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Centroid precision as a function of total counts in a windowed CMOS image of a point source

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ABSTRACT

We obtained 960,200 22-by-22-pixel windowed images of a pinhole spot using the Teledyne H2RG CMOS detector with un-cooled SIDECAR readout. We performed an analysis to determine the precision we might expect in the position error signals to a telescope's guider system. We find that, under non-optimized operating conditions, the error in the computed centroid is strongly dependent on the total counts in the point image only below a certain threshold, approximately 50,000 photo-electrons. The LSST guider camera specification currently requires a 0.04 arcsecond error at 10 Hertz. Given the performance measured here, this specification can be delivered with a single star at 14th to 18th magnitude, depending on the passband.

Keywords: CMOS, guider, LSST, centroiding

1. INTRODUCTION

The Large Synoptic Survey Telescope (LSST) will run primarily in a mode where it obtains 3-by-3-degree 15-second exposures. Pointing and guiding will be provided by a complex system, one of whose inputs will be the positions of images of stars in detectors in all four the corners of focal plane, co-mounted with the science detectors, behind the shutter, approximately 1.5 degrees (30 centimeters) from field center. Error budgets have been imposed and a control system simulator has been built with the requirement that the collective signal from the guiders is updated at 10 Hertz with a 0.04 arcsecond error. The baseline guider camera design identifies CMOS imaging arrays, specifically Teledyne's H2RG, for the guider cameras.

The primary concerns for providing guide-star centroid information to the telescope control system are

1. consistency of delivering unchanging pointing information while changes occur to other conditions such as seeing, sky brightness, and star intensity due to atmosphere
2. sensitivity to change in pointing conditions
3. a measured change independent of location on the array or condition of the image
4. computation time.

This paper addresses consistency. Consistency should be distinguished from an "astrometric" requirement, because the precise position of the stars is less important than consistency of position error signal. As outlined in the working document by Sebag *et al.*[1], the guiding system will report centroids to the telescope control system, and also provide signal-to-noise, total counts in peak, and full width half maximum.

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This paper presents the sample-based error of a centroid applied to nearly one million H2RG pinhole images obtained by Hanold and Figer[2] at the Rochester Institute of Technology (RIT). We measure the spread in reported centroids for repeated images of the same pinhole as a function of total counts in the peak. This work builds on previous work by Simms and others at SLAC[3,4] using CMOS arrays for guiding at the Kitt Peak 2.1-meter telescope, Baker and Moallem[5] regarding selecting centroiding algorithms for Shack-Hartmann sensors, and Thomas *et. al*[6] for selecting centroiding algorithms for Shack-Hartmann sensors. Warner[7] at CTIO built a Simulink® software model of the LSST guiding control system and determined that a few 10^4 photoelectrons in a star's PSF are required for a closed-loop guider control system to meet the allowed 0.04 arcsecond error at 10 Hertz. This paper addresses the question whether the real CMOS detector could provide 0.04 arcsecond errors for a few 10^4 photoelectron star-like spot.

2. DATA SET

Hanold and Figer obtained the data set with a Teledyne H2RG CMOS detector with un-cooled SIDECAR readout. See Simms *et al*. 2007[3] for general operation and calibration details for the similar Teledyne H4RG system. The H2RG camera has 18 micron pixels. These pixels are equivalent to 0.36 arcsec using LSST's platescale of 50 microns/arcsec. The camera was running at a gain where there are approximately 8.6 photons per ADU. The data set consists of 22×22 pixel windowed images of a pinhole taken up-the-ramp in 200 reads over 2.26 seconds, approximately 11.35 additional milliseconds between consecutive reads (25 microsecond pixel time). After these data were obtained, the bias voltage control code was improved, leading to smaller drifts. Errors estimated in this paper should get smaller when the camera system is run under the new code. The pinhole is mounted on a stage moved by stepper motors. It is moved one micron at a time over 30 positions in x. Then it is moved one micron in y and stepped through 30 more positions in x, for a total of 30 moves in y. The whole process is repeated at four different positions in z to change the apparent size of the pinhole spot. We thus have 200 consecutive images at different integration times, 31 × 31 sets of the 200 at different positions in the image, and 5 of all those sets with different spot sizes. This gives 4805 files of 200 images each. Four of those files are corrupt, so there are a total of 4801 good files.

The requirement on the error[1] in the centroid is an error gain of 0.02 arcsec at 50% -- meaning 0.04 arcsec standard deviation -- for a 0.6 arcsec FWHM star image. Hanold and Figer[2] report that the FWHM of the spot runs between 2.393 and 3.035 pixels (43.0 to 54.6 microns, or 0.86 to 1.09 arcsec at LSST's platescale) for the different z positions, so the spots analyzed here are a little bigger than the guider requirement's nominal value.

3. DATA REDUCTION AND ANALYSIS

We subtract the first up-the-ramp image to remove offset variations among the pixels. We compute a centroid for the remaining 199 offset-subtracted images. Thus we obtain centroid information for 955,399 pinhole images. Using a set of background frames, we computed the gain and offset of each pixel; however, without a calibrated source, true photoelectrons were difficult to estimate, so this experiment does not correct for estimated 2% gain variations among the pixels. The fixed pattern from gain variations should have a very small effect on shifting the centroid from image-to-image. Because the edge pixels of the windows get excess dark current through interpixel capacitance from the pixels outside the window, the centroid is computed on only the central 20 × 20 pixels. We did four trials with Baker and Moallem's best general-purpose algorithm, the "iteratively-weighted" centroid algorithm with a sigma weight of 0.5 and 1.0 pixels and 5 and 10 iterations. Five iterations takes approximately 0.6 milliseconds per 20 × 20 image on a 2.16 GHz Intel Core Duo Mac OS X. Ten iterations takes nearly 1 millisecond. One millisecond is one percent of the frame rate and should not be expected to be the dominant part of the control loop latency. Changes in the sigma weight barely affect these timings. For the images of the largest pinhole, the sigma weight of 0.5 led to a larger scatter in the centroid than for sigma = 1.0. There were no significant differences in the computed centroid scatter between 5 and 10 iterations. The analysis below uses sigma of 1.0 and 5 iterations.

This paper uses "sample-based error" to study consistency, meaning we look directly at the spread in measured parameters for a large number of nearly identical experiments. If we had data taken repeatedly at exactly the same spot on the detector, we would be able to measure the error in repeated centroids. Instead, we have pinhole images either at small increases in integration time, or repeated *y*-positions with small motions in *x*. In either case, we can analyze 950,598 differences between centroids of images taken under nearly identical conditions. So we have two options: centroid under the same mechanical conditions with an additional 11.35 milliseconds between them, or computed *y*-value for consecutive steps in *x* of the same integration time. The second option presumes that the movement of the *x*-stage is precisely lined-up with the rows of the detector. A small tilt applied across the *x*-step of a micron will have a small effect on the *y*. Note however that if it is consistent, it only introduces a constant offset in the *y*-difference, and the spread can still be measured. In either case, we obtain the spread in centroids by making a histogram of the shift and estimate the error in computed centroid using the width of a Gaussian fit. We will use the data with the small difference in time for the sample-based error.

Because the images vary in integration time and spot-size, we can look at the spread of the centroid as a function of number of counts and size of spot. We process the window so that the only counts remaining should be from the spot. Then we can obtain the total of peak photoelectrons, and perform the centroid. First we remove from each pixel, as noted above, the first up-the-ramp image, and then a uniform ("sky"-like) background estimated using Stetson's DAOPHOT[8] MMM routine, see Figures 2 and 3. Then we perform the centroid and peak estimates using the remaining accumulated counts in the image**.** A typical 200th exposure in the data contains 40,000 ADU in the pinhole peak. Using conversion information provided in Simms[4] (86 microvolts/ADU when gain is 0.7, and 10 microvolts per photoelectron), 40,000 ADU is approximately 300,000 photoelectrons. This works out to 1500 additional photoelectrons per pinhole image per 11.35 milliseconds, so somewhere between the 10th and 20th read we will find the total photons in the peak to be the amount required by Warner[7].

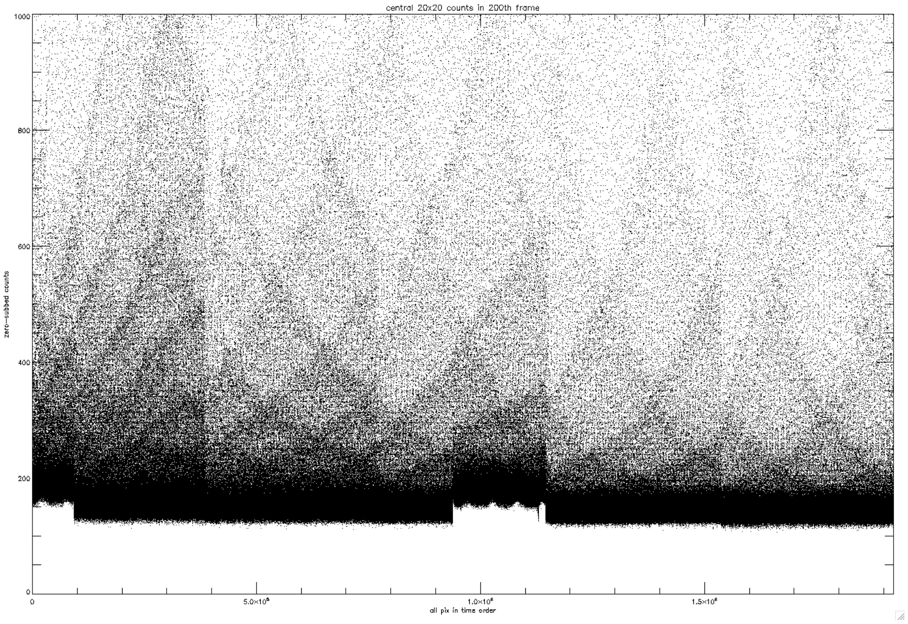

Figure 1: Counts in each of the central 20 × 20 pixels in the 200th frame of all the pinhole images, after subtracting the zeroth frame. The x-axis is pixel number in time order. The pixels in the "bar" around 150 to 200 counts are the background pixels, whose values are both non-zero and varying in time. Pixels with higher counts include photoelectrons from the pinhole image.

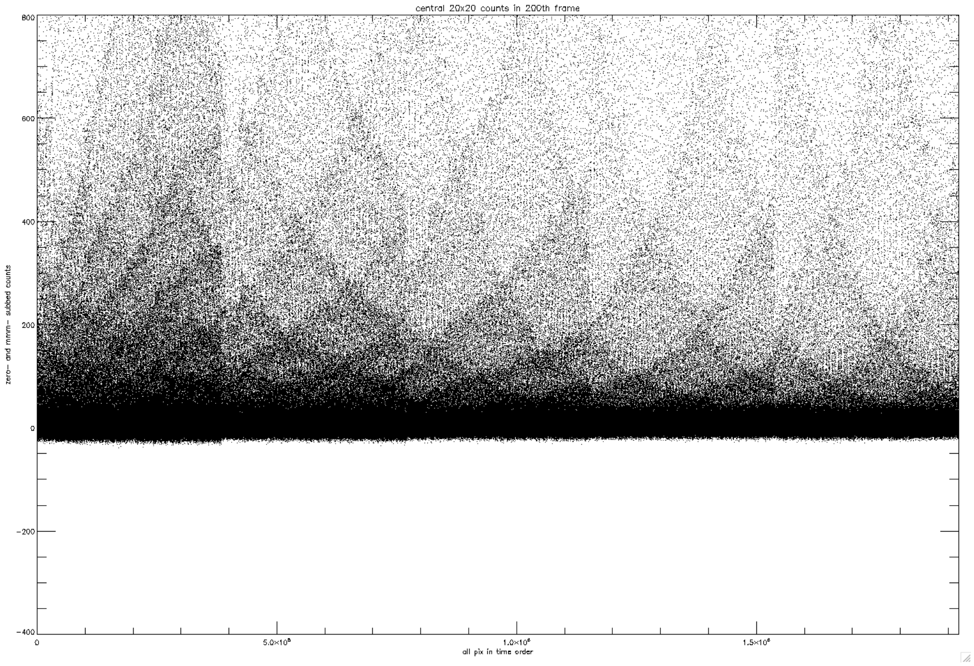

Figure 2: Counts in each pixel in the central 20 × 20 pixels in in the 200th frame of all pinhole images, after subtracting both the zeroth frame and each frame's mmm "sky". Pixels with non-zero counts can be presumed to contain photoelectrons from the image of the pinhole.

Figure 3 shows the difference in *y*-centroid for consecutive images, reduced as described above, as a function of total counts above background in the peak. The graph is truncated above 10,000 counts. Images with greater than 10,000 counts do not change in spread of centroid. Below 6,000 counts or so, the centroid precision is a strong function of number of counts.

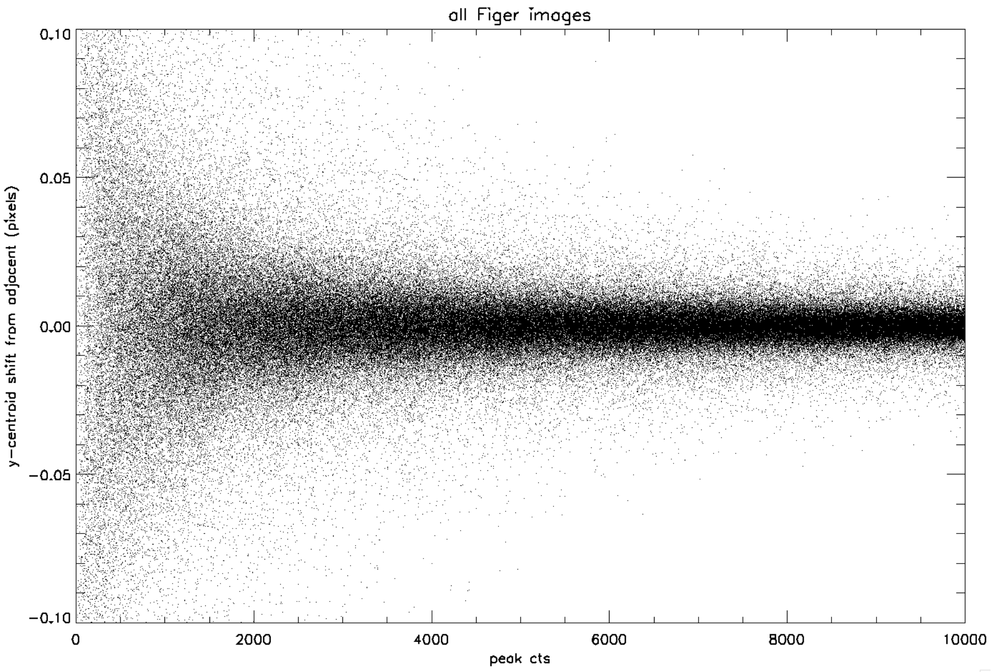

Figure 3: The shift in *y*-centroid between temporally adjacent images, versus total counts above background in image. A typical image with 10,000 counts (the maximum shown here) is the 50th read.

Figure 4 shows the full-width half-max of a fitted gaussian of the shifts between the *y*-position for a series of fixed read-times and for identical spot-size as a function of total photoelectrons in the spot. The *y*-axis is the scatter in centroid shift in one dimension, multiplied by √2 to estimate the two-dimensional shift and converted to LSST arcseconds. The values of photoelectrons along the *x*-axis in the plot correspond with each of the images of the pinhole (showing the range of counts measured for every image instead of just the average). The eight positions of the *y*-centroid are obtained for every tenth up-the-ramp integration time from the tenth through the 80th read.

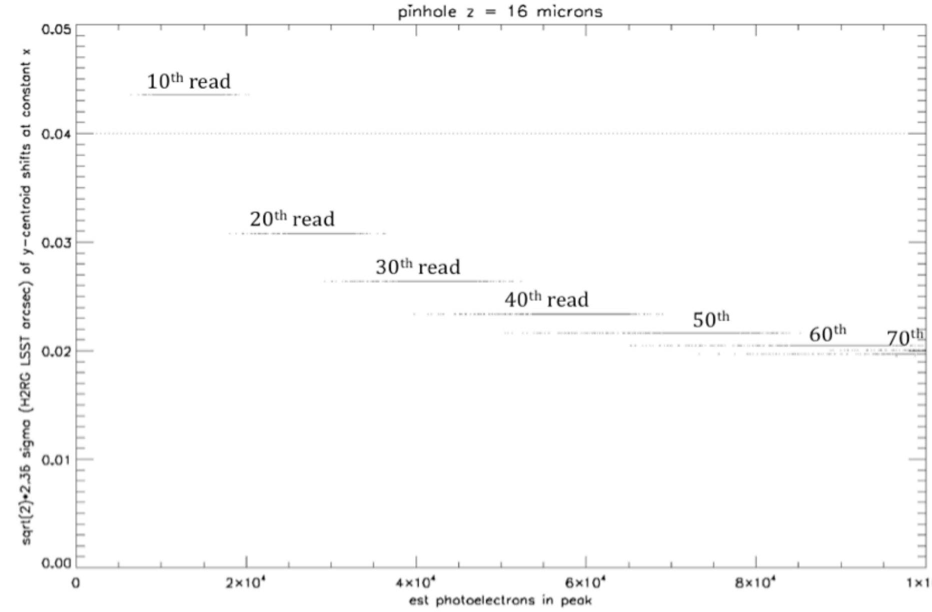

Figure 4: Consistency of y-centroid in LSST arcseconds as a function of accumulated photoelectrons in an image of a pinhole.

These estimates show that √2 times the error in the *y*-centroid computed using the above routine drops below 0.04 arcsec FWHM for ~1.0 arcsec pinhole images containing approximately 20,000 photoelectrons. As noted above, 20,000 photoelectrons is in the range that Warner estimated that his guiding model will operate, so the CMOS detector is well-matched to the simulated control system.

4. CONCLUSION

An analysis of 955,399 20 × 20 pixel images of pinhole spots obtained with an H2RG array converted to 950,598 differences of centroid parameters – even under non-optimized conditions – shows that it is possible to obtain centroids with errors below 0.11 pixels when the peak of the image contains tens of thousands of photoelectrons. For the LSST telescope with a 0.1 second integration time, this is equivalent to errors less than 0.04 arcsec FWHM for single guide stars in the range of 14 to 18 magnitudes, depending on passband. Two years of further optimization of the CMOS detection system has occurred to improve linearization, readnoise, drifts, etc. Similar data from the improved system, with smaller "star" pinhole sizes and windows comparable to the LSST guider's planned operation, should yield better results, improving the faintness of acceptable guide stars.

5. ACKNOWLEDGEMENT

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