	0.108 + 0.748	0.996	9.56

Table 1: The Linear Fit equations, R^2 values and DSNU values the of the mean dark frame counts.

are given in Table 1. The linear trend found in Fig. 2 compares well to the dark signal as a function of integration time in Fig. 5.5.7, from a similar study on a CMOS image sensor documented by Jain, U [7]. The initial results for -10° C show a smaller goodness of fit, and is currently being re-investigated, to ensure that there was no contamination due to stray light during the testing.

4. Discussion and conclusions

The small rise in the mean bias frames, shown in Fig. 1 are to be expected, because although the exposure time is only 0.001s, the average temperature and therefore the average amount of thermal electrons present on the sensor will increase as the the temperature increases. This increase in the counts is very linear (R^2 = 0.996). This will mean that bias frames will need to be taken for each temperature that a science frame is taken at to match the correct bias level. The KL4040's temperature control is rated at a stability of 0.1 degree Celsius if the ambient temperature is constant.

Fig. 2 and Table. 1 shows a linear increase of the dark current with exposure time. However, the slope is not one. Therefore, it will be recommended that dark frames are taken with the

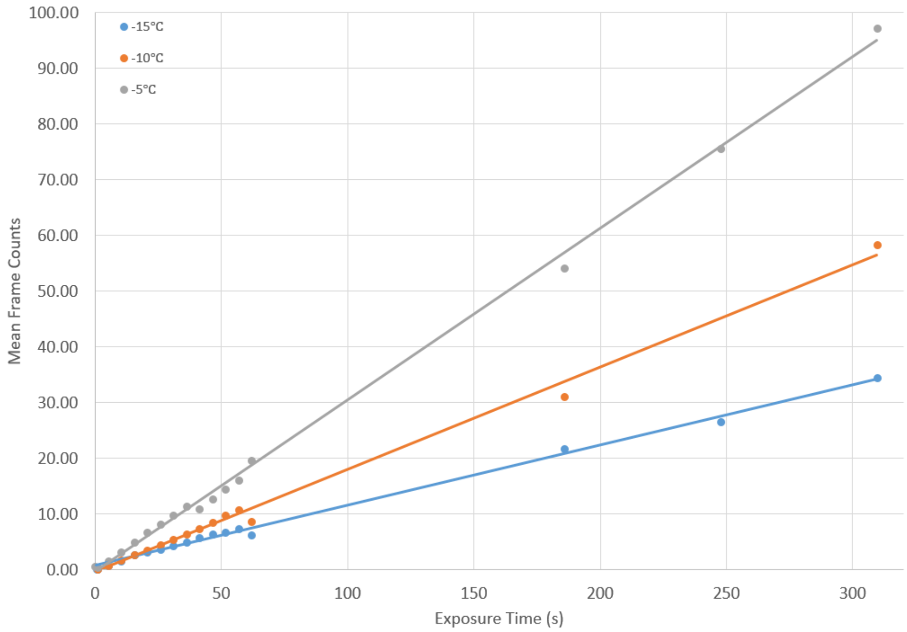

Figure 2: The dark current plot of -15, -10, -5 ° C absolute for exposure times ranging from 0.1 seconds to 300 s.

same exposure length as the science observation. Alternatively, a library of dark frames can be constructed. Fig. 2 also shows that for temperatures of up to -5°C and exposure times of up to 5 minutes the dark signal is still very low. Further tests are currently being undertaken to test the behaviour of the dark currently at longer exposure times.

Acknowledgments

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