Performance Characterization of the Chromospheric Lyman-Alpha Spectro-Polarimeter (CLASP) CCD Cameras

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Abstract

The Chromospheric Lyman-Alpha Spectro-Polarimeter (CLASP) is a sounding rocket instrument which is currently being developed by NASA's Marshall Space Flight Center (MSFC) and the National Astronomical Observatory of Japan (NAOJ). The goal of this instrument is to observe and detect the Hanle effect in the scattered Lyman-Alpha UV (121.6nm) light emitted by the Sun's Chromosphere to make measurements of the magnetic field in this region. In order to make accurate measurements of this effect, the performance characteristics of the three on-board charge-coupled devices (CCDs) must meet certain requirements. These characteristics include: quantum efficiency, gain, dark current, noise, and linearity. Each of these must meet predetermined requirements in order to achieve satisfactory performance for the mission. The cameras must be able to operate with a gain of no greater than 2 e-/DN, a noise level less than 25e−, a dark current level which is less than 10e−/pixel/s, and a residual non-linearity of less than 1%. Determining these characteristics involves performing a series of tests with each of the cameras in a high vacuum environment. Here we present the methods and results of each of these performance tests for the CLASP flight cameras.

Dark Current

Dark current is a type of noise caused by thermally excited electrons being excited into the conduction band and registered by the CCD, even when no radiation is incident on the detector. These electrons are indistinguishable from the photo-generated electrons emitted when photons strike the detector. Because this is caused by thermally excited electrons, cooling the camera to low temperatures (<-20C) can help limit this noise. Another limiting factor is the exposure time of the camera; longer exposure times result in higher dark currents than shorter exposure times. The method we use for correcting this issue in our analysis is to take a series of "dark frames", or exposures with the cameras in dark environments. From this series of images, a "master dark" frame can be constructed by taking the mean pixel value, over the entire series, at each pixel position and compiling those into a single frame. This "master dark" frame (See Figure 1) is then made up of the dark current noise, fixed pattern noise, read noise, and bias. Subtracting this from each "light frame" in a series can remove most of the noise and allows for further analysis. Because the dark current depends on exposure time, it can be measured by taking dark frames at varying exposure times and plotting the intensity at those times. The slopes of the corresponding best fit lines is the DN/pix/s, while the y-intercept represents the bias in the frame. Figure 2 shows a plot of this, with the bias subtracted out. Multiplying the slopes of the individual sides by the respective gain value gives the dark current in e-/pix/s.

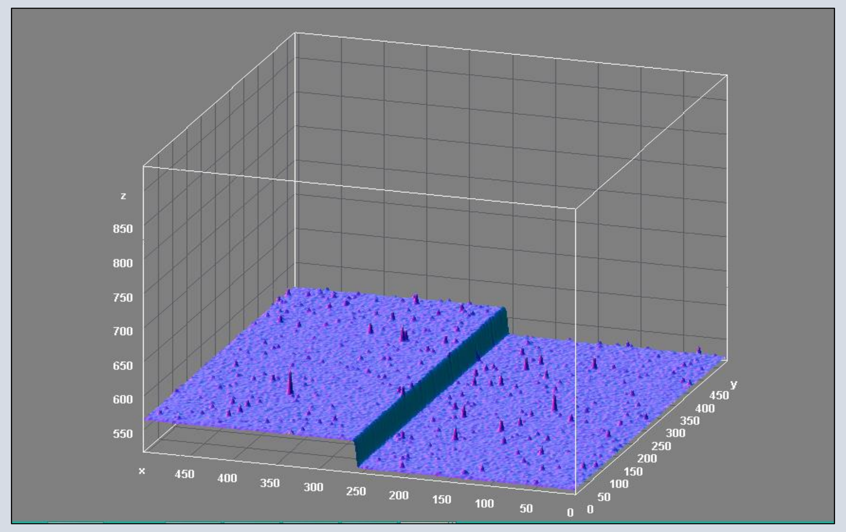

Figure 1: A sample "master dark" frame from a series of dark images take with 10 second exposures at a temperature of -20C. Also a good visual of the offset between the two sides.

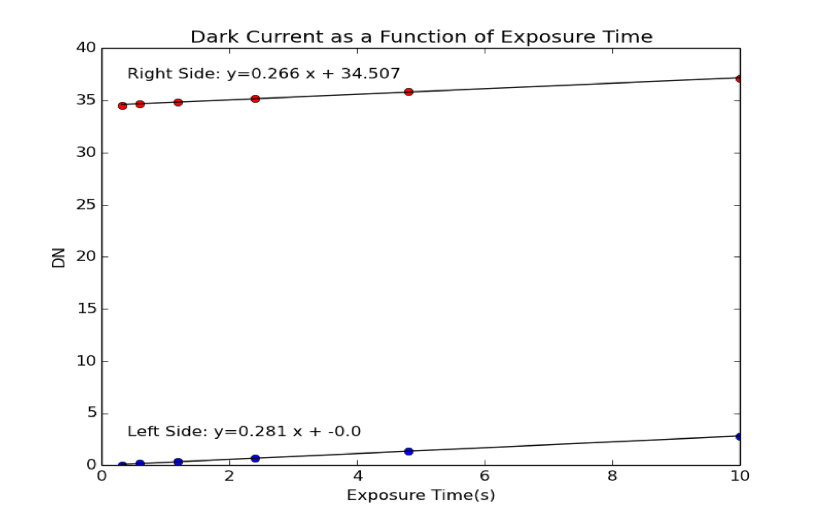

Figure 2: A plot of the Intensity in dark frames versus exposure time. The slope of the best fit lines represent the DN/pix/s, and the y-intercept represents the bias of the frame. For this plot, the bias has already been subtracted, and so the y-intercept of left side best fit line is set to zero while the y-intercept of the right side represents the offset between the two sides of the detector.

Read Noise

The read noise in an image is due in part to the read out electronics of the camera. Determining the read noise involves subtracting the master dark frame from a single dark image. The width of a Gaussian curve fit to the histogram of the remaining pixel values is the read noise. Multiplying this by the gain gives the total read noise electrons. Figure 7 shows an example of this read noise analysis.

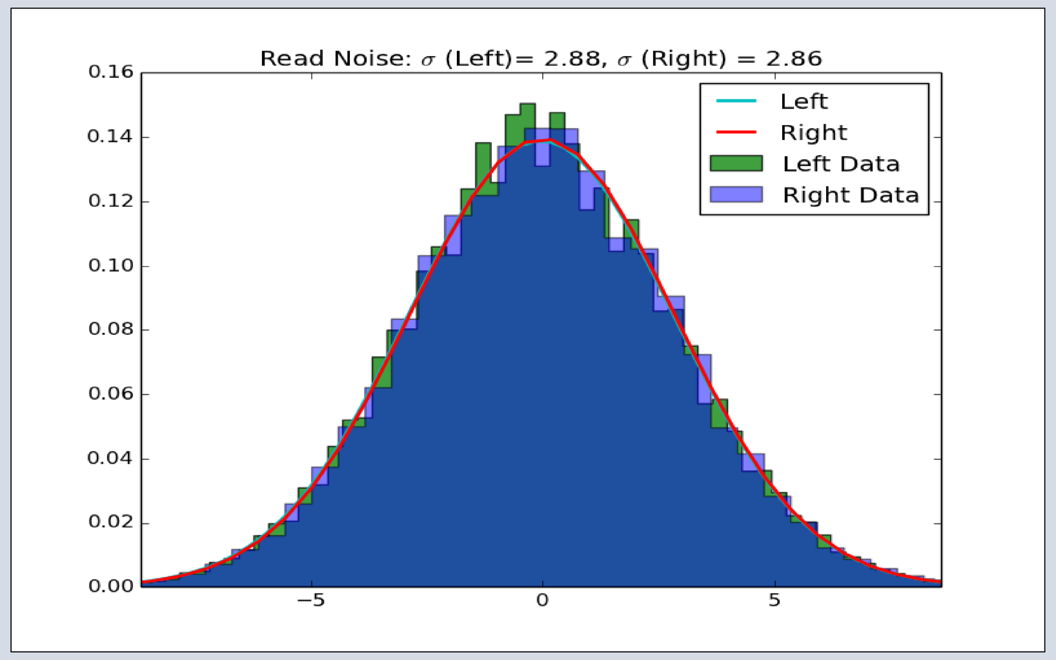

Figure 8: A histogram of the residual pixel values, after subtracting the master dark frame from a dark image. The values of 2.88 and 2.86 DN represent the read noise of the left and right side, respectively, of an image.

Camera Overview

The cameras to be used in the CLASP mission are three, dual readout CCD cameras. Each CCD is constructed of 528x560 pixels, with 12 leading and trailing pixels which are considered "dead" as they are unresponsive to photons hitting them. The two readout channels increase the readout speed of the CCD, however, small differences in the two readout channels cause an offset between the two sides of the CCD (See Figure 1), meaning that nearly all analysis must be done separately for the two sides. Each of the cameras were designed and built at MSFC allowing for easy modifications to the cameras as well as repairs if necessary.

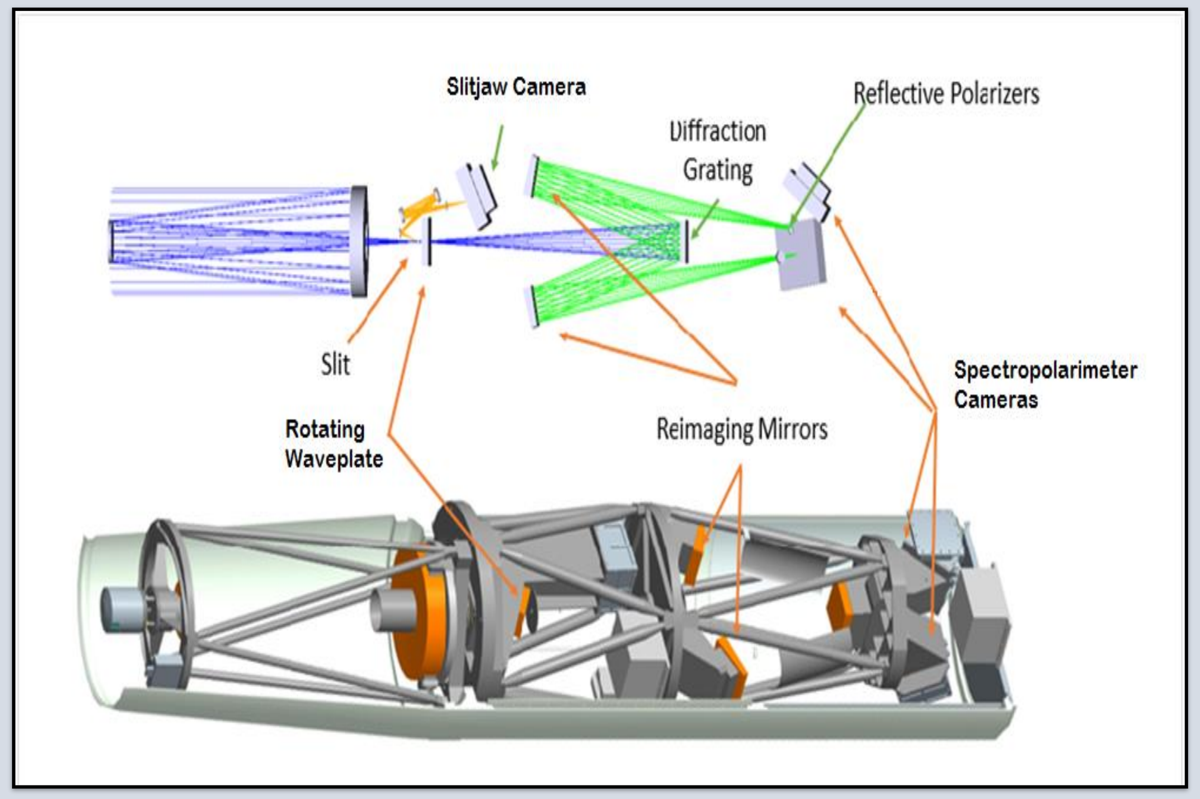

Figure 6: Diagram of the CLASP instrument showing the locations of the three CCD cameras. The instrument consists of a cassegrain telescope, which collects light and, through a series of mirrors and gratings, projects it onto the faces of the cameras.

Gain

The gain of the CCD is the conversion factor between DN and electrons. The gain for these cameras is determined using an x-ray emitting ^{55}Fe source, as the $^{55}FeMn\ K_{\alpha,\beta}$ lines produce a number of electrons which is proportional to their energies. This sample is placed in front of the camera which detects the incoming x-rays. These are registered as extremely bright pixels, or "hits" .After subtracting out the dark current, a hit finding program is run over the series of images. Sometimes, there can be multi-pixel hits which are not recorded.

However, if the hits occur over the region of a single pixel, then the hits are stored. Fitting a Gaussian to a histogram of these values produces plots like those seen in Figures 9 and 10. This gain is returned parameter of the fitting function.

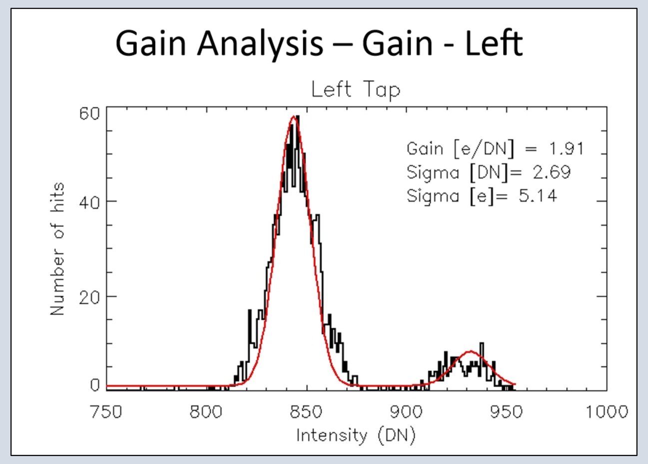

Figure 9: Left side gain plot

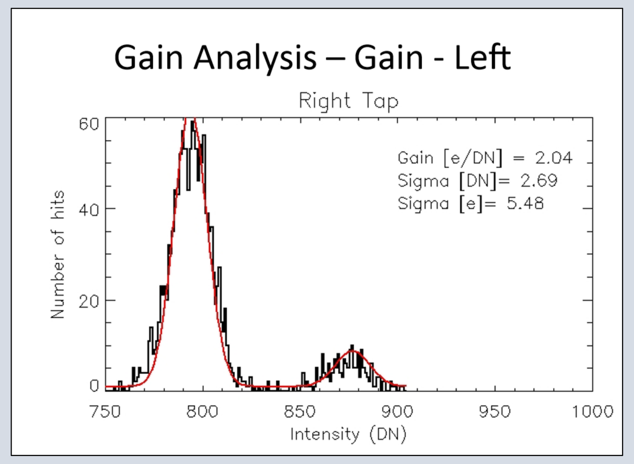

Figure 10: Right side gain plot

Quantum Efficiency

Quantum efficiency (QE) is the ratio of photons incident on the detector to the photons which are actually detected. Ideally, this ratio would be a 1:1 relationship, however this is not the case. Because the wavelength of the Lyman-α line is relatively short (121.6nm) the quantum efficiency of the cameras at this wavelength would normally be very small. However, a Lumogen coating has been added to the CCDs. This coating absorbs photons in the UV range and reemits them in the visible region, where the CCD is more sensitive [1] which greatly improves the quantum efficiency. The number of photons which are detected at each pixel over a certain time can be determined by assuming that for each photon detected at the CCD, a single electron is generated. Using series of light and dark images the number of electrons per pixel is found. This is done by creating a master dark frame which is subtracted from all images. Then, from what's left of the light exposed images, a master light image (See Figure 11) is created. The number of electrons per pixel is determined from this images using the gain for each side of the detector. The result of this process should be equal to the number photons per pixel. To find the photons incident on the CCD, a photodiode is placed directly in front of the CCD, and the same light (121.6nm) and dark data is taken. The photodiode current can be converted to photons/area in the same process mentioned above. Comparing these values produces a value for the QE.

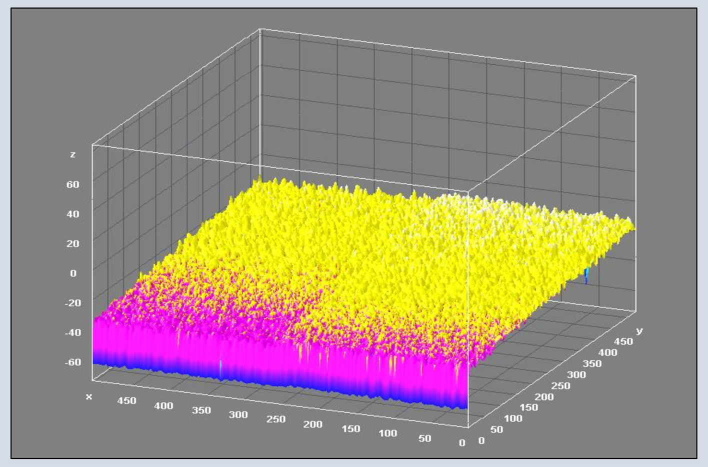

Figure 11: A sample master light image, produced from a series of data with the camera illuminated with Lyman-α light.

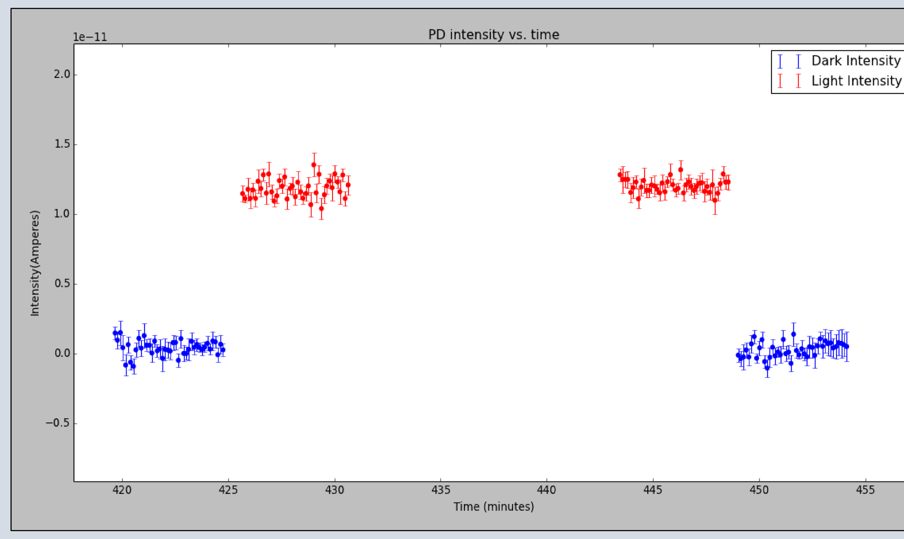

Figure 12: A plot of the photodiode current versus time, showing the stability in the intensity of the light hitting the detector throughout both light and dark series.

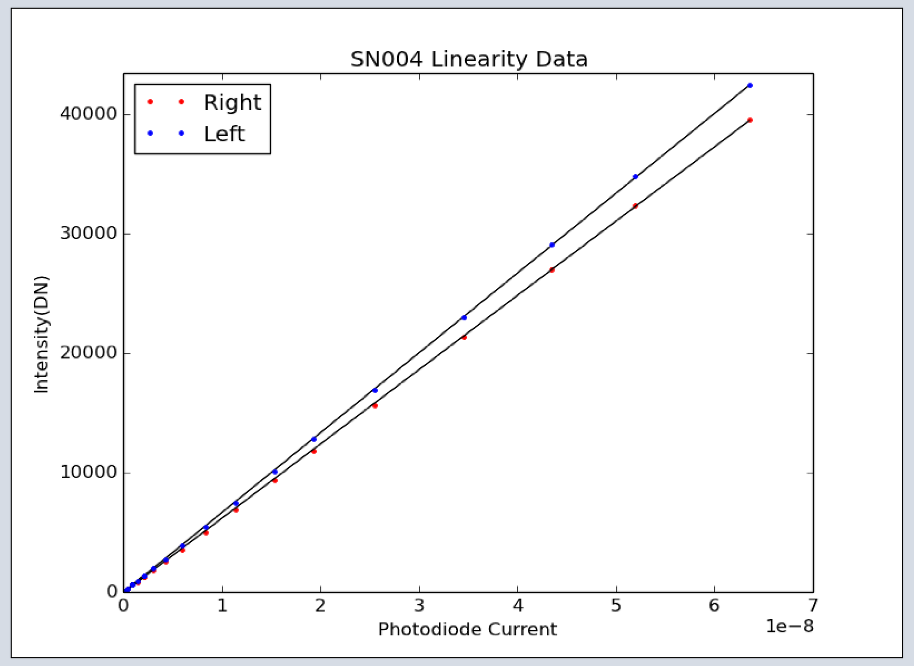

Figure 3: Linearity data from the first of the three on board cameras, showing the difference in linearity for the left and right sides of the CCD.

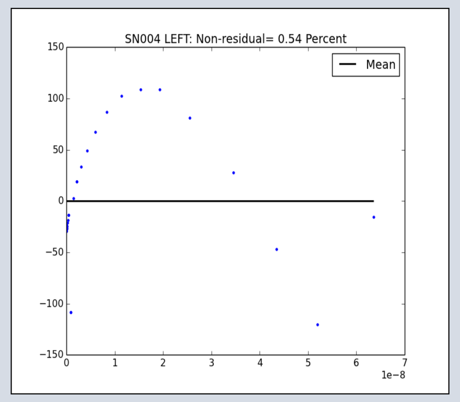

Figure 4: Non-residual plot for left side of CCD

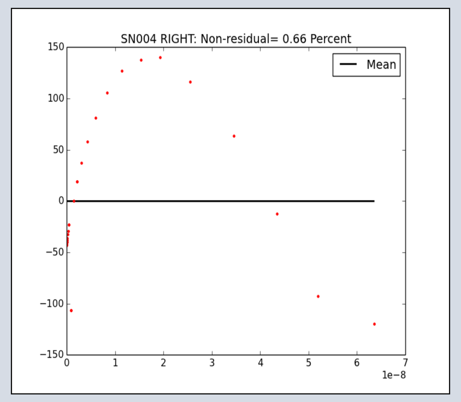

Figure 5: Non-residual plot for right side of CCD

Linearity

This test measures how well the device responds to different intensities of light. Ideally, the number of electrons read out by the CCD should be linearly related to the intensity of the light hitting the detector. To measure this feature of the cameras, an LED, with an adjustable intensity is used to illuminate the CCD. A series of images are then taken, as well as photodiode data, for different LED voltages. The non-residual linearity can be determined by plotting the DN (from the image series) versus the photodiode current for the different intensities. Subtracting these values from the best fit line gives the residual DN, and the non-residual linearity can be calculated from Equation 1 below.

$$Non-Residual\ Linearity(\%) = \left[\frac{(\sigma_+ + \sigma_-)}{I_{max}}\right] \times 100 \quad \boldsymbol{EQ.1}$$

Where σ_+ is the maximum positive deviation from the best fit line, σ_- is the maximum negative deviation from the best fit line, and I_{max} is the maximum pixel intensity.

Future work

One of the things in determining the characteristics of these cameras which needs to be addressed is the QE measurement. The problem, at the moment, is the gradient in intensity in the light images (See Figure 11). One possible way to fix this would be to add a mask to the photodiode and just perform the QE analysis over a portion of the CCD. Besides better QE measurements, different features of the cameras could also be measured with the data already taken, for example the charge-transfer efficiency (CTE), temperature dependency and performance, etc. Fortunately, most of this is already possible with the data collected for measuring the characteristics detailed here.

Results

The results of the camera testing thus far :

Camera	Expectation	SN04 (Left/Right)	SN05 (Left/Right)	SN06 (Left/Right)
Gain (e-/DN)	<2.0	1.91/2.04	--	--
Dark Current (e-/s)	<10	0.53/0.54	--	--
Read Noise (e-)	<25	5.5/5.8	--	--
Linearity (Non-Residual)	<1%	0.5%/0.6%	--	--
QE	--	15.7%/15.5%	--	--

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Acknowledgements and References

Dunlap, J.C., 2010, *Exposure Time Dependence in CCD Imagers,* IEEE T ELECTRON DEV

Janesick, J.R., 2001, *Scientific Charge-Coupled Devices*, SPIE Publications

Kano, R.et al., 2012, *Chromospheric Lyman-alpha Spectro-Polarimeter(CLASP)*, SPIE

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