High Precision Photometry with Back-Illuminated CCDs

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Abstract. The intrinsic precision of a back-illuminated CCD was examined using an artificial starfield in a laboratory setting. Whhen the systematic effects of image motion were compensated for, the CCD performed as a nearly shot-limited photometer with only a few ppm of error at a flux level of $10^{10} e^-$ per sample (with a corresponding shot noise of 10 ppm). Thus, current CCDs have the precision required to detect terrestrial planets by the transit method, given our understanding of stellar variability.

1. Introduction

Limitations on the photometric precision of CCD arrays are important considerations for the proposed *Kepler* mission (see Borucki et al., this issue) to detect photometric signatures of extrasolar planetary transits. These transits last from 4 to 16 hours and cause reductions of 80 ppm in the parent star's brightness. The transits must be recognized against intrinsic stellar variability, photon noise, and detector noise. Previous work has shown that front-illuminated CCDs can achieve the precision required for this application (Robinson et al. 1995). This paper describes laboratory measurements of the photometric precision of a back-illuminated CCD, which has a quantum efficiency nearly double that of front-illuminated CCDs. We conclude that back-illuminated CCD's are also capable of performing at the required precision for *Kepler*.

2. Experimental Setup

The CCD used in these experiments was a Reticon 512x512 back-illuminated CCD with 27 mm pixels. It was thinned, delta-doped (Nikzad et al. 1994), had

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a full well capacity of about 4 x 10^5 e^- in MPP mode and a read noise of 12 e^- at -109C. The CCD was operated using the SNAPSHOT data acquisition system (Dunham et al. 1985, Dunham 1995) to provide constant exposure times. The optical system included a 660 nm LED, diffusers, condensing lenses, one of several artificial star field plates, and imaging lenses. Light from the LED passed through perforations in the star field plate, projecting an artificieal star field with stars of about seven pixels in diameter on the CCD (i.e. the full width half max (FWHM) of each star was about 7 pixels). The entire projection system was mounted on a micro-positioning stage which provided reliable sub-pixel motion in both the column and row directions. To simulate the Kepler photometer, no shutter was used. The instrument was mounted vertically and enclosed in an insulated housing for mechanical stability. Data were acculmulated as sums of 20 2.5-s exposures on 3-s centers resulting in approximately 2.4 x 108 e^- in each summed star image. Several runs have been performed to date with fairly uniform results. This paper describes one particular run in detail, in which sub-pixel scale motions similar to those expected for *Kepler* were applied to the apparatus.

3. Data Reduction and Analysis

The summed images obtained during the experiment were processed to obtain relative light curves for each of the 13 artificial stars on the star plate. Overclocked pixels were used to estimate the bias current, which was then subtracted from each pixel. Dark current was negligivle at the operating temperature. The flux time series for each star was obtained by summing the counts in a 15x15 pixel aperture with the central pixel containing the average centroid of its respective star. This aperture seize was chosen so that it contained at least 80% of each star's light, as per the optical design for *Kepler*. No nonlinearity or flat field corrections were applied to the images. Each star's flux time series was divided pointwise by the sum of the other stars' fluxes to obtain relative flux, which was then normalized by its mean value. Linear least squares regression was applied to the light curves with the x and y coordinates as the independent variables, as per Robinson et al. (1995), with the excepetion that we did *not* regress on the raw flux. The star positions for the regression were obtained directly from the images. Finally, the residual relative fluxes were bin-averaged by successive powers of 2 to assess their variability at longer timescales.

The motions were inteded to move the star images ov a 0.1 x 0.1 pixel grid in 9 uniform increments. As figure 1 demonstrates, this was nealy the case for motions in x, but the actual range in y was closer to 0.05 pixels, likely due to a weak micropositioner spring. Figure 2 shows the displacement of one star as a function of time relative to its starting position. The motions caused significant changes in each star's lightcurve, as shown in figure 3. Instrument precision was obtaind by subtracting the shot noise contribution from the measured standard deviation of the residual lightcurves in quadrature.

The shot noise accounts for nearly all of the scatter in the measurements (see figure 4), yielding an instrument precision of better than a few ppm at a flux of 4.8×10^9 e^-. Moreover, the range of motions in this test were several times larger than those expected for the *Kepler* spacecraft, so that even better precision may be expected for *Kepler*.

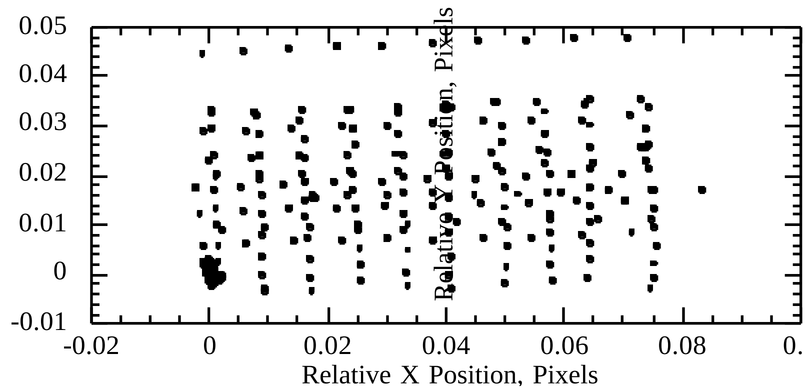

Figure 1. The position measured for each image of one star during the experiment.

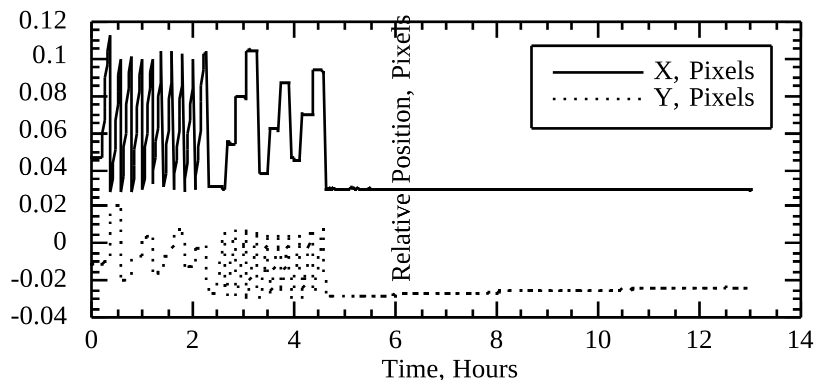

Figure 2. Relative X and Y position of one star's centroid as a funciton of time during the experiment.

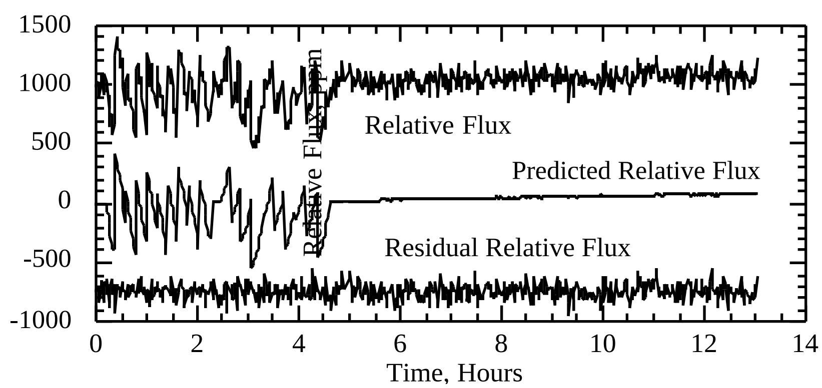

Figure 3. One star's relative flux is shown at the top (offset), with the relative flux predicted by regression on x and y coordinates shown in the center, and the residual relative flux at the bottom (offset).

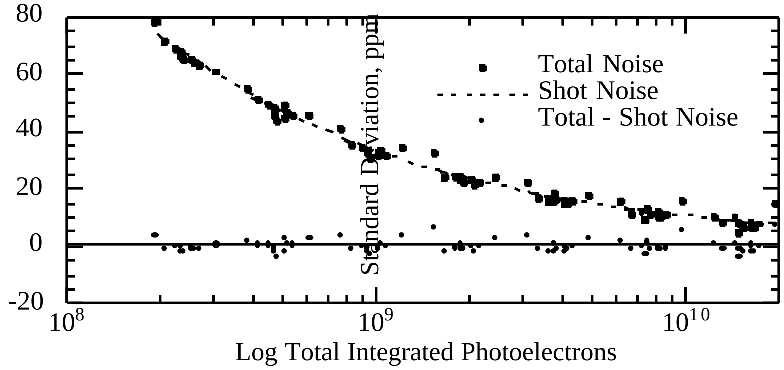

Figure 4. The statistical behavior of the instrument precision is shown as a function of integrated photoelectrons per sample. The squares represent the standard deviation for each star's bin-averaged, corrected light curve, with the shot noise level denoted by the dashed curve. The pluses are the difference between the measured precision and the shot noise, showing that the measurements follow the shot noise curve.

4. Conclusions

The test reported here is typical of those conducted to date. When the effects of motion are calibrated, back-illuminated CCDs are essentially shot noise-limited photometric detectors. At the demonstrated instrument precision of better than 3 ppm at a flux of 5.1 x 10^9 e^-, these CCDs are capable of detection transits of tererestrial plantes in orbit about solar-type stars which produce reductions of 80 ppm in the star's brightness.

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