Performance characterization of UV science cameras developed for the Chromospheric Lyman-Alpha Spectro-Polarimeter

Champey, P.[a,b] Kobayashi, K.[b] Winebarger, A.[b] Cirtain, J[b] Hyde, D.[b] Robertson, B.[b] Beabout, D.[b] Beabout, B.[b] and Stewart, M.[a]

[a]University of Alabama in Huntsville, Huntsville, AL, United States
[b]NASA Marshall Space Flight Center, Huntsville, AL, United States

ABSTRACT

The NASA Marshall Space Flight Center (MSFC) has developed a science camera suitable for sub-orbital missions for observations in the UV, EUV and soft X-ray. Six cameras will be built and tested for flight with the Chromospheric Lyman-Alpha Spectro-Polarimeter (CLASP), a joint National Astronomical Observatory of Japan (NAOJ) and MSFC sounding rocket mission. The goal of the CLASP mission is to observe the scattering polarization in Lyman-α and to detect the Hanle effect in the line core. Due to the nature of Lyman-α polarization in the chromosphere, strict measurement sensitivity requirements are imposed on the CLASP polarimeter and spectrograph systems; science requirements for polarization measurements of Q/I and U/I are 0.1% in the line core. CLASP is a dual-beam spectro-polarimeter, which uses a continuously rotating waveplate as a polarization modulator, while the waveplate motor driver outputs trigger pulses to synchronize the exposures. The CCDs are operated in frame-transfer mode; the trigger pulse initiates the frame transfer, effectively ending the ongoing exposure and starting the next. The strict requirement of 0.1% polarization accuracy is met by using frame-transfer cameras to maximize the duty cycle in order to minimize photon noise. Coating the e2v CCD57-10 512x512 detectors with Lumogen-E coating allows for a relatively high (30%) quantum efficiency at the Lyman-α line. The CLASP cameras were designed to operate with $\leq$10 e$^-$/pixel/second dark current, $\leq$25 e$^-$ read noise, a gain of 2.0$\pm$0.5 and $\leq$1.0% residual non-linearity. We present the results of the performance characterization study performed on the CLASP prototype camera; dark current, read noise, camera gain and residual non-linearity.

Keywords: Characterization, CCD, EUV, Sounding Rocket

1. INTRODUCTION

The Chromospheric Lyman-Alpha Spectro-Polarimeter (CLASP) is a sounding rocket instrument that is currently in the testing and integration phases. The National Astronomical Observatory of Japan (NAOJ) and the NASA Marshall Space Flight Center (MSFC) collaborated in building, testing and calibrating the CLASP instrument.

The purpose of CLASP is to measure the linear polarization profiles caused by scattering processes and the Hanle effect in the Lyα line. The magnetic field information will be obtained from the measured Q/I and U/I profiles themselves and mainly through detailed radiative transfer modeling of the observed Lyα intensity and polarization using the most advanced magnetohydrodynamic models of the solar atmosphere. This will provide, for the first time, a diagnostic tool for magnetic field measurements in the upper chromosphere and transition region.

The CLASP instrument consists of a Cassegrain telescope, optimized for reflecting Ly-α line (121.6 nm), a slit jaw imager and the spectro-polarimeter. The spectro-polarimeter produces two spectra simultaneously (corresponding to two orthogonal polarization states). It consists of a slit, polarization modulation unit (PMU), diffraction grating, two reimaging mirrors, two polarization analyzers, and two cameras. The spectro-polarimeter

Further author information: (Send correspondence to Patrick Champey)
Patrick Champey: E-mail: patrick.r.champey@nasa.gov, Telephone: 1 215 378 9657
Ken Kobayashi: E-mail: ken.kobayashi-1@nasa.gov, Telephone: ()

uses a rotating 1/2 waveplate, which allows for measurement of both Stokes Q and U with fixed polarization analyzers. The rotation of the waveplate sends simultaneous trigger pulses to the spectrograph and polarization analyzer cameras to initiate frame transfer, effectively ending an exposure and beginning the next. The trigger pulses will be sent to the cameras every .3 seconds, and a total of 16 pulses will be sent for every rotation of the waveplate. The polarization produced by the Hanle effect in Ly-α is expected to be on the order of 0.1%. Therefore the two cameras must be synchronized to a high accuracy and optimized for precision and stability.

The strict science requirements impinged on the CLASP cameras require a complicated design and a demanding development process. For this reason, the Heliophysics Instrument Group at the Marshall Space Flight Center deemed it necessary to develop the CLASP camera in-house. While the CLASP camera design is the first developed at MSFC, it's stabe, low-noise performance and high-speed operation demonstrates MSFC's ability to develop precision science cameras suitable for sub-orbital UV, EUV and X-ray observations. Below we discuss a series of tests performed on the CLASP laboratory prototype camera, which characterize key parameters of the the camera's performance.

2. PERFORMANCE CHARACTERIZATION

The CLASP mission requires a stable gain (2.0+-0.5 e^-/DN), low dark current ($\leq$ 10 e^-/pix/sec) and low read noise ($\leq$ 25 e^-) to facilitate sensitive measurements of Lyα polarization modulation. Meeting the low dark current requirement will be achieved by actively cooling the CCD to 253 K (-20 °C). The CCD has a thermal strap connected to a copper cold block, which is housed in the camera chassis and will be cryogenically cooled with liquid nitrogen. However, the prototype version of the CLASP camera was assembled for laboratory testing and therefore does not have the capability to be cryogenically cooled. Consequently, prototype camera testing was performed in a thermal chamber, purged with gaseous N_2, at atmospheric pressure. The thermal chamber provided enough flexibility to run a number of tests with the camera stabilized at different temperatures.

The e2v CCD57-10s used in the CLASP cameras operates in frame transfer mode, which allows for continuous exposure without the use of a shutter. These CCD57-10s are normally 512×512 detectors, but they have additional active and nonactive pixels, which produce 528×560 frames. Because of the high cadence requirement for measuring polarization modulation, the camera has two readout channels, which allows the CCD to be read out effectively twice as fast as single channel readout. Reading the CCD with two separate channels produces slight differences in background intensity (DC bias and dark current) and in the gain. This can be seen in a typical dark frame, e.g. figure 1. In dark conditions, there is a visible difference between the left half and right half of the detector: the background intensity of the two halves are slightly offset. These slight offsets in the detector are caused by minute differences in the performance of the two mirrored analog chains. This offset is present in each CLASP camera, but the magnitude of the offset varies from camera to camera. Given this behavior, it is required that the CCD be treated as two detectors in the sense that both halves have different performance characteristics. Analysis of data taken during characterization tests was completed for the two sides of the detector independently.

2.1 Dark Current & Read Noise

The dark current and read noised were measured at a range of CCD temperatures from 268 K to 297 K (-5 °C to 24 °C). 300 dark frames were captured at each temperature, while the CCD temperature was monitored by an RTD attached to the CCD mount. Master dark frames were generated for each data set by calculating the mean pixel value at each pixel position then constructing a 528×560 frame with these mean pixel value. Pixel masks were also generated to ignore defective pixels or columns. The calculated mean for each pixel is the sum of the DC bias, dark current, read noise and fixed pattern noise. Averaging over the left and right halves of the detector eliminates read noise and fixed pattern noise, leaving the average DC bias and dark current. For each side of the detector, the average of the 528 by 268 region was calculated and plotted versus RTD temperature. A fitting routine calculated the average dark current rate and the DC bias in DN using this function:

$$< j_{d+B} >= B + 2.55 \times 10^{15} t_{exp} A_{pixel} D_{FM} T^{1.5} e^{-E_g/2kT} \tag{1}$$

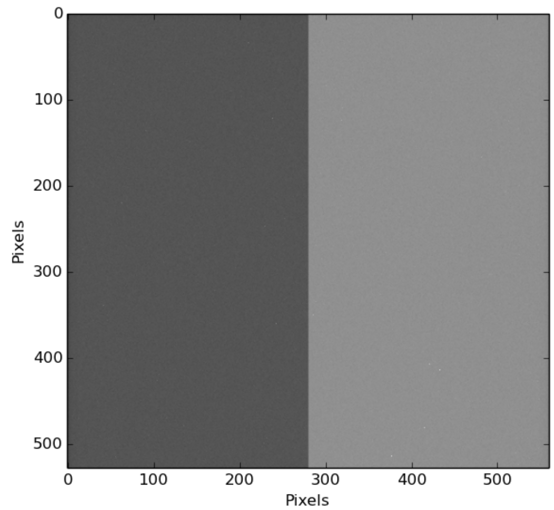

Figure 1: A sample dark frame taken at 268 K. The offset in the background is due to the two independent read out channels having different DC biases.

where B is the DC bias, A_{pixel} is the pixel area of the detector, D_{FM} is the dark current figure of merit, T is the temperature of the CCD, E_g is the bandgap energy of Silicon, and k is Boltzman's constant in eV. The DC bias and dark current figure of merit terms were free parameters calculated by the fitting routine. The DC bias was determined to be 538 DN and 603 DN, while the dark current figure of merit was calculated at 0.030 nA/cm^2 and 0.027 nA/cm^2 for left and right sides respectively.

The average dark current in electrons per second was calculated by subtracting the DC bias from the left side of equation 1, then multiplying by the gain of the camera and dividing by the effective exposure time:

$$\left\langle \frac{dj_d}{dt} \right\rangle = (< j_d > -B) * G/t_{exp} \tag{2}$$

At -5 C, we calculated a dark current of 41 e$^-$/pix/sec for both left and right sides of the detector (refer to figure 2). Solving equation 1 for the flight set temperature of -20 °C, and applying equation 2 yields a dark current of 7.1 e$^-$/pix/sec and 6.5 e$^-$/pix/sec for left and right sides respectively.

The read noise in a camera accounts for the random distribution of noise introduced by the pre-amplifiers and readout electronics. The CLASP camera requirement is a read noise $\leq$25 e$^-$ RMS. Read noise is measured by subtracting the master dark frame from a typical dark frame, then calculating a histogram of the residual pixel values. The histogram is fitted with a Gaussian function, and the width of that Gaussian is the read noise of the camera. Figure 3 is the fitted histrogram of the left and right sides of the CCD. The read noise of the prototype was calculated at 6.07 e$^-$ rms and 6.01 e$^-$ rms for the left and righ sides of the CCD.

2.2 Gain

A 0.25 mCi ^{55}Fe X-ray source was used to measure the gain of the CCD and electronics chain. ^{55}Fe Mn $K_{\alpha,\beta}$ lines produce a number of electrons proportional to their energies when absorbed by silicon. The gain is determined by the location of the Mn $K_{\alpha,\beta}$ lines in the histogram of total ^{55}Fe X-rays detected. In the thermal chamber, the ^{55}Fe source was placed a few centimeters directly in front of the CCD. For each measurement, at least 1000 exposures were captured, so that a large sample of ^{55}Fe hits were detected.

In the analysis of ^{55}Fe data, bias and dark current were subtracted from each frame. The same method described above was used to generate master dark frames for ^{55}Fe data. We again made use of a pixel mask that

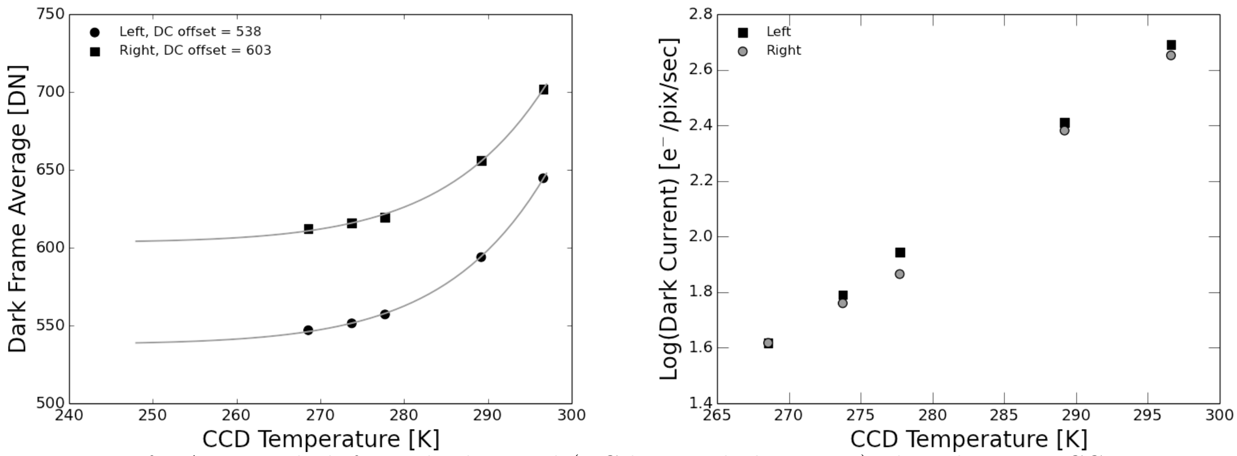

Figure 2: Left: Average dark frame background (DC bias + dark current) plotted against CCD temperature. The two trends are offset by the difference in DC bias between the left and right sides of the CCD. Right: The log of the calculated dark current rate plotted against temperature.

identified defected pixels or columns. Those pixels were ignored in the analysis of ^{55}Fe data to eliminate false detection of ^{55}Fe photons.

A ^{55}Fe hit finding routine was run on the background subtracted data to find and record single pixel hits. When ^{55}Fe photons are absorbed by the detector, it is often the case that the energy from the incident photon is spread out and absorbed by multiple pixels, a phenomenon known as charge spreading. During this process, some energy is lost in the system and efficiency of electron-hole pair generation is reduced. Single pixel hits experience minimal energy loss from charge spreading, which suggests a greater efficiency of electron-hole pair generation. We define single pixel hits as ones where all the adjacent pixels have intensities less than 3σ. A histogram of the ^{55}Fe single pixel hits was calculated and fitted with a Gaussian function (refer to figure 3). The gain was a returned parameter of the fitting routine along with the centroid and width of the Gaussian fit. The

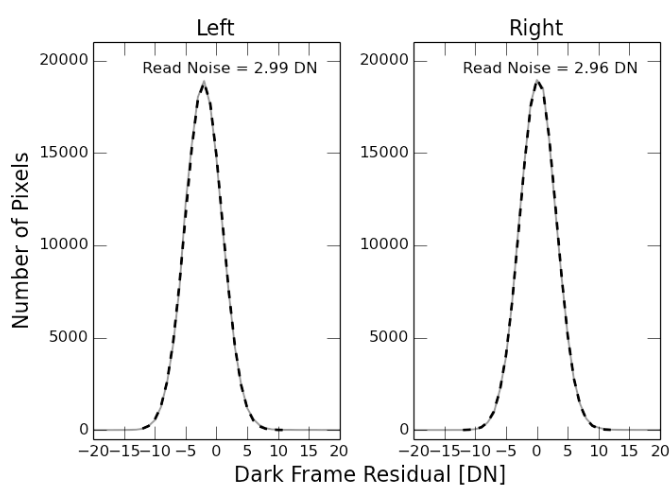

Figure 3: The residual of a background subtracted image, fitted with a Gaussian function. The width of the Gaussian function is the read noise.

measured gain of the CLASP prototype camera was 2.03 on the left tap and 2.03 on the right tap; both taps are within the required range of gain for CLASP (2+-0.5).

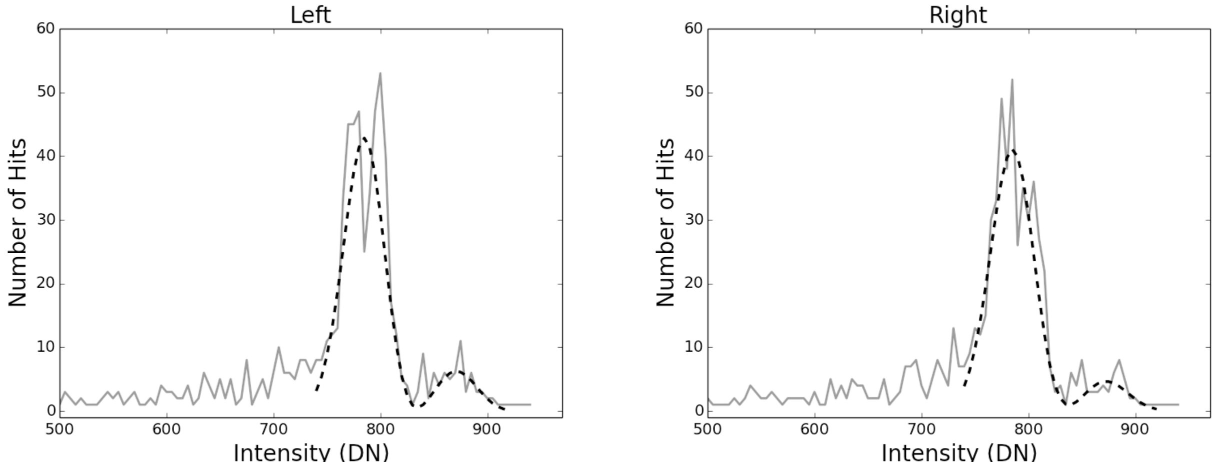

Figure 4: Histogram of single pixel hits from ^{55}Fe photons. The primary peak is the distribution of K_α lines and the secondary peak is the distribution of K_β lines. The Gaussian function fitted to the data is the sum of four Gaussian distributions, which represent the two dominating photon energies at the K_α and K_β peaks respectively.

2.3 Linearity

CCDs are suitable for science imaging for a number of reasons: one significant reason is that CCDs are linear devices. The electronic output of a CCD is directly proportional to the photonic flux absorbed by the CCD. Despite this inherent property, the linear response of CCDs varies from device to device, and camera to camera. It is necessary that good science imagers have a low percentage of non-linearity over a dynamic range of photonic flux intensities. The CLASP cameras require a residual non-linearity of $\leq$1.0% for accurate polarization measurements.

The linearity of a detector can be measured using standard flat fielding techniques. One popular flat fielding method is to image a uniformly illuminated scene at a series of exposure times, then plot the average image background vs. exposure time. This method, although straight forward, was not an ideal method for testing the CLASP camera because the prototype model had a fixed exposure time. As an alternative, we implemented a configuration that made use of a variable output LED. A red ($\lambda \approx 630$ nm) LED and white frosted glass provided a uniform beam, which illuminated the CCD. The output intensity of the LED was controlled via fine adjustment of the input voltage (ΔV = 0.05), allowing the camera to expose from near dark levels, up to full saturation. A photodiode was placed next to the CCD to measure relative incident photon flux by reading the output current via picoameter.

Residual non-linearity calculated by taking the ratio of the peak-to-valley deviation from the regression line, to the maximum intensity recorded in the dataset:

$$Non-Linearity(\%) = [(\sigma_+ + \sigma_-)/I_{max}] \times 100 \tag{3}$$

where $\sigma_{+,-}$ is the maximum positive and maximum negative deviation from the regression line and I_{max} is the maximum intensity fitted with the regression line. Figure 4 shows the average DN plotted against the photodiode current (left subplot) and the residual in DN plotted against the log of the average intensity (right subplot).

Applying equation 3 to the data from the left and right sides of the detector yielded residual non-linearity of 0.045% and 0.197%, respectively. This suggests that the prototype is well within the CLASP camera requirement of $\leq$1.0% residual non-linearity.

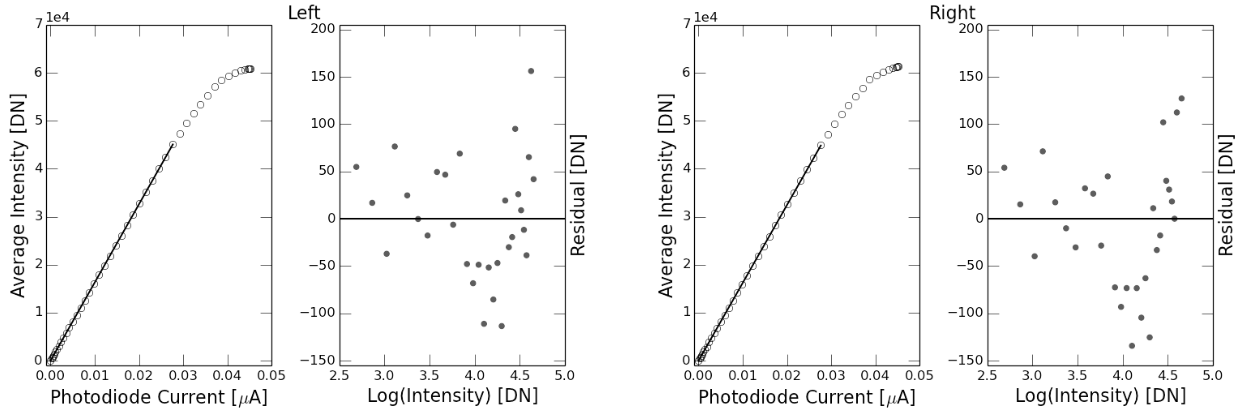

Figure 5: *Left: telescope mirror assembly; Right: spectrograph assembly*

3. CONCLUSION

Testing the CLASP prototype camera in a thermally controlled environment proved to be a sufficient method for characterizing and verifying the prototype's performance. A series of 3 tests were performed and subsequent analysis determined dark current, read noise, camera gain, and residual non-linearity. The dark current at 268 K (-5 °) was measured at 41 e^-/pix/sec for both left and right sides of the CCD, while the dark current at the flight temperature of 253 K (-20 °C) was calculated at 7.1 e^-/pix/sec for the left side and 6.8 e^-/pix/sec for the right side of the CCD. The calculated dark current of the prototype model indicates that the CLASP cameras meet the 10 e^-/pix/sec dark current requirement. The read noise of the prototype camera was determined by calculating the width of the Guassian function that was fitted to the distribution of pixels in a DC bias and dark current corrected image. The measured read noise was well within the CLASP requirement of $\leq$25 e^-, with an average read noise of 6.07 e^- on left and 6.01 e^- on the right. The gain of the CLASP camera was measured by detecting ^{55}Fe X-ray photons and calculating the location of the well know Mn $K_{\alpha,\beta}$ lines in a histogram of photon hits. The gain was determined to be 2.03 and 2.05 for the left and right sides respectively, meeting CLASP's 2.0+-0.5 requirement. Lastly, the linearity of the prototype camera was determined using standard flat fielding techniques. Subsequent analysis revealed a 0.045% and 0.198% residual non-linearity for left and right sides respectively. The results from analyses reveal offsets in the measured and calculated values for the left and right sides of the detector. We are currently working to fully understand the differences between the two read out channels.

4. FUTURE WORK

The performance characterization described herein pertains to the laboratory prototype model of the CLASP camera. The engineering model and flight cameras are subject to rigorous testing in a vacuum environment. Testing in a high vacuum environment with the cryogenic cooling system will allow for a better understanding of the camera performance under flight-like conditions and it also allows for the implementation of a VUV monochromator for narrow band UV measurements. Vacuum testing will include the characterization studies performed on the prototype model, in addition to studies on the quantum efficiency at Ly-α and other characteristics, such as charge transfer efficiency (CTE).

ACKNOWLEDGMENTS

We acknowledge the Chromospheric Lyman-Alpha SpectroPolarimeter grant funded by the NASAs Low Cost Access to Space program under Research Opportunities in Space and Earth Sciences (ROSES). NASA/MSFC led this project; partners include the National Astronomical Observatory of Japan (NAOJ), Lockheed Martin (LMSAL), Instituto de Astrofisica de Canarias (IAC), and Astronomical Institute of ASCR.