Characterisation and Calibration of the Kepler KL4040 sCMOS camera for Optical Observations at the UFS/Boyden Observatory

Hendrik J. van Heerden[1], **B. van Soelen**[1] **and W. Smit**[1]

[1]Department of Physics, University of the Free State, Bloemfontein, South Africa

E-mail: `vanheerdenhj@ufs.ac.za`

Abstract. The Kepler KL4040 sCMOS camera by Finger Lakes Instruments was evaluated for its suitability as an affordable alternative to older CCD sensors for optical photometry at the Boyden Observatory. Due to the sensor architecture where each pixel has its own electron to voltage converter, a thorough characterization and calibration study was conducted to identify key performance factors and necessary considerations for operational implementation. The KL4040 achieves a high dynamic range by merging two 12-bit images into a single 16-bit image, with binning performed via software. Laboratory tests examined bias stability, dark current, and photo-response characteristics. Bias frames exhibited a 7.5% increase in mean counts as temperature rose from -15°C to 10°C, with dark current showing a linear temperature dependence. A small offset between the merged images for the 12-bit to 16-bit conversion was identified but was correctable through adjustments to the gain transition parameter that determines the offset value between high and low gain. Photo-response curves for the B, V, R, and I bands confirmed linearity across all bands. Fixed pattern noise (FPN), a known issue in sCMOS sensors, was effectively mitigated through bias and dark corrections. An on-sky test of the SA 107 star field, achieved photometric correction magnitudes on average within 2% of reported values. Additionally, we demonstrate photometry of the pulsating white dwarf binary system AR Sco which was performed on a 6 s cadence over a full orbit and show that the 118.2 s beat period could be easily recovered. These results confirm the KL4040 as a viable, cost-effective alternative to CCDs for photometry at the Boyden Observatory.

1 Introduction

Scientific-grade charge-coupled device (CCD) cameras have long been the standard for optical astronomical observations due to their low readout noise and well-understood behavior. However, recent advances in scientific Complementary Metal Oxide (sCMOS) camera technology offer an appealing alternative, particularly in cost-sensitive environments.

The Kepler KL4040 sCMOS camera by Finger Lakes Instruments (FLI) was acquired for deployment at the Boyden Observatory[1] as a potential upgrade path for aging CCD systems. This camera features a large-format 4096 × 4096 pixel array, 9 × 9 µm pixel pitch, and a 52.1 mm sensor diagonal. Key specifications are provided in Table 1. Its architecture merges two 12-bit images (low and high gain) into a 16-bit output, enabling high dynamic range imaging, albeit with unique calibration challenges.

This paper presents the results of a laboratory and on-sky characterization of the KL4040, focusing on dark current, bias stability, linearity, and photo-response. We also demonstrate its scientific performance by recovering the known beat period of the white dwarf binary AR Sco from short-cadence photometry.

[1]The Boyden Observatory is located approximately 20 km North-East of Bloemfontein, South Africa and is operated by the University of the Free State.

Table 1: KL4040 Camera Specifications

Specification	**Value**
Peak Quantum Efficiency (QE)	74%
Effective Pixels	4096 × 4096
Pixel Size	9 µm
Sensor Diagonal	52.1 mm
Full Well Capacity	70,000 electrons
Typical Readout Noise	3.7 electrons
Dynamic Range	85.2 dB
Frame Rate	8 FPS via USB3 (23 FPS via QSFP V2)
Temperature Stability	0.1 °C
Dark Current at −10 °C	0.4 electrons/sec
Image Bit Depth	16-bit (merged from 2 × 12-bit)

2 Laboratory tests

For control of the operating environment (temperature, humidity and ambient light) during characterization of the KL4040 a laboratory setup inspired by [1] and [2] was used. The setup consisted of a *dark box* to which the camera was mounted. Inside the box was an integrating sphere, which was illuminated by a VeraSol-2 AAA LED solar simulator from Newport[2]. This created a uniform light source and provided a simulated blackbody spectrum[3]. A variety of Johnson and Cousins photometric filters, as well as neutral density filters[4], were positioned between the solar simulator and the inlet to the dark box to control the colour spectrum as well as the intensity of the light reaching the sCMOS sensor. Tests done in the environment-controlled laboratory included bias response, dark current characterization and dark signal non-uniformity and stability [3], as well as the photo-response linearity, colour dependence, and non-uniformity [2, 3].

2.1 Bias and Dark response

The characterization of the bias and dark response of the camera found that the bias level has a linear temperature dependence as can be seen in figure 1. An interesting result that was found was that there is an interplay between the bias level and the dark current for short dark exposure times, where the average dark current is less than the average bias current. Following the standard procedure of performing bias subtraction on the dark frames, can result in a subset of frames that have negative values (refer to figure 2). Possible causes may be either a buildup of charge in the imaging sensor pixels and registrars, or could be due to incorrect black level calibration values as discussed in a post by Thiam-Guan Tan[5] and an online article by Qiu[6].

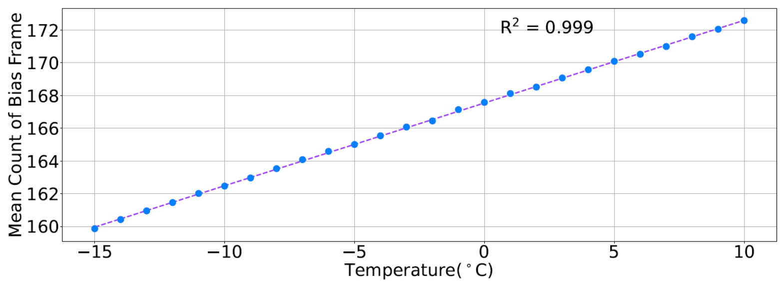

Figure 1: The mean count value of the bias frames as a function of the set sCMOS temperature.

[2]https://www.newport.com/p/VeraSol-2
[3]https://www.newport.com/n/solar-simulator-standards-definitions-and-comparisons
[4]https://www.edmundoptics.com/knowledge-center/application-notes/optics/ understanding-neutral-density-filters/
[5]http://pestobservatory.com/cmos-for-photometry/
[6]https://www.gamaelectronics.com.au/files/Dr.Qiu's Talking about Astronomical Photography.pdf

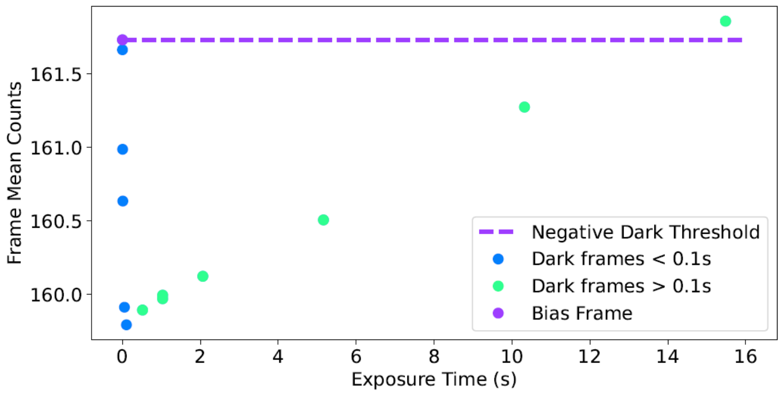

Figure 2: The mean count value of the bias (purple dashed lines) and dark frame (blue and green circles) as a function of exposure time.

The dark response is shown for exposure time and sensor temperature in figure 3. There is a clear and strong increase in dark counts towards higher sensor temperatures and, to a lesser degree, longer exposure times. However, due to the higher dark signal non-uniformity (DSNU) (a consequence of the physical architecture of the sensor) it is not advisable to use the mean dark level read from such a dark response curve. It was found that the best operational procedure is to use a dark frame - obtained at the same exposure time and temperature as the light (flat and data) frames - that has not been bias-corrected, in order to subtract both the bias and dark current simultaneously.

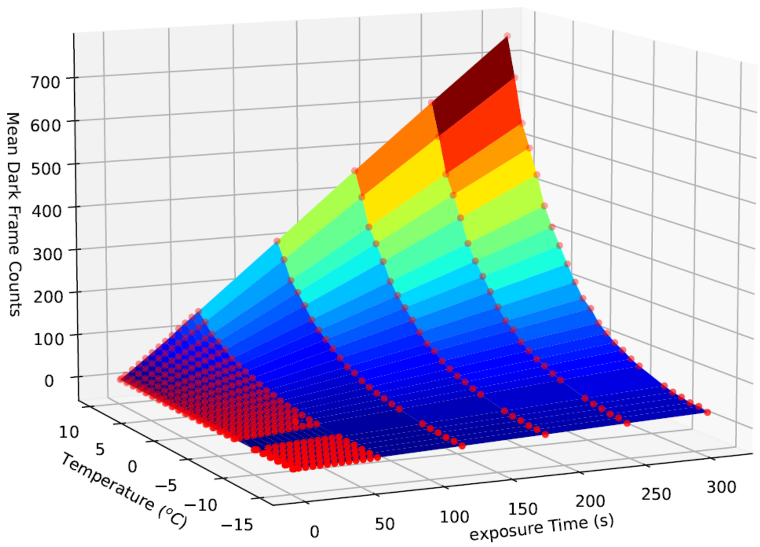

Figure 3: The dark response curve indicating counts relative to temperature and exposure times.

2.2 *Photo-response and flat-fielding*

During photo response tests using exposures through B, V, R_C, I_C filters, it was found that the sensor output over the generated 16-bit full well depth is linear up to 65000, as can be seen in figure 4. This 16-bit image is generated by combining two 12-bit images, one read out at low gain and one read out at high gain, with the gain cross-over value set around 3800 counts. The cross-over gain region can be offset by setting the value in the camera software. This can be used to improve data quality that falls within this region, which is shown as the "V-Offset" in the figure.

When examining the logarithmic plots of pixel count distributions for a raw flat field versus a bias and dark corrected flat field (see Figure 5), distinct sensor characteristics become evident. A noticeable difference in photon

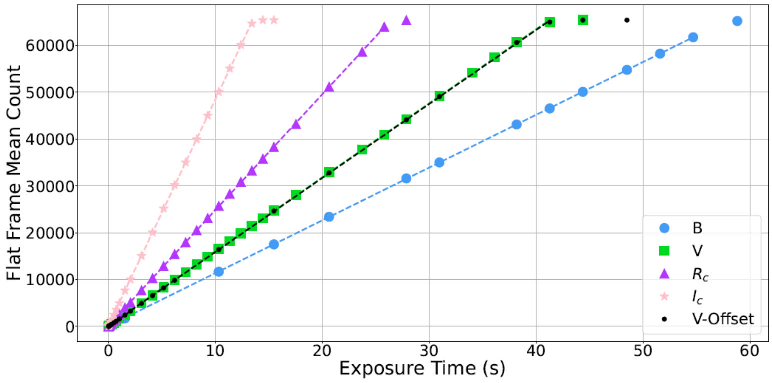

Figure 4: Photo response curve and test for linearity for B, V, R_C, I_C and V-offset.

response is observed between the top and bottom sections of the sensor. This variation arises from the architecture of the GSENSE4040 sensor chip, which is composed of four individual sub-chips arranged in a square configuration. The top two and bottom two sub-chips each have their own readout registers[7] [8].

Additionally, the raw flat field image (left) exhibits a prominent side lobe at higher counts, particularly on the right-hand side, which is indicative of bias and dark noise. After applying the bias and dark corrections, these side lobes are effectively removed, as seen in the corrected flat field image (right).

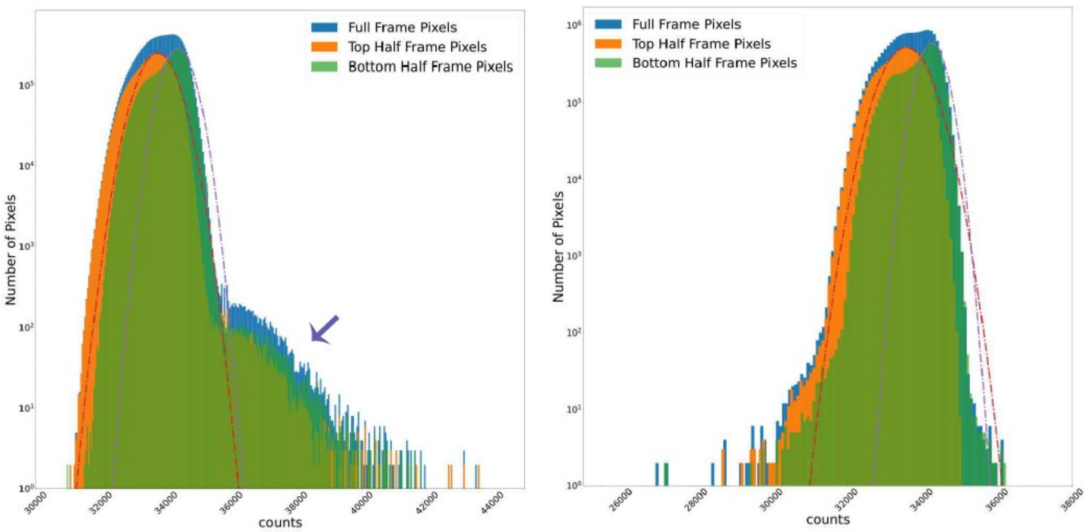

Figure 5: (*Left*) The raw flat field pixel counts distribution. A clear difference can be seen between the photo-response for the top and bottom chip sections, as well as bias and dark noise to the side as indicated by the arrow. (*Right*) The bias and dark corrected flat field clearly indicating a more even pixel distribution along with clearing of the side lobe due to bias and dark correction.

3 On-Sky tests

The most important tests were to see what quality of on-sky or science data the camera delivers. To make the tests independent of the telescope used, on-sky tests were performed using both a Celestron 14-inch as well as the large 60-inch Boyden Reflector. Using the Celstron 14-inch, photometric calibration observations of standard

[7] https://www.gpixel.com/en/pro_details_1199.html

[8] https://note.youdao.com/ynoteshare/index.html?id=ae2fabb24d1742f207ba75613648e7c4\&type=note\&_time=1647458420460

stars of different magnitudes and colours using UBV$R_C I_C$ filters were performed. This was done using stars in the SA 107 standard star field. After calibration the measured instrumental magnitudes and colour indices were calculated to within 2% of the reported catalogue values. There are some interesting features to note in figure 6. First, the raw uncorrected stellar image (left) shows significant fixed pattern noise (FPN), a well known issues of CMOS sensors, which is due to the sensor architecture [4]. This pattern is also clearly visible in the column profile below the image. Second, is the clear break between the top and bottom sections of the sensor visible in the row profile on the right side of the image. Both of these features are corrected for by using a master dark (which also acted as a bias corrector) compiled from an equivalent temperature and exposure length dark signal frame set, and performing flat-fielding using the appropriate filter.

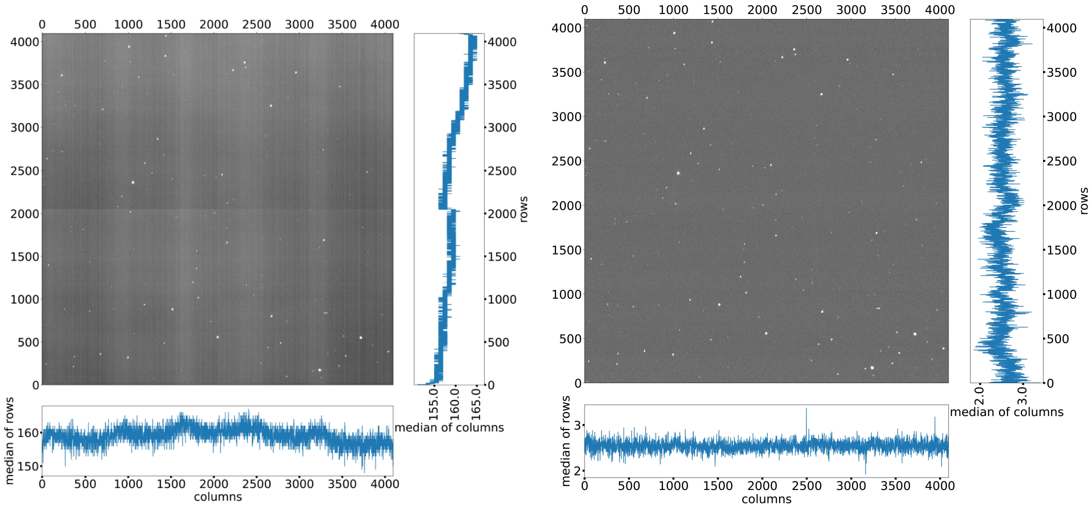

Figure 6: (*Left*) Raw star image from the SA 107 standard star field. (Right) Corrected star field. The median count value along the rows and columns are also shown.

A second test was performed using the 60-inch Boyden Reflector to investigate for how long, and how consistently the the camera could operate in a continuous imaging mode. To this end a sequence of operations were conducted on AR Scorpii. AR Scorpii (AR Sco) is a unique white dwarf–red dwarf binary system that emits powerful pulsations across the electromagnetic spectrum, driven by the spin-down energy of a rapidly rotating magnetic white dwarf. It behaves like a pulsar, making it the first known white dwarf system to show such non-thermal, magnetospheric emission [5]. Observations were performed for several hours at a 6 second cadence, and analysis resulted in the expected phase diagram (Figure 7) with the well known beat period value of 118.2 seconds extracted from the data sets.

4 Conclusion

The characterization of the KL4040 sCMOS camera highlights its viability as a modern, cost-effective alternative to traditional CCDs for optical photometry. Our laboratory tests confirm the sensor's sensitivity to thermal variation, which requires stable temperature control to ensure bias stability. A strong temperature dependence in dark current was observed, underscoring the importance of accurate calibration for low-light observations.

The dual-gain image merging introduces a small but correctable offset, manageable via proper gain crossover tuning. While fixed pattern noise is an inherent feature of sCMOS architectures, it was effectively mitigated through bias and dark frame correction.

On-sky testing with the SA 107 standard star field demonstrated photometric consistency within 2% of catalogue values. Further validation through fast-cadence photometry of AR Sco confirmed the system's ability to recover known periodic signals, including the 118.2 s beat period.

While some software packages may produce artifacts during software binning, these can be avoided through careful pipeline selection or custom routines. With appropriate calibration workflows and attention to gain behaviour, the KL4040 is well suited for time-series photometry and other scientific imaging tasks at Boyden Observatory.

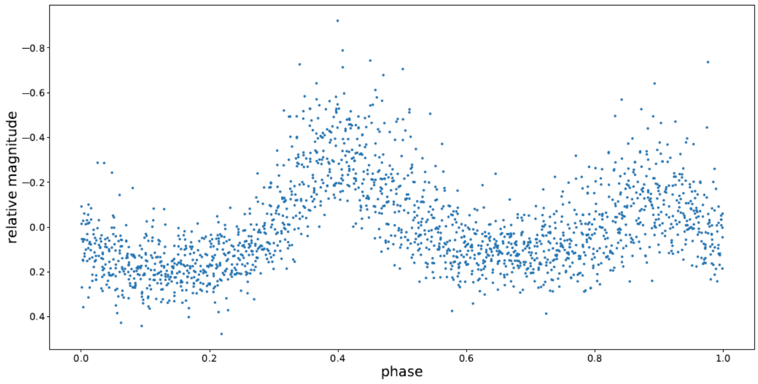

Figure 7: Phase diagram for AR Sco based on light curve data acquired using the KL4040 sCMOS.

References

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