

Photometric nonlinearity in SBIG 6303 images with low light levels

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Summary

Several LCO users have reported problems with photometry derived from images acquired with some of the SBIG 6303 cameras on the 0.4m telescopes. From examining science data, as well as testing cameras in the LCO lab, we have verified that some cameras produce inaccurate photometry; the severity of the inaccuracy correlates inversely with the background levels in the images. Because the problem manifests as a nonlinear detector response at low light levels, we named the problem “photometric nonlinearity.” Our description of the nonlinearity is empirical; we cannot explain the flaw in the camera hardware that causes the apparent loss of charge.

We characterized the nonlinearity exhibited by one camera (kb96) by making repeatable experiments on a test apparatus. We fit a function to a plot of ADUs versus illumination cycles (tantamount to exposure time), then used the inverse of that function to correct representative science data from the same camera. The uniformity of the zero points after the correction justifies the application of the lab result to the on-sky data.

Because it is impractical to recall all SBIG cameras and test them in the LCO lab, we also used science images from cameras in the network to estimate functions that could be used to correct data. The result of a function fit to data from the kb95 SBIG camera is presented as a demonstration of the procedure.

We expect the photometric nonlinearity to be significant only on some cameras and only when the sky background is low (i.e. when exposure times are short). *We strongly recommend that LCO users who have acquired images with the SBIG cameras inspect their data to determine whether the effect on photometry is significant.* For images that have been affected by the nonlinearity, we conclude that the photometry can be improved by applying a correction that’s based on fitting a function to the trend in zero point with magnitude.

Lastly, we remind users that LCO plans to replace the SBIG cameras beginning in 2022.

1. BACKGROUND

PIs who made observations with the SBIG 6303 cameras on the 0.4m telescopes reported problems with the calibration of photometry in their science data. Although the language used by the reporters varied, a signature characteristic can be succinctly described: faint sources appear too faint. We have named this effect *photometric nonlinearity*. Some users pointed out a possible correlation of the photometric nonlinearity with a low background level*. We have verified this correlation.

To elicit the photometric nonlinearity from a controlled set of observations, we observed the same field with different exposure times with the kb95 camera on the 0m4a telescope at Teide Observatory

*A nonlinear response at low light levels is a different problem from the linear response of a detector over the full dynamical range and its breakdown (“nonlinearity”) near the full-well limit.

(TFN). We used exposure times of 10, 60, and 120 seconds, and the background levels were measured at ≈ 20 , 170, and 370 e^- , respectively. The panels in Figure 1 show the differences between the catalog and instrumental magnitudes as a function of the magnitudes in the refcat2 catalog (Tonry et al.) for single images. The differences, which indicate the photometric zero points of the stars, should be

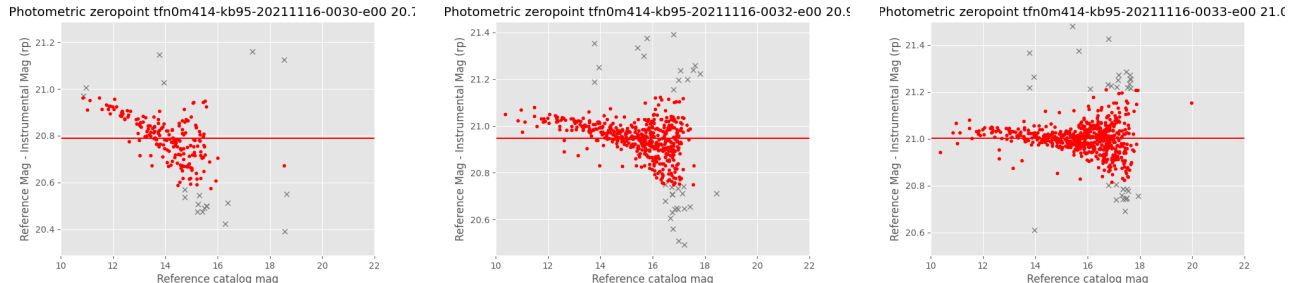


Figure 1. Photometric zero point relations for images of the same field with exposure times of 10s (left), 60s (center), and 120s (right). Each panel shows the differences between instrumental and reference catalog magnitudes (i.e. zero points) as a function of the reference catalog magnitude.

approximately uniform over the range of catalog magnitudes. The left panel of Figure 1 illustrates the photometric nonlinearity. For the 10 s exposure times ($\approx 20 e^-$ background levels), the zero points decline within a range of approximately 0.4 magnitudes. In the middle and right panels, the exposure times (and background levels) increase, and the slope of the magnitude differences decreases. For some short exposures, we found a zero point range > 0.4 mag. The steeper the slope, the less accurate the photometry derived from the images.

The characteristic shape of the photometric nonlinearity is often attributed to a fixed amount of charge missing from each star. Possible causes for this missing charge that have been excluded are:

1. **Charge traps in the CCD substrate that affect all pixels in a similar way.** We ruled out charge trapping as the underlying cause because the subsequent release of charge would have detectable effects. Hot pixels or cosmic ray hits in dark exposures would be smeared out; the PSFs of stars would appear asymmetrical, or photometry would show variations with position on the detector.
2. **A systematic error in the data processing**, such as bias and dark subtraction. The apparent loss of charge might occur if, for example, dark exposures were contaminated with stray light, or if numerical biases were introduced by the data processing pipeline (BANZAI). We ruled out the pipeline as the source of charge loss by validating each processing step and by reproducing the photometric nonlinearity from raw, unprocessed data.
3. **Poor telescope tracking**, which causes stellar flux to contaminate the sky background measurement. Although the 0.4m telescopes occasionally have issues with focus and tracking, we saw the photometric nonlinearity even in well-guided, well-focused images.

Because the severity of the photometric nonlinearity increases as the background level on the detector decreases, we suspected that the SBIG cameras have anomalous responses to low levels of illumination. An examination of the response of a particular camera (kb95) under laboratory conditions showed that

the detector had $< 1\%$ deviation from a linear response over the camera’s dynamical range. However, those measurements did not probe the $\leq 2000\text{ e}^-$ illumination range very well due to systematic shutter effects.

2. THE EFFECT OF A NONLINEAR DETECTOR RESPONSE AT LOW LIGHT LEVELS

For the purpose of demonstration, let’s assume that a camera produces a simple point spread function (e.g. due to active PSF shaping) without wings, i.e. a top hat function. The signal from the star plus the sky is measured entirely in the linear regime of the camera. Further, we assume that the true sky background is $100\text{ e}^-/\text{pixel}$, but due to a nonlinear response at the low level, it is measured at 110 e^- , a 10% overestimation. The flux of the star plus the sky background is measured in an aperture with a radius of 2 arcseconds. For the SBIG cameras, this aperture corresponds to 3.5 pixels. When the sky background is subtracted from the aperture to derive the star’s flux, we would oversubtract the following amount:

$$\Delta = \pi \times 3.5^2 \text{ pixels} \times 10\text{ e}^-/\text{pixel} = 38 \text{ pixels} \times 10\text{ e}^-/\text{pixel} = 380\text{ e}^-$$

This offset is subtracted from each star’s flux measurement, regardless of the star’s magnitude.

The photometric zero points of the SBIG cameras are approximately $z_p \sim 21\text{ mag}$. A one second exposure of a $V = 12$ star will generate approximately $10^{\frac{-(12-21)}{2.5}} = 3980\text{ e}^-$ signal. Oversubtracting 380 e^- from this flux is a 10% effect! For a $V = 14$ star, we expect a flux of approximately 630 e^- , and oversubtracting 380 e^- would be have an effect $> 50\%$!

This simple model recovers the basic shape of the photometric nonlinearity that’s observed in the SBIG data (see Figure 2). The model becomes nonphysical as the stellar flux becomes smaller than the oversubtracted sky.

3. MEASURING AND MODELING THE DETECTOR RESPONSE

We quantified the photometric linearity of the kb96 SBIG camera, which was available in the LCO lab. We tested the camera at -20 C , which is the same temperature at which the camera operates when installed on a telescope. We mounted the camera on the LCO camera test bench, which is a dark, internally baffled tube with a homogeneous LED illumination at one end. [For a detailed description of the tests, please contact science-support@lco.global.] The measurements resulted in the relation between illumination cycles (similar to exposure time) and the retrieved signal shown in Figure 3. The orange line indicates a linear fit to the brighter half (illumination cycles ≥ 400) of the lab data. The residuals of the fit over the entire illumination range are shown in Figure 4. The blue points show an obvious increase in residuals below 1000 ADU. The residuals are $> 15\text{ ADU}$ at the lowest illumination point ($\sim 60\text{ ADU}$). At the faint end, the deviation from a linear detector response is significant.

A function that models the camera’s response must have the following properties:

- At high illumination levels, the measured signal must be identical to the true signal.
- At low illumination levels, the measured signal must be larger than the true signal.
- With no illumination, the measured signal must equal 0.

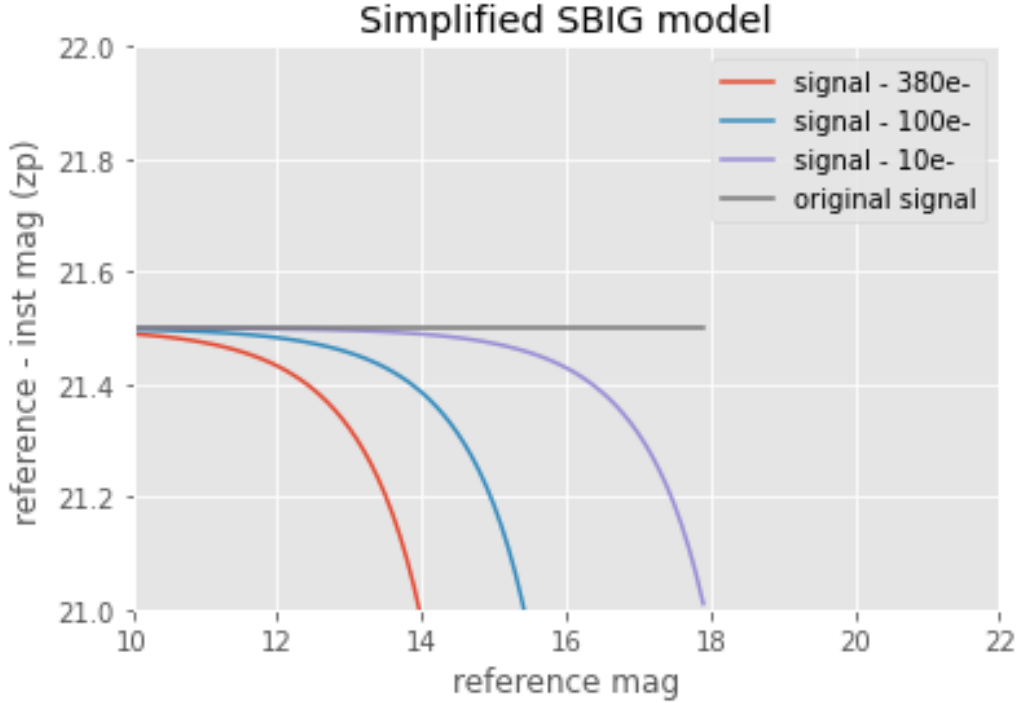


Figure 2. Simple models that demonstrate the effect of oversubtracting the sky when performing aperture photometry.

A function with a suitable form is:

$$s = (x^k + z^k)^{\frac{1}{k}} - z$$

where x is the true level, and s is the signal measured by the camera. [This is similar to a function for adding an offset z in quadrature, except that it allows for exponents k other than 2.] The residuals from fitting a function of this form to the kb96 data are displayed with the orange dots in Figure 4. As the legend indicates, the offset is $z = 238.5$, and the exponent is $k = 1.046$. The amplitude of the residuals is now much smaller.

Prior to its residence in the lab, the kb96 SBIG camera had been mounted on the 0m4a telescope in Aqawan A at LCO's CTIO site (LSC). To test the applicability of the function applied to the kb96 lab data, we retrieved science data from December 2019 from the LCO archive. Figure 5 shows zero point versus magnitude relations for an example image. The upper-left panel shows the relation from the photometry determined directly from LCO's BANZAI data pipeline. The upper-right panel shows the relation derived independently by a software package that we use to monitor the throughput of LCO's telescopes. The data in the upper-right panel are noisier because the aperture photometry is less sophisticated than BANZAI, but the photometric nonlinearity is evident regardless of which software is used.

The kb96 data were modified by the inverse of the fitting function, i.e.

$$x = ((s + z)^k - z^k)^{\frac{1}{k}}$$

before performing the aperture photometry. Some pixels in the data had negative values (due to read noise and shot noise). We set those pixels to 0 to avoid computational errors.

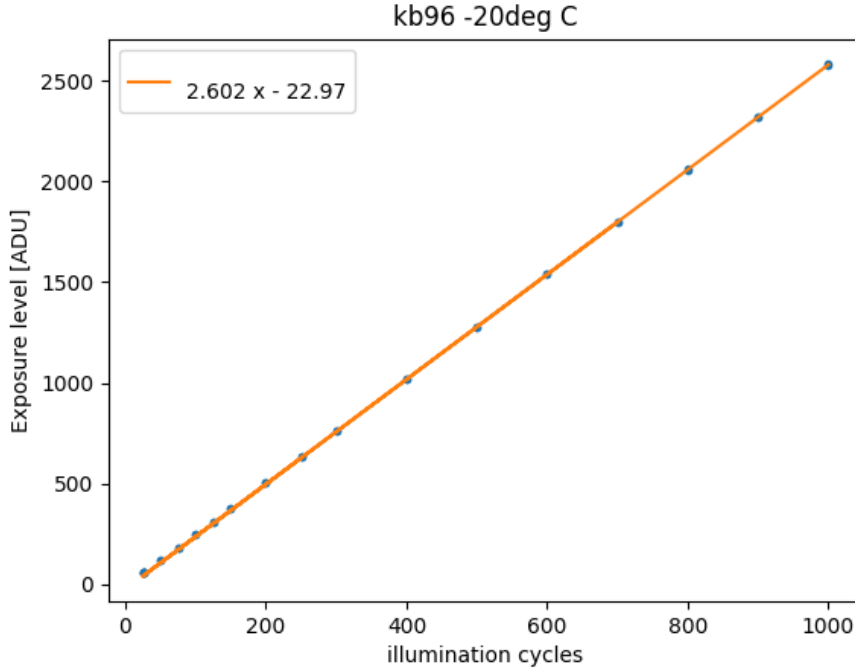


Figure 3. Relation between LED illumination cycles and exposure level measured by the camera.

The bottom panel of Figure 5 shows the zero point plot derived from the photometry of the transformed data. The trend in zero points is flat throughout the range of magnitudes. *This result demonstrates that the nonlinear response of the detector, measured at low light levels in the lab, can be used to correct the photometry of on-sky data from two years earlier.* At the fainter magnitudes, the zero points may even be too faint, suggesting that the data may be better corrected by a more complex function. However, for the brighter stars, the accuracy of the photometry is significantly improved.

4. PHOTOMETRIC NONLINEARITY CORRECTIONS FROM ARCHIVED DATA

In the preceding section, we demonstrated that, for a single camera, measurements made in the lab can be used to derive a function from which the science data can be corrected. We have started a program to make these measurements for other SBIG cameras (see Appendix A), to determine whether the method is generally applicable. However, it is an operational impracticality to recall all SBIG cameras in the network to LCO headquarters to measure the response curves. Also, LCO will begin replacing the SBIG cameras during 2022. Our plan is to test each camera after it is replaced in the network with a new instrument. In the meantime, we are investigating the applicability of nonlinearity corrections derived from the science data themselves.

As with the lab measurements, the goal is to determine, for each camera, the optimal values for z and k . We approach this goal systematically by transforming the data in each image by inverse fitting functions defined by a range of z and k values. (Pixels with negative values are set to 0. We acknowledge that this adjustment can bias the result.) Following each transformation, we perform the photometry and create a plot of zero points as a function of catalog magnitudes. We then fit a linear function to

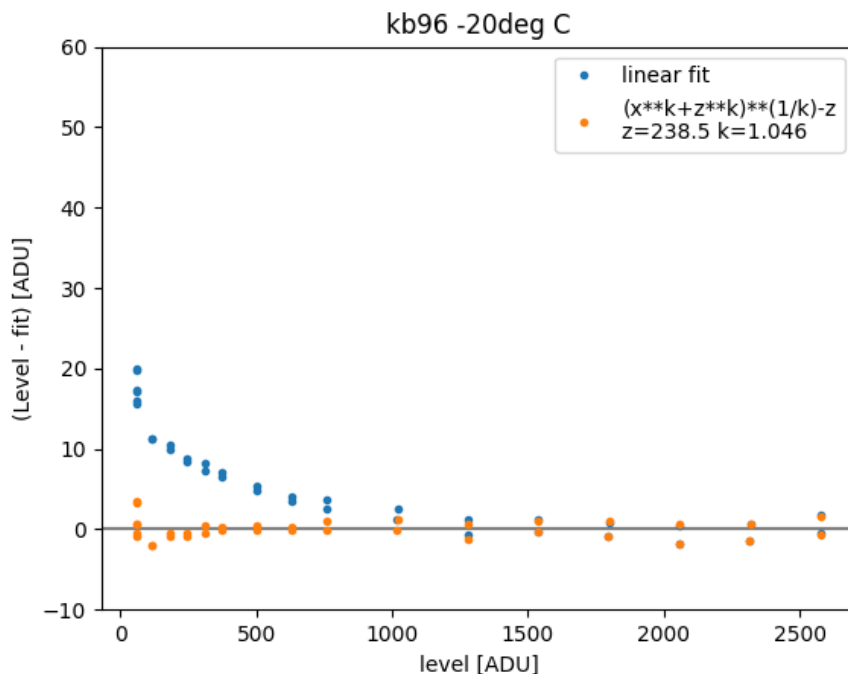


Figure 4. Residuals from a linear and non-linear fitting function to the LED exposure level / ADU relation from Figure 3.

the data from the brightest four magnitudes. The optimal values for z and k are those that minimize the absolute value of the slope in the final zero point plot. Figure 6 shows an example of steps in the procedure as applied to data from an image from the kb95 camera. The right panel shows the zero point plot after correction by the optimal linear fit. The slope of the corrected data is essentially zero, which suggests that the selected z and k parameters have mitigated the nonlinearity in the original data.

5. CONCLUSION

The purpose of this report is to encourage users to examine the photometry derived from their SBIG images carefully. We also want to reassure LCO users that, if their data are affected by photometric nonlinearity, improvement is possible. We acknowledge that this report has several limitations:

- The form of the function that we have adopted to fit to the data is not optimal, but it is sufficient for improving the photometry.
- An examination into the long-term stability of the parameters of the fitting function is in progress. At this point, we do not know whether the parameters we have determined are appropriate for correcting all data from the same camera.
- We have not yet analyzed data from all SBIG cameras. We have determined that different cameras exhibit the photometric nonlinearity with different severity, however we do not know what factors (camera age? warm-up/cool-down cycles? enclosure environment?) exacerbate the nonlinearity.

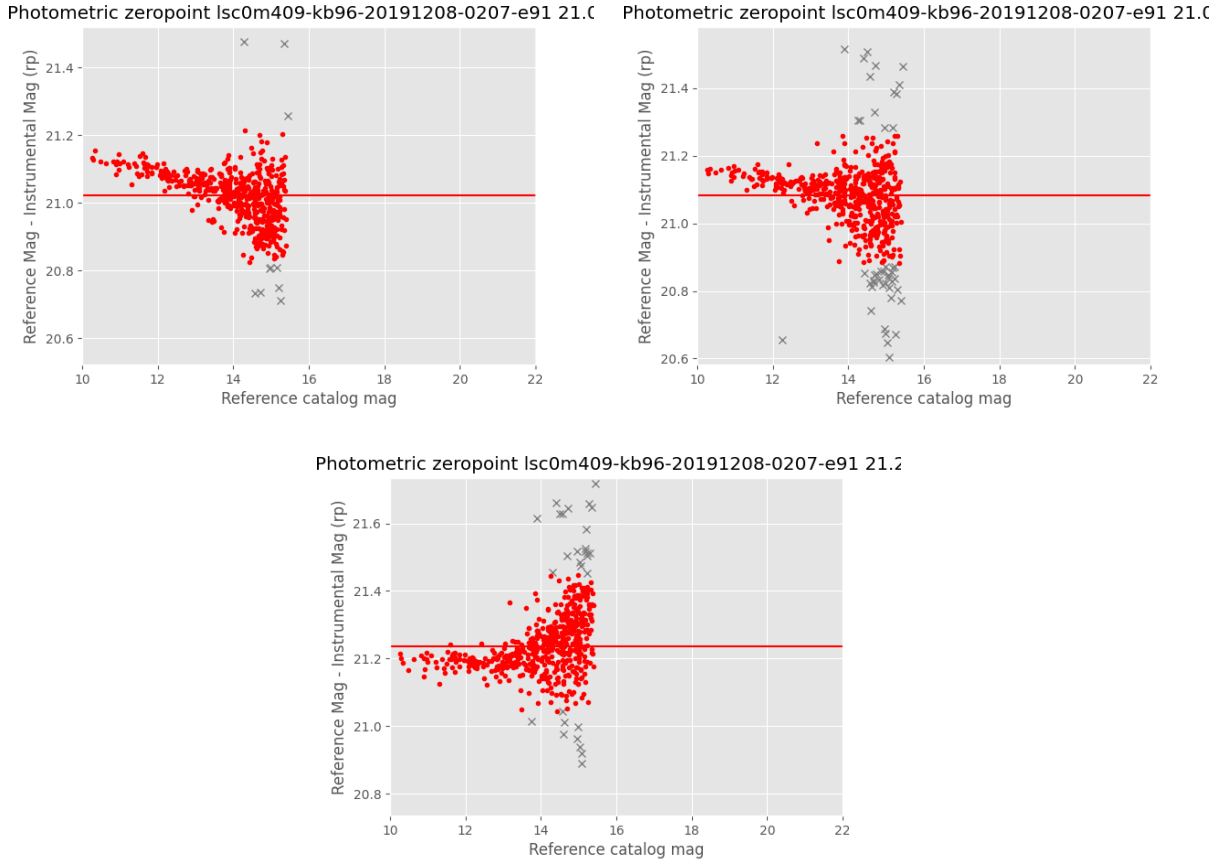


Figure 5. Top: BANZAI photometry (left) and forced aperture photometry (right) show the nonlinearity trend in the uncorrected data. Bottom: data are corrected for the lab-measured nonlinearity before aperture photometry, and the nonlinearity is mitigated.

We will add results from lab tests of other cameras to this report as we investigate them. Table 1 in Appendix A shows results from the tests of the SBIG cameras that we have completed so far.

LCO plans to replace all of the SBIG cameras and 0.4m telescopes in the network beginning in 2022. The new cameras will be tested for photometric nonlinearity before they are shipped. After the substitute make and model have been selected, the pace of the transition will be governed by the rate at which LCO’s engineering and instrument teams can travel to each site. During the transition, the network will include both new and old cameras.

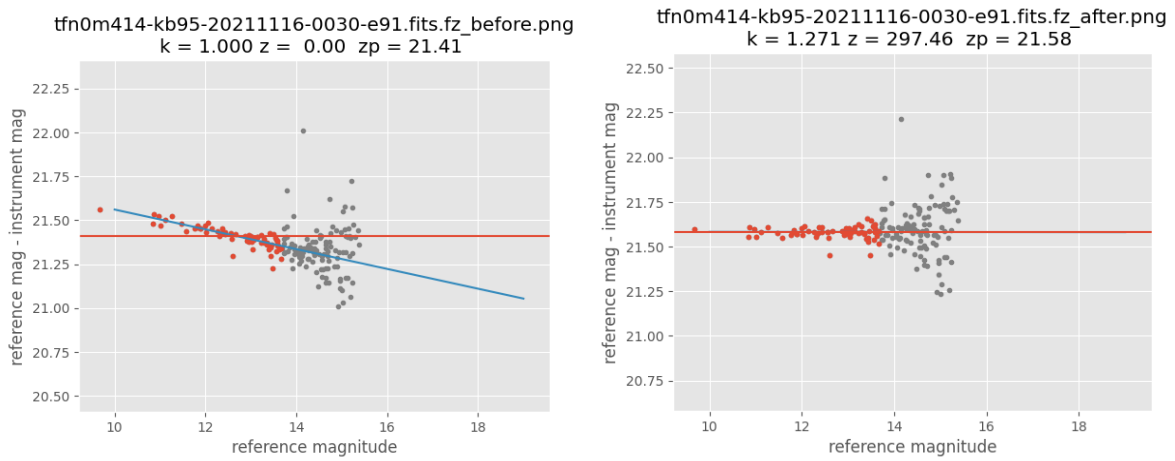


Figure 6. The photometric zero points versus catalog magnitude for stars in an image acquired with the kb96 camera. The exposure time was 10 s. In the left panel, the blue line is the best linear fit to the uncorrected data. In the right panel, the data have been corrected by a linear fit following the application of a fitting function with parameters $z = 297.5$ and $k = 1.37$.

APPENDIX A. SUMMARY OF CAMERA INVESTIGATIONS

Four cameras have been tested for photometric nonlinearity at low illumination levels in the LCO lab. The residuals from linear and nonlinear fits to the LED exposure levels to ADU relations are shown in Table 1.

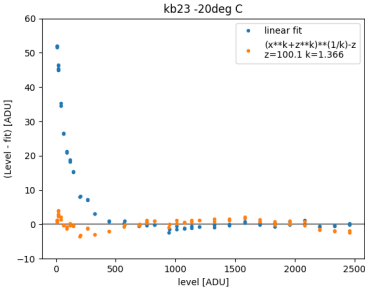
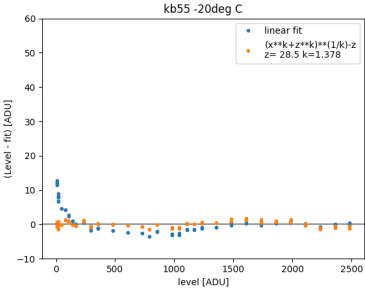
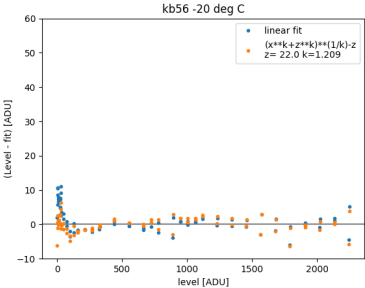
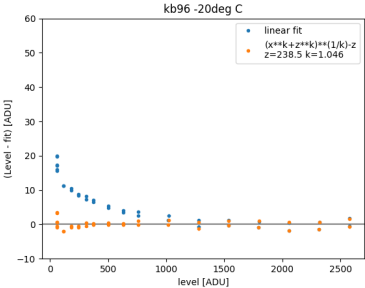
Camera	Residuals	k	z
kb23		1.366	100.1
kb55		1.378	28.5
kb56		1.209	22.0
kb96		1.046	238.5

Table 1. As in Figure 4, the residuals are determined by fitting linear (blue) and nonlinear (orange) functions to the LED exposure level / ADU relation. The k and z values are the exponents and offsets of the nonlinear functions.

APPENDIX B. IMPACT OF BINNING ON NONLINEARITY

Some users associated the onset of the photometric nonlinearity with the change from binned to unbinned readout mode in April 2018. However, we have identified examples of nonlinearity from when the cameras were operated in binned mode (see Figure 7). Binning pixels 2x2 increases the signal by a factor of 4, and therefore the background level increases more rapidly with exposure time from the nonlinear to the linear regime.

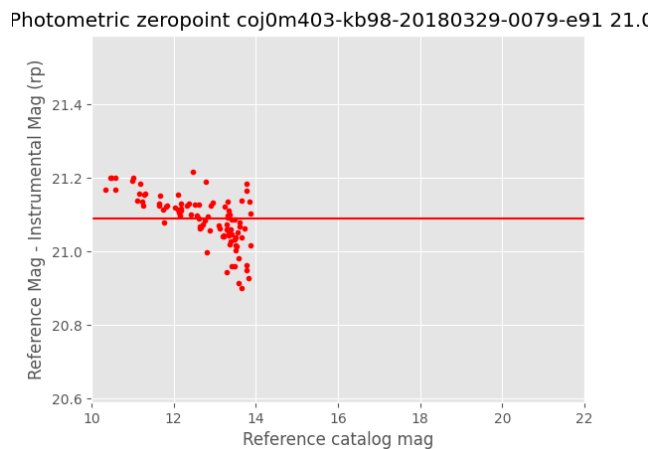


Figure 7. An example of photometric nonlinearity in a 2x2 binned image. The background level of the 2.8 s exposure is about $30 e^-$.