**BFE Note**

1. **Introduction**

The CCD pixel are sensitive to their environment: the variance of flatfields does not rise linearly with illumination, but the rise flattens out, departing from exact Poisson distribution. The paper shows that a variety of CCD sensors deliver stellar images that broaden with increasing flux to some level. This “brighter-fatter” effect complicates the direct use of stars as PSF models.

This paper shows the correlations between neighbour pixels and the brighter-fatter effect can be explained by alterations to the drift field caused by charges already collected in the potential wells of the CCD. The size of the induced distortions and how they decay with distance from the source both depend on manufacturing details of the CCD.

The paper uses three instruments to establish the hypothesis: MegaCam, DECam and the LSST CCD E2V-250. For each instrument, the data set is constituted by both point source illumination exposures and by uniform illuminations.

1. **Flat Field**

The broadening of spot with increasing flux presented in the previous section can be depicted as a reduction of image contrast. In this section, a similar contrast reduction also appears in flatfield images, manifesting itself as a non-linearity of the PTC. Considering only Poisson noise, the relation between two observables is expected to be linear. However, we see that a significative departure from linearity is actually observed and that it is associated with linearly increasing pixel correlations.

* **PTC non-linearity**

The non-linearity of the photon transfer curve is illustrated in the figure below using eight different segments of the CCD E2V-250. The variance measured at high-flux is significantly lower than expected from extrapolating the variance of low-flux flatfields according to Poisson law: the discrepancy is as high as in the case of the CCD E2V-250.

A close up of a map

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* **Pixel Spatial Correlations**

**Masking:** The hot, dark columns and CCD defects are masked when being detected. Correlations that cannot be attributed to any specific feature in the image can be otherwise detected from a non-zero intercept when fitting a given correlation coefficient vs. flux.

**Differencing:** The correlation coefficients are computed from the difference of two flatfield images that have received the same overall illumination. This is done to remove apparent correlations due to non-uniformity of the flatfield image typically due to pixel size variations, QE variations or spatial variations of the illumination.

**Spatial Correlation:** The spatial correlation between pixels are evaluated using covariances normalized by variance refers to the correlation coefficient between pixels separated by columns and rows. The statistical precision on any correlation coefficient is where is the number of pixels. The statistics is doubled for the off-axis correlations by combining the measurements of two quadrants ( and for instance). The statistical precision is further increased by using many pairs of flatfield, the PTC from the CCD E2V-250 contains points, which allows us to improve the improve precision on correlation measurement down to .

**High Flux Level:** Correlation features appear when the pixel contents are approaching full well. These are seen as blooming effects that increase up to saturation. The correlation shows a quite linear behaviour up to full well. In the next section, we focus our analysis of pixel spatial correlations on the dynamic range below this flux level.

* **Spatial Correlations vs. BSS**

Pixel spatial correlations are detected on three instruments up to a distance of pixels. For the LSST and DECam, the correlation is about three times larger than . This anisotropy vanishes at larger distances. At a separation of pixels, all correlations of all CCDs are as low as few which approaches the limit of sensitivity of the instruments.

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| A picture containing screenshot  Description automatically generated | A close up of a map  Description automatically generated |

The pixel correlation maps are found to scale with fluxes for all detectors. There is no evidence for chromaticity dependence for this trend.

* **Spatial Correlations vs. Flux**

It has been shown in previous work that increasing the parallel clocking voltage (CV) decreases the level of the correlation while keeping all other coefficient unchanged. In this paper, we complete the study of the impact of varying pixel’s backside voltage. The correlation increases as the BSS is decreased down to , below this level, the correlation starts decreasing. On the same interval, the correlation coefficient with next pixel in the serial direction decreases and shifts to negative values below . The other correlation coefficient monotonously increases as BSS decreases. The diffusion mechanism cannot explain the evolution with BSS and CV, the prediction from simple electrostatic simulation are compatible with the observations.

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* **Total Flux**

The connection between non-linearity of the PTC and the linearly increasing correlations can be illustrated by summing all the correlations and adding them to the PTC. It can be verified that the process that correlates the pixels also conserves charges. This is also straightforward to see from a linear fit of flatfield mean flux versus exposure time.

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* **PTC Non-Linearity vs. Linear Correlation**

The gain function can be modified in the following way, with being an empirical parameter that is introduced to describe the quadratic behaviour of the PTC, which is expected given a linear rise of the correlations

1. **Model of Columbian Force**

In this section, we derive a parametrized model of the effects of electric field distortion in a CCD that are induced by charges residing within the CCD during exposure. We model the displacement of effective boundaries of pixel cases by a charge in a bucket at position as . In this equation, we have expressed the perturbing electric field due to charge proportional to the charge . indexes the four boundaries of the pixel and we label each boundary by the coordinates of the pixel that shares it with . .

* **Perturbed Charge**

The difference between charge contents with and without the perturbing electric field is called the *charge transfer*. The *pixel boundary displacement* induces a charge transfer between pixel and pixel . This charge transfer is proportional to both the pixel boundary displacement and to the *charge density* flowing on this boundary. The charge density drifting on the boundary between and pixel is given as

Therefore, the *net charge transfers* due to perturbing electric fields between pixel and its neighbour is given by

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* **Correlation**

Using this parametrization, the variance between pixels in a uniform exposure of average and variance reads

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The electrostatic influence from collected charge induces covariances between pixels in uniform exposures that scale with the average and the variance of pixel contents. If one measures correlation coefficients (ratio of covariance to variance), those are expected to scale linearly with the illumination level of the uniform exposure.