



# 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 currently being developed by NASA's Marshall Space Flight Center (MSFC), the National Astronomical Observatory of Japan (NAOJ), and other partners. 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. The polarized spectrum imaged by the CCD cameras will capture information about the local magnetic field, allowing for measurements of magnetic strength and structure. 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, read 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  $2.0 \pm 0.5$  e-/DN, a read noise level less than  $25e^-$ , a dark current level which is less than  $10e^-/\text{pixel}/s$ , 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.

## Camera Overview

The three cameras developed for the CLASP mission (Figure 1) are 512x512m dual read out, frame transfer CCD cameras. 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.

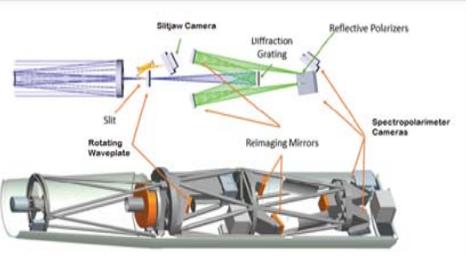


Figure 1: Diagram of the CLASP instrument showing the locations of the three CCD cameras. The instrument consists of a Cassegrain telescope and a spectrograph. One CCD camera is used to image the slitjaw, while the two others image the polarized spectra of Lyman-Alpha.

## Gain

The gain of the CCD is the conversion factor between DN and electrons. The gain for these cameras is determined using an Fe55 isotope as an x-ray emitting source. The photons produced by the source generate a specific number of electrons that are proportional to the photon energies. The sample is placed directly in front of the camera which detects the incoming x-rays as extremely bright pixels, or "hits". After subtracting out the dark current, a hit finding program is run over the series of images. A pixel mask is applied to prevent the inclusion of false hits. Single pixel events are recorded and stored. Fitting a sum of four Gaussians to a histogram of these detected hits produces plots like those seen in Figures 2 and 3. The gain is returned parameter of the fitting function.

## Gain Analysis - Gain - Left

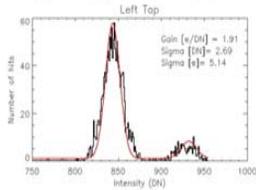


Figure 2: Right side spectrum

## Gain Analysis - Gain - Right

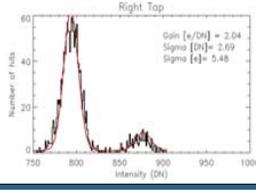


Figure 3: Left side spectrum

## 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 the Gaussian curve, fit to the histogram of the remaining pixel values is the read noise (Figure 6). Multiplying this by the gain gives the total read noise in electrons.

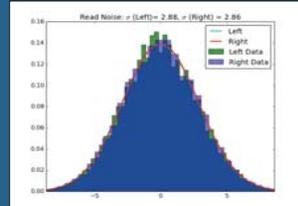


Figure 6: A histogram of the residual pixel values, after subtracting the master dark frame from a dark image. The values of 2.88 and 2.86 DN represent the read noise of the left and right side, respectively.

## Dark Current

Dark current is a type of noise caused by electrons being thermally 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 4) is then made up of the dark current noise, fixed pattern 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 dark current rate (DN/pix/s), while the y-intercept represents the bias in the frame. Figure 5 shows the average dark intensity plotted versus exposure time. Multiplying the slopes of the best fit lines for the individual sides by the respective gain value results in the dark current rates of the two sides.

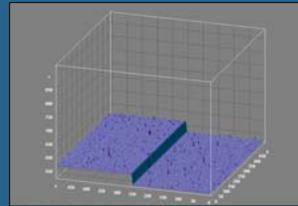


Figure 4: A sample "master dark" frame from a series of dark images take with 10 second exposures at a temperature of  $-20C$ . Also a good visual of the offset between the two sides.

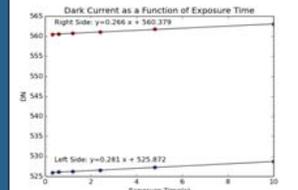


Figure 5: A plot of the Intensity in dark frames versus exposure time. The slope of the best fit lines represent the DN/pix/s, and the y-intercept represents the bias of the frame.

## Quantum Efficiency (1)

Quantum efficiency (QE) is the ratio of the photons detected to the number of photons incident on the camera. The cameras were built using commercial, off the shelf CCDs with anti-reflection coatings that block UV light. Therefore they were coated with Lumogen to regain this sensitivity. This coating absorbs photons in the UV range and reemits them in the visible region, where the CCD is more sensitive which greatly improves the quantum efficiency. The number of photons 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. A deuterium lamp and a monochromator are used to produce Lyman- $\alpha$  light for this test. Using a 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 10) 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 calibrated by NIST 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. However, we discovered the light source was not uniform (note the gradient in the light image in Figure 10), meaning the average number of photons incident on the CCD was not necessarily the same as the photons incident on the photodiode.

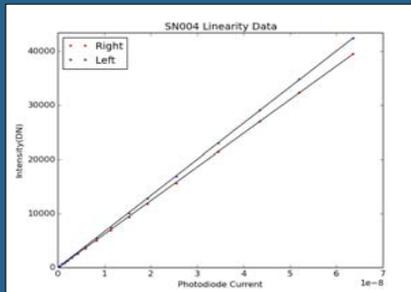


Figure 7 Linearity data from the first of the three on board cameras, showing the difference in linearity for the left and right sides of the CCD.

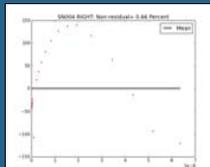


Figure 8: Residual plot for left side of CCD

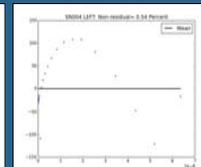


Figure 9: Residual plot for right side of CCD

## 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 currents. The residual non-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 residual non-linearity can be calculated from Equation 1 below.

$$Non - Linearity(\%) = \left[ \frac{\sigma_r + \sigma_l}{I_{max}} \right] \times 100$$

Where  $\sigma_r$  is the maximum positive deviation from the best fit line,  $\sigma_l$  is the maximum negative deviation from the best fit line, and  $I_{max}$  is the maximum pixel intensity.

## Results

Camera	Goal	SN04 (Left/Right)	SN05 (Left/Right)	SN06 (Left/Right)
Gain (e-/DN)	$2.0 \pm 0.5$	1.92/2.04	1.94/2.03	1.88/1.90
Dark Current (e-/pix/s)	$<10$	0.4/0.3	0.3/0.1	0.5/0.4
Read Noise (e-rms)	$<25$	5.3/5.6	5.5/5.6	5.6/5.4
Residual Non-Linearity	$<1\%$	Requirement Met	Requirement Met	Requirement Met
QE	30%	$12.1 \pm 1.5\%$	$20.0 \pm 2.5\%$	$20.0 \pm 1.9\%$

## Quantum Efficiency (2)

We added a mask (a piece of metal with small hole drilled into the center) to the test system. This restricted the number of photons incident on the photodiode and CCD. We then calculated a correction factor to the QE to account for the non-uniformity of the beam. We calculated the correction factor with a prototype camera, as all science cameras had been delivered and integrated. The QE of each camera is given in the results table. The two SP cameras have a QE of 20%, less than published for Lumogen coating (20% at 121 nm). After discussions with the manufacturer, it was determined that the published QE of Lumogen at 121 nm was in error.

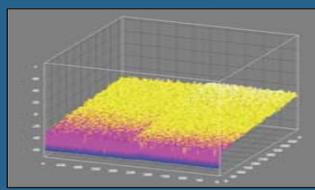


Figure 10: A sample master light image, produced from a series images with Lyman- $\alpha$  illumination

## Acknowledgements and References

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