**THE CCD RIDDLE REVISTED:
SIGNAL VERSUS TIME – LINEAR
SIGNAL VERSUS VARIANCE – NON-LINEAR**

Mark Downing, Peter Sinclaire;
European Organization for Astronomical Research in the Southern Hemisphere

**Abstract**

The photon transfer curve is one of the most valuable tools for calibrating, characterizing, and optimizing the performance of CCDs. Its primary purpose is to determine the conversion gain of the CCD system from which many of the other performance parameters such as read noise, dark current, QE, full well, etc. are determined. Non-linearity in the photon transfer curve has been reported by the author in previous papers and confirmed by others. Previous studies isolated the source of the non-linearity to the CCD image area. Spatial autocorrelation analysis showed that the mechanism behind the non linearity was due to a "sharing of charge" between pixels in the image area which increases with signal level. This paper reports on further investigations carried out to explain the mechanism behind the non-linearity.

**Introduction**

The photon transfer curve (PTC) is one of the most widely used techniques to determine the end-to-end conversion gain (e/ADU) of a camera system. As it is simple to use (only requires the taking of progressive increasing time series of two flats at constant illumination) and does not require complicated or specialized equipment, it is widely used at the telescope to check the health of Charge Coupled Devices (CCDs) and Complementary Metal-Oxide-Semiconductor (CMOS) imagers and their camera system. Most other parameters such as read noise, dark current, quantum efficiency (QE), and full well are determined using this conversion gain.

The PTC relies on photon events being detected in a statistically independent way by the imager such that the characteristic shot noise of the light source is maintained and thus for a linear (conversion of photons to ADU) system, the mean signal (S) versus variance is related by a constant system conversion gain as follows:

\[ K_{e/ADU} \cdot S = \text{var}(ADU) \]

Previous studies by the author have shown this is not the case in reality and non-linearity in excess of 20% has been observed on backside illuminated CCDs even though having excellent signal linearity. In addition, the non-linearity is greater for thicker device made from higher resistivity silicon. An investigation to locate the cause of the non-linearity concluded that it was due to the amount of charge collected within a pixel and not due to lateral diffusion of charge in the undepleted region.

**"CHARGE SHARING" MECHANISM**

The apparent non-linearity seen in the PTC is not due to just the "sharing of charge" between pixels, but to the change in this sharing.

In Figure a) above, the pixels have not yet collected any charge and the electric field from each pixel extends evenly towards the backside to collect charge. When an electron is generated, it will drift towards the potential wells under the influence of the electric fields and be collected. The direction arrows attached to the electrons illustrate the electric field in the depleted region and the drift velocity of the electrons. With a higher drift velocity, electrons have less time to "wander" and end up in neighboring pixels.

**PHOTON TRANSFER CURVE (PTC)**

To compare results, the PTC was determined under the same conditions as the PSF.

The plots of the slope and y-intercept of the linear fit of the PTC curves show similar square root relationship in agreement with the equation that describe the PSF, where \( x_{\text{thick}} \) is the thickness of the depleted region and \( E_e \) is voltage across the device. The linear change of PTF with signal indicate that the thickness of the depleted region is reduced as electrons build up in the pixel further validating the model.

**CONCLUSION**

A mechanism has been presented to describe the non-linearity seen in the PTC. Results of measurements of PSF, the PTC, and autocorrelation of signal and collection phase voltage have validated this model.