Calibration of the HBCAM on quadruple pixel readout

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Introduction

HBCAMS are integral components of the ATLAS alignment system and must meet precision standards in order to obtain confidence in measurements made. Experimental physicists must always account for error in their experiments due to both systematic and random errors. In this case, many systematic errors arise that stem from manufacturing errors in the HBCAMS, such as a tilted CCD with respect to the lens. Calibration does not *fix* these errors, but rather tests whether the HBCAMS meet the precision standards necessary. For a detailed description of the calibration process, visit the BCAM User Manual and BCAM Calibration Manual on the Brandeis HEP website [1].

Deriving a relation between the single and quadruple pixel settings

The HBCAMS combined with the BCAM instrument are designed to view a point source (or two sources) and identify its location. The current CCD used in the HBCAMS is the ICX424, which has an additional quadruple pixel setting, referred to as the ICX424Q, that bins 2×2 arrays of pixels together and as a result can take images four times faster, due to a transmission of a quarter of the pixels. Single pixels are $7.4 \times 7.4\,\mu$m and quadruple pixels are $14.8 \times 14.8\,\mu$m. A detailed description regarding how the CCD reads out an image on both settings is described in HClocking.

The current calibration software is applied to only images taken on the single pixel setting and applies set calibration constants. The binning of pixels on the quadruple pixel setting yields different position measurements from the single setting, which will affect calibration. If the offset between quadruple and single pixel setting were known, the quadruple pixel measurements could simply be converted into single pixel measurements and the same calibration software could be applied. To obtain an understanding of the offset, an HBCAM was mounted along a rail 3 meters away from two point sources, one red and one blue. The sources were then moved across along a stage 50 mm in 1 mm increments with an HBCAM orientation such that the sources moved along the $+x$ direction and $+y$ direction in image sensor coordinates.

Problems with the A3025

The horizontal clock signals in the A3025 HBCAM boards were previously known to not reach the desired voltage levels in the time frame allotted, most notably on the quadruple pixel setting. Further investigation has been done on this incomplete transition and is documented in HClocking. The effects of the incomplete transition were seen when taking images of the light sources on the quadruple pixel setting.

Below in Figure 1 shows an example of measurements on the single pixel setting. Displayed is the BCAM instrument that shows the last image taken by the HBCAM as well as analysis below the image. The columns given by the analysis, each separated by white spaces, in order from left to right are measurement number then: x position (μm), y position (μm), number of pixels above threshold, peak intensity, accuracy (μm), and threshold counts. These measurements are then repeated a second time because the BCAM instrument is set to analyze two spots and in this case since only one spot exists (boxed in red), an error for the second set of measurements is returned.

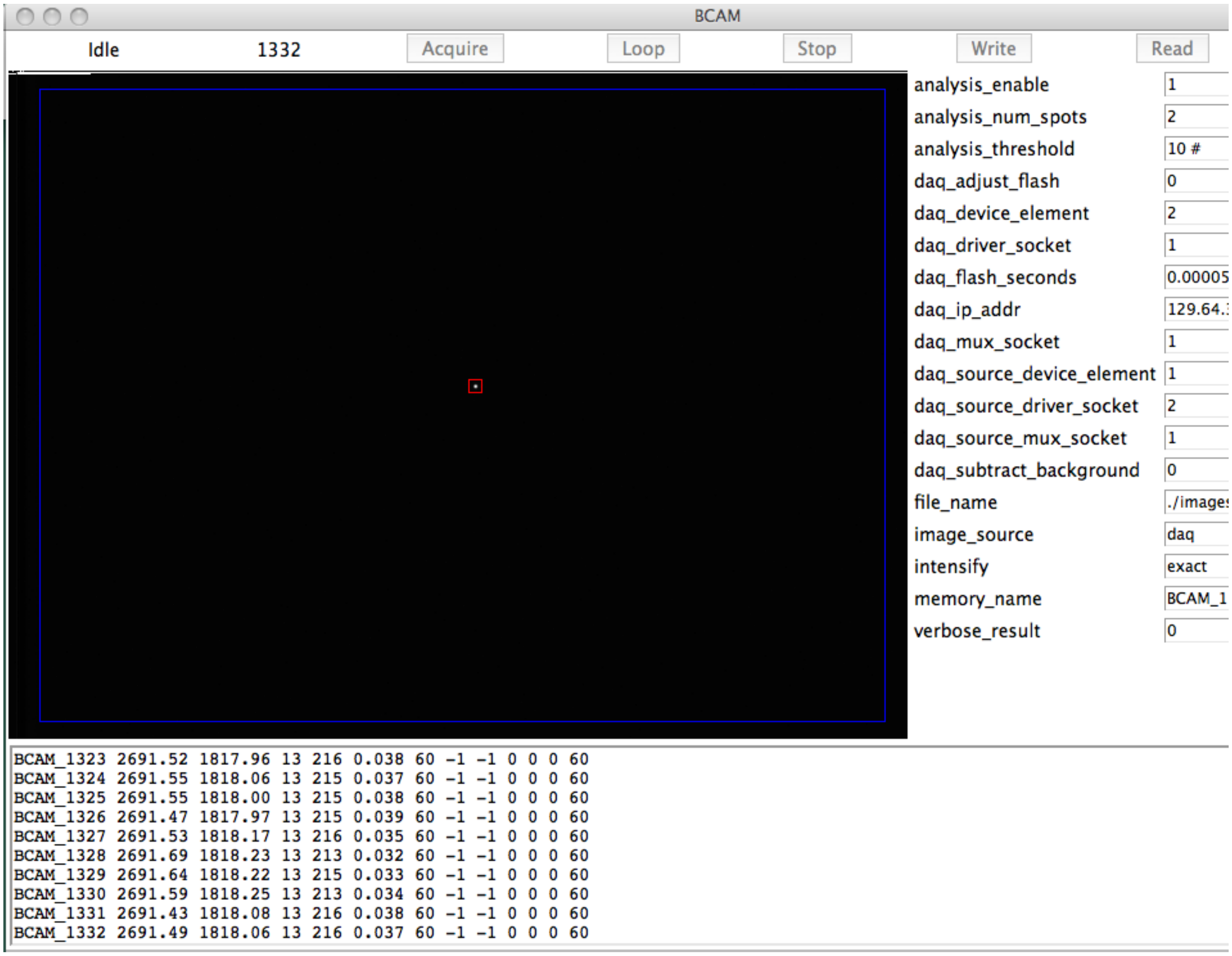


Figure 1: Display of the BCAM instrument on the single pixel setting with input parameters after looping for a series of measurements.

Before the display of the BCAM instrument was captured in Figure 1, the instrument had been looped to constantly acquire series of images from the HBCAM and measurements. We see in the analysis fairly consistent x and y positions that are accurate to less than a tenth of a micron. This consistency does not hold on the quadruple pixel setting, as seen in Figure 2. Instead, we see a spot smeared horizontally with a rapidly decreasing x position and an accuracy that is not comparable to the single pixel setting. The y positions, however, seem to have the same consistency as before which, combined with the horizontal smearing, suggests a problem with the horizontal clocking.

It is also interesting to note that the x position only decreases with progressive measurements and that the rate of decreases slows, with improved accuracy. In fact, the spot seems to traverse across the image, which one can clearly see in a side by side comparison in Figure 3 where only the area of the image near the spot is shown, with the first letter of the input fields on the right for spatial reference. Eventually, however, the spot seems to settle, though no where near the precision achieved on the single pixel setting. Analysis after over 700 measurements were taken is shown in Figure 4 with the associated image. The horizontal smearing is still present and fairly inaccurate and the measured spot has shifted approximately 740 microns in x, or the length of 100 pixels on the image sensor. The traversal across

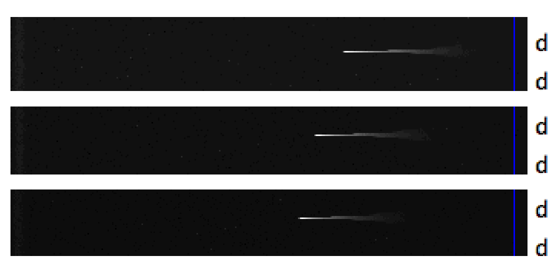


Figure 3: Horizontal shift of the spot on the quadruple pixel setting.

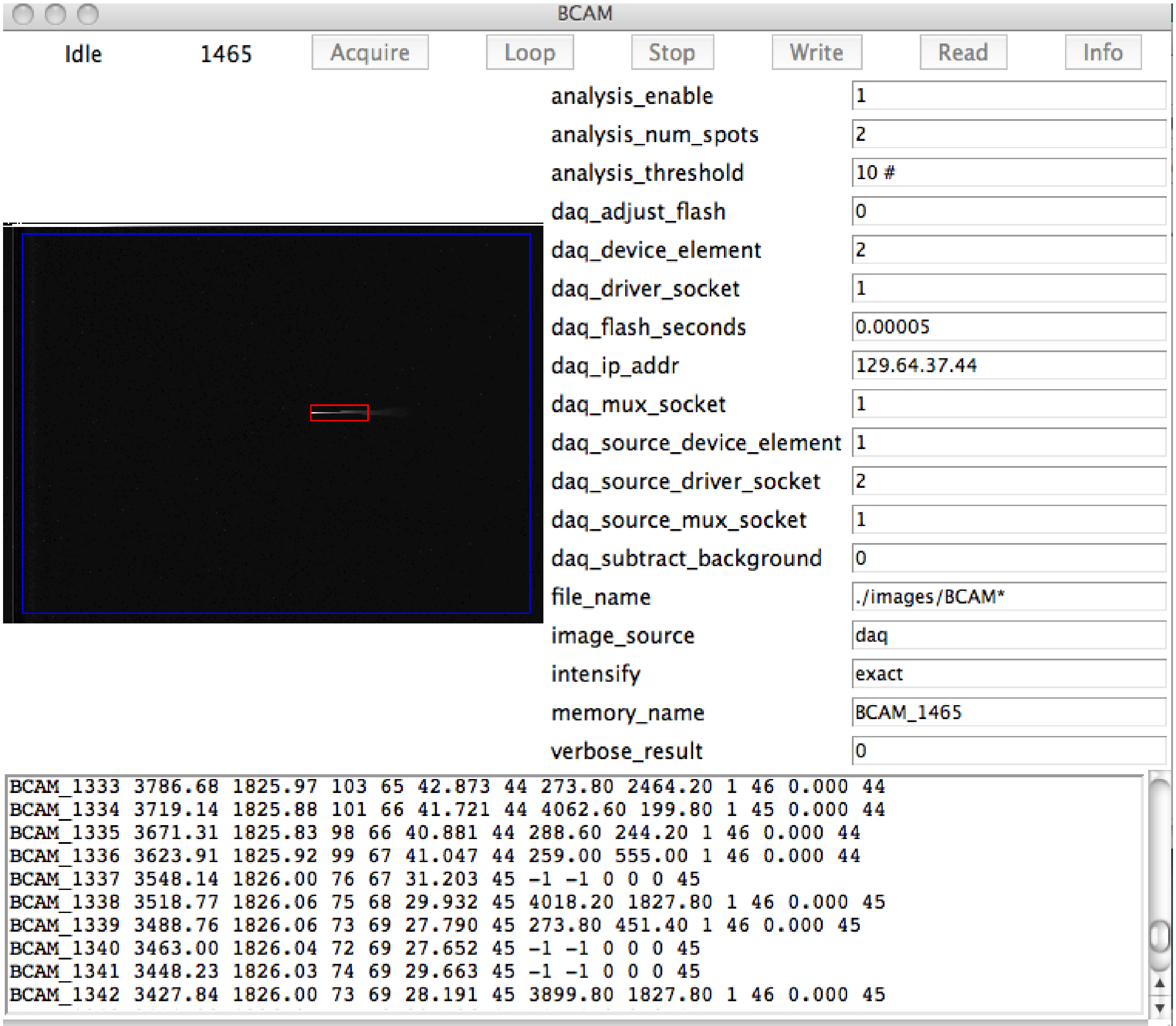
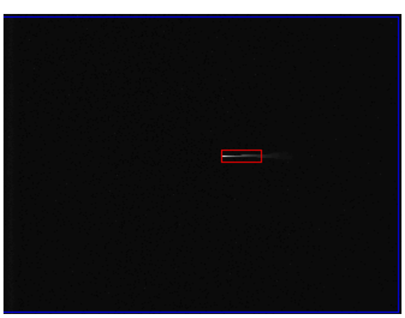


Figure 2: Display of the BCAM instrument on the quadruple pixel setting with input parameters after looping for a series of measurements.



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BCAM_2056 3039.79 1826.02 52 86 14.289 46
BCAM_2057 3043.03 1825.85 53 86 14.871 46
BCAM_2058 3038.84 1825.92 51 87 13.492 46
BCAM_2059 3040.08 1826.22 55 87 17.110 46
BCAM_2060 3039.27 1825.84 51 87 13.824 46
BCAM_2061 3042.51 1825.75 53 86 14.298 46
BCAM_2062 3041.95 1825.85 51 87 13.500 46
BCAM_2063 3041.43 1825.84 54 85 15.656 46
BCAM_2064 3042.20 1825.89 52 86 14.050 46
BCAM_2065 3041.17 1825.83 51 86 13.498 46
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Figure 4: Analysis of the BCAM instrument on the quadruple pixel after looping for several hundred measurements (right) with the associated image (left).

the image, however, seems to be due to an increase in temperature of the CCD. Cooling the CCD results in a position measurement that returns to its original location (on the right-side of the image), though smearing remains. Changing the exposure time, daq_flash_seconds, also affects the angle of the smear. All previous figures were taken with an exposure time of 50 μs, but increasing to 10 ms results in a wider, conical smear as shown in Figure 5.

Figure 5: Conical smearing with increased exposure time of 10 ms.

No smearing with the modified A3025

In the modified version of the A3025 that shows far more promising clock signals, the same horizontal smearing and shifting of the spot are not present on the quadruple pixel setting. Below in Figure 6 are display panels of the BCAM instrument replacing the HBCAM with a modified version, modifications described in HClocking. Figure 7 shows a 10x zoom image of the spot and it shows no signs of smearing. Both figures were taken with a 50 μs exposure time.

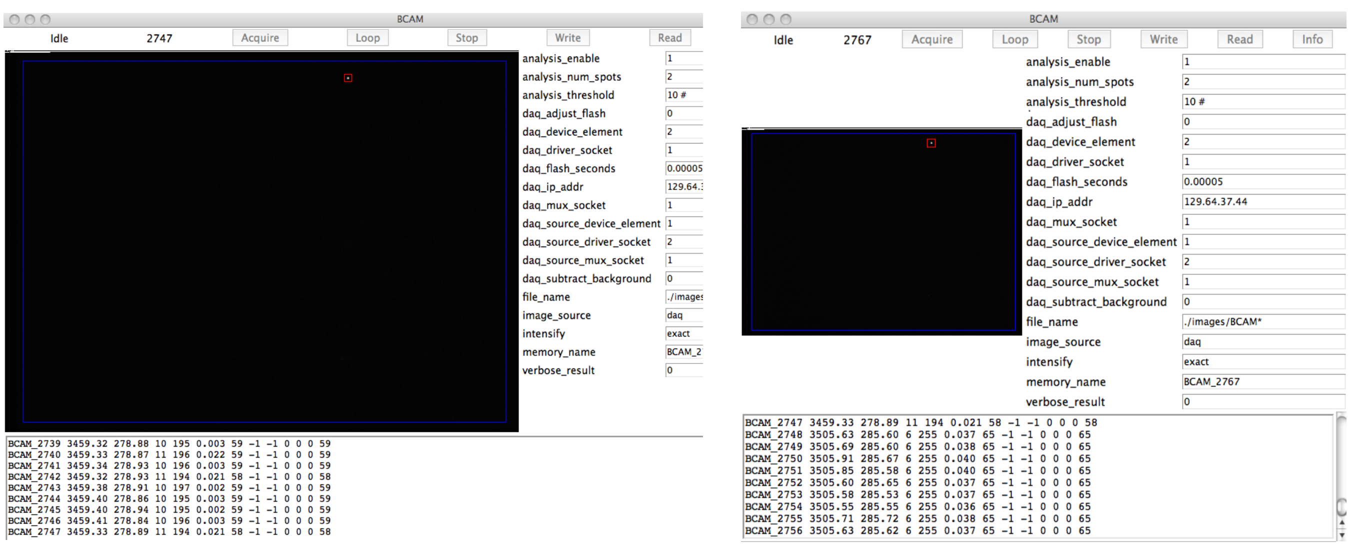


Figure 6: Display of the BCAM instrument on the single (left) and quadruple (right) pixel settings with the modified A3025.

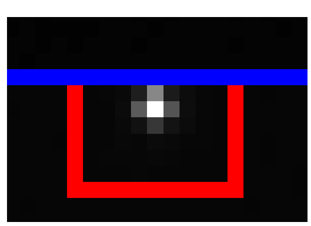


Figure 7: 10x zoom image of the spot taken on the quadruple pixel setting with the modified A3025.

Position analysis

To understand the offset between quadruple and single pixel settings, a basic understanding of how the position of a spot is calculated and the process of reading out an image is needed. Given an array of pixels, where each pixel has an associated intensity, the position analysis software scans through each row and each column to find the position of the centroid. It scans through the rows and measures the intensities at each pixel, an additive sum as each successive row is scanned. The end result is a plot of intensity versus horizontal displacement along the CCD. The horizontal location is then determined by a weighted sum of intensities along each pixel in order to find the horizontal pixel that lies at the centroid and the process is repeated for the columns to find the vertical pixel corresponding to the centroid. Once the position of the centroid is found in terms of number of pixels across the image, it is converted into x and y coordinates by multiplying the number of pixels by their size.

The readout of pixels from the CCD is not a straightforward transmission. Rather, there exists a pipeline that registers as they are clocked horizontally pixels before they are read from the CCD that is effectively 6 pixels in length. This has an effect on the offset because on the quadruple setting, pixels are clocked in 2×2 groups so four times as many pixels are sent through the pipeline.

Expected horizontal offset

For the single pixel setting, 6 pixels would be sent through the pipeline before any pixels were read out from the CCD, resulting in a "pipeline length" of 6 pixels. On the quadruple pixel setting, 4 pixels are sent through each stage of the pipeline, but only 2 horizontally. This results in a pipeline length of 12 pixels, resulting in a $12 - 6 = 6$ pixel $= 44$ μm offset for each horizontal measurement. Even though four pixels are read out and converted into one pixel on the quadruple setting, there should be no position offset when the first pixel is read out. Though two pixels are "squeezed" into one, the software multiplies by the centroid position in pixels by the pixel length, which is doubled on the quadruple setting.

Expected vertical offset

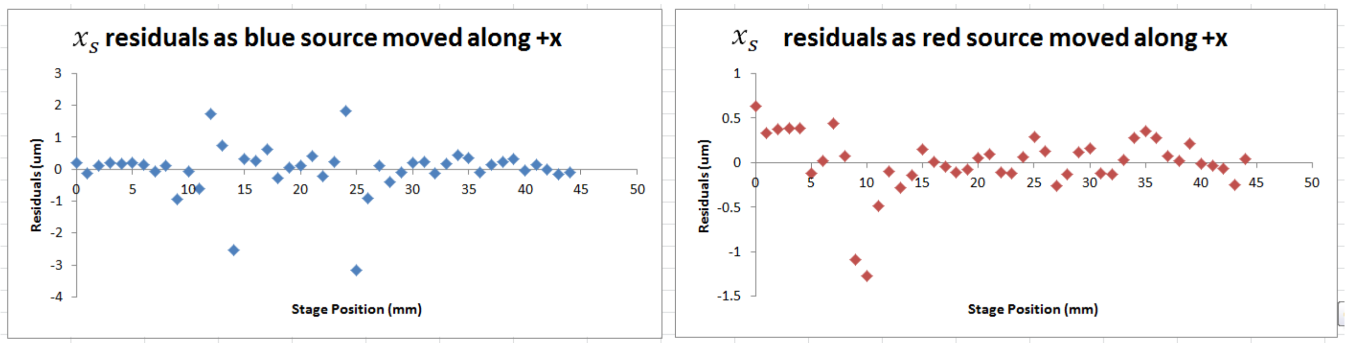
The pipeline should create no vertical offset, as no pipeline exists for the vertical clocking. For reasons explained above, the squeezing of 4 pixels into one should not create an offset.

Experimental findings

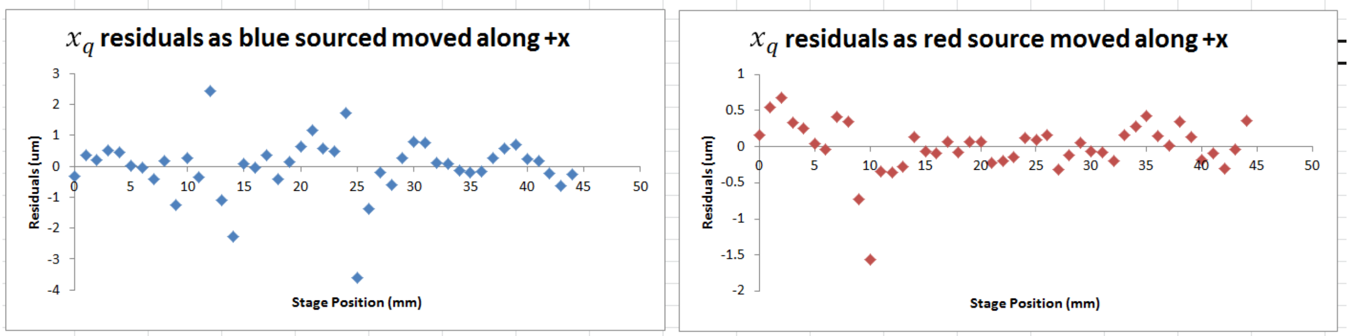
As the sources were moved across the $+x$ direction of the CCD, the average measured quadruple pixel x position, x_q, minus single pixel x position, x_s was found to be $+44.84$ μm for blue and red sources. The difference in y positions, $(y_q - y_s)$, was found to be 7.36 μm for the blue source and 7.38 μm for the red source. The ratio between slopes of linear fits of x positions of quadruple to single were 1.00055 for blue and 1.00018 for red. Plots of the residuals for measured x position against stage position are shown in Figure 8a, 8b. Plots of $(x_q - x_s)$ are shown in Figure 9.

As the sources were moved across the $+y$ direction of the CCD, the average $(x_q - x_s)$ was found to be $+47.21$ μm for the blue source and $+47.12$ μm for red source. The difference in y positions, $(y_q - y_s)$, was found to be 7.00 μm for the blue source and 7.02 μm for the red source. The ratio between slopes of linear fits of y positions of quadruple to single were 0.999586 for blue and 1.00000 for red. Plots of the residuals for measured y position against stage position are shown in Figure 8c, 8d. Plots of $(y_q - y_s)$ are shown in Figure 10.

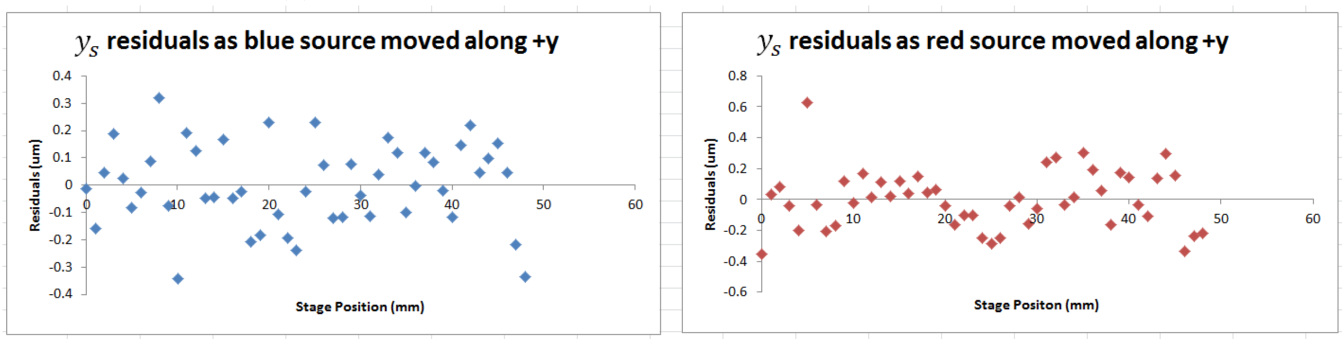
Note that the last few stage displacements are not included on the graphs because the spring within the stage that controls displacement locks up on the far end (towards 50 mm).



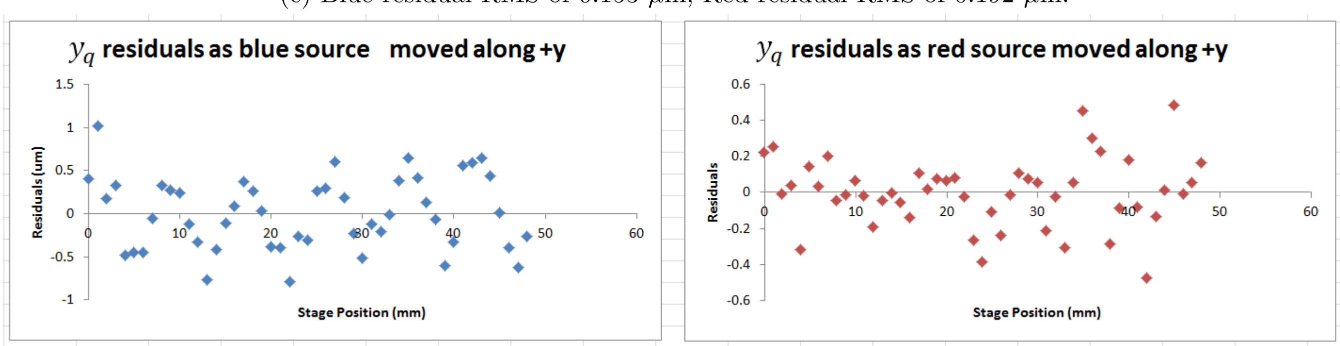
(a) Blue residual RMS of 0.796 μm; Red residual RMS of 0.342 μm.



(b) Blue residual RMS of 0.952 μm; Red residual RMS of 0.362 μm.

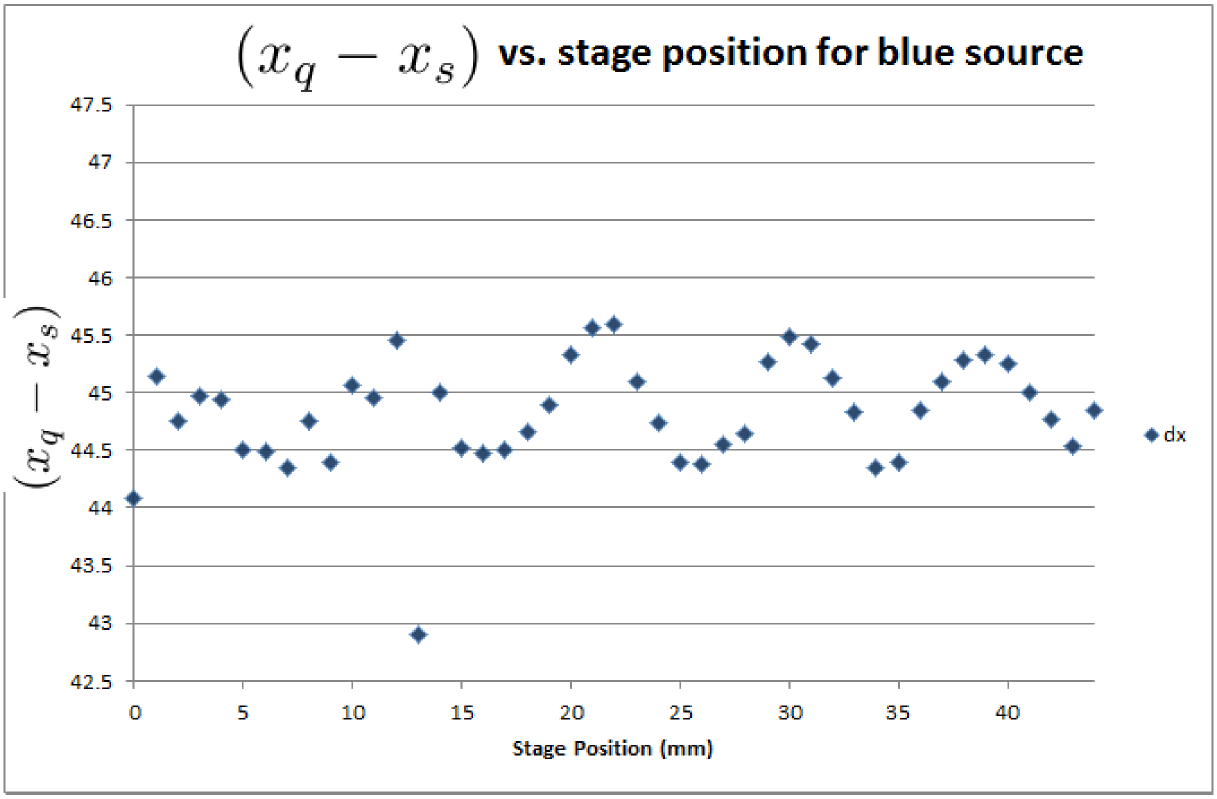


(c) Blue residual RMS of 0.153 μm; Red residual RMS of 0.192 μm.

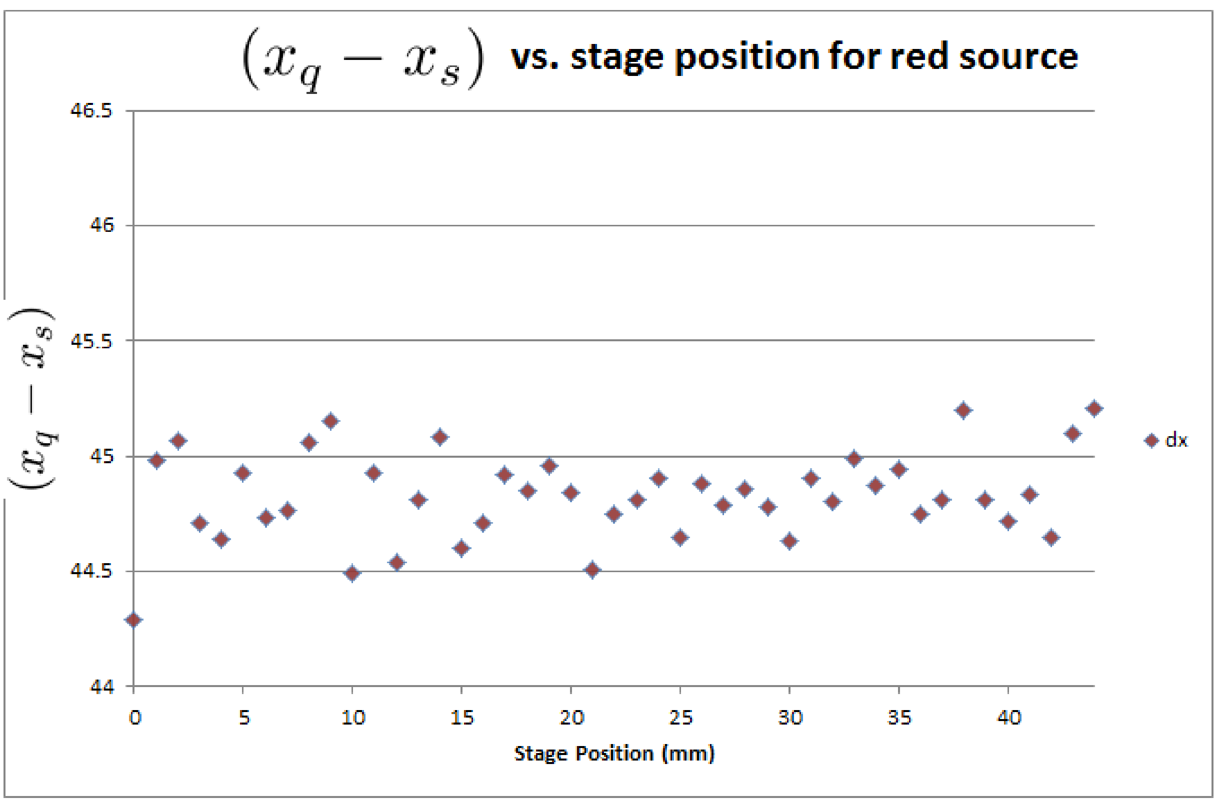


(d) Blue residual RMS of 0.424 μm; Red residual RMS of 0.195 μm.

Figure 8: Residuals of measured positions on single and quadruple pixel settings for red and blue sources as a function of stage position. Residuals are calculated as the sources traverse the CCD in both the x and y directions.

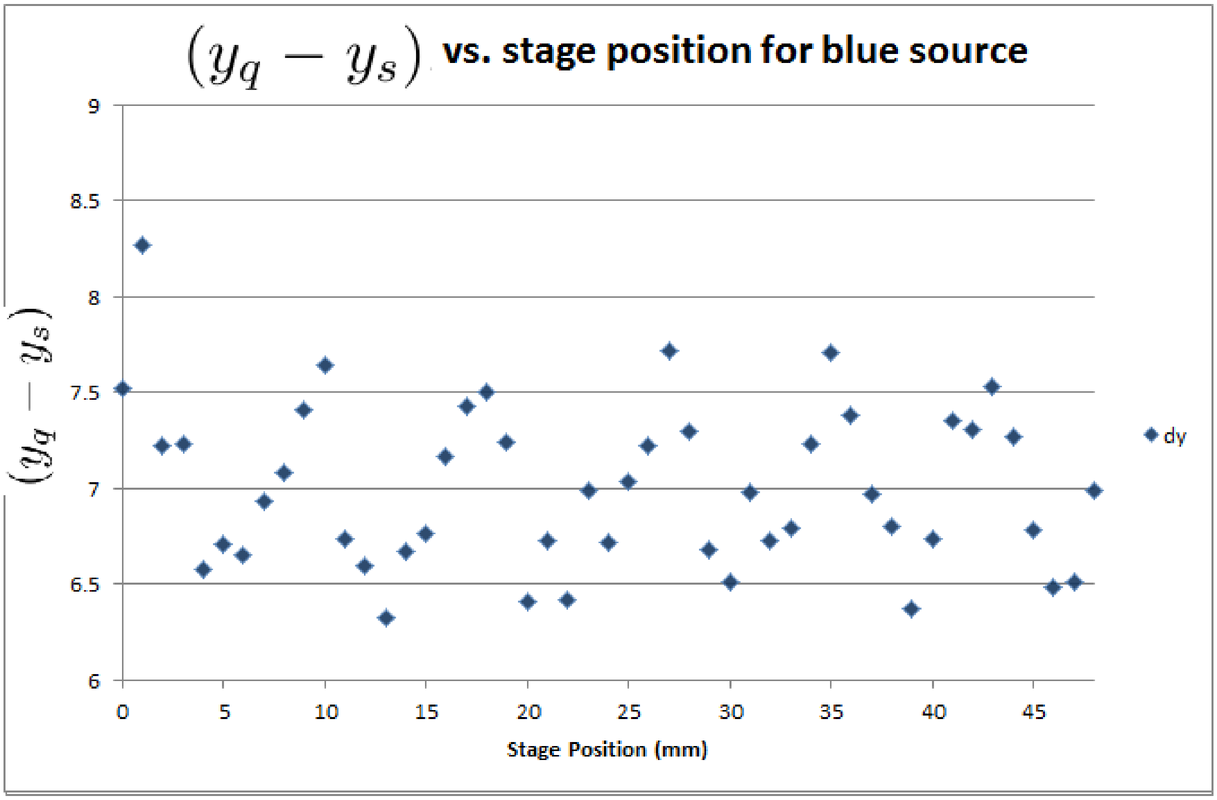


(a) Average $(x_q - x_s) = 44.8$ μm $= 6.06$ pixel offset.

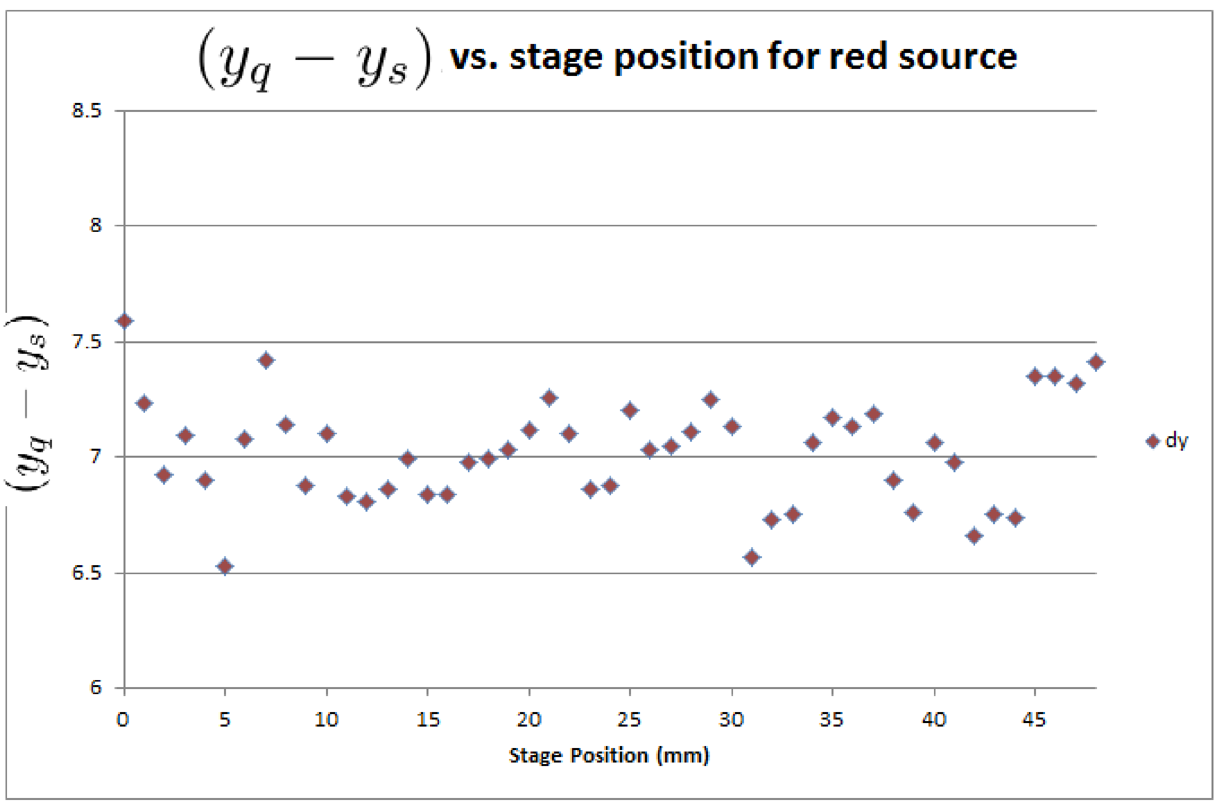


(b) Average $(x_q - x_s) = 44.8$ μm $= 6.06$ pixel offset.

Figure 9: Measured difference in quadruple and single x position versus source displacement along $+x$ of the CCD for blue and red light.



(a) Average $(y_q - y_s) = 7.01\ \mu\text{m} = 0.947$ pixel offset.



(b) Average $(y_q - y_s) = 7.02\ \mu\text{m} = 0.948$ pixel offset.

Figure 10: Measured difference in quadruple and single y position versus source displacement along $+y$ of the CCD for blue and red light.

Discussion and future work

The predicted offset in horizontal position is matched reasonably well for the case where the light sources are moved across the CCD in the $+x$ direction. The experimental offset in vertical position, however, remains unexplained though seemingly consistent. As the sources are moved in the $+y$ direction along the CCD, a new offset arises in both x and y. This is perhaps due to an experimental error, as the HBCAM was merely rotated on its side and held down with tape, as opposed to lying on a three-ball mount. We also see oscillatory behavior in the difference between measured quadruple and single x positions. This cyclic error may be due to the weaker intensity of blue light, as it is generated by an LED channeled through a fiber optic cable, rather than a laser.

While the offset between the quadruple and single pixel settings is consistent for the same experiment, as demonstrated by agreement in red and blue light, the offset in y and additional offset from a different orientation is still not well understood. Repeating the experiment at closer ranges may shed light on the cyclic error by effectively increasing the intensity of light and creating a larger spot. It may also be useful to repeat the experiments, especially moving the sources along the $+y$ direction to see if the additional offset remains.

References

[1] *Brandeis University High Energy Physics Electronics Shop.* <alignment.hep.brandeis.edu> 1 September 2013.