Measurement of CTE Degradation by CCD Defect Analysis

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Abstract

This paper presents a simple method of measuring Charge Transfer Efficiency (CTE) degradation for large CCDs which can be accomplished without the need for adaptable readout electronics or radioactive sources required for standard methods. This method relies on the presence of non-saturating ‘hot’ pixel defects on the image, and is therefore not applicable for small high quality CCDs lacking multiple single pixel defects. This procedure has applications in space-based, remote cameras, cases where data is only available in standard image format, and applications where controlled illumination conditions cannot be easily arranged.

Introduction

Currently accepted methods of CTE measurement involve the use of radioactive sources[1], highly focussed light sources[2], or adaptable readout electronics which allow for charge injection[3,4], ‘over-clocking’[5], or split-frame delays[6]. In many cases where measurement of the CTE would be helpful for quantitative data analysis such as space-based star trackers or otherwise remote cameras subject to high energy radiation, these methods are not always available. To overcome this difficulty, a method is proposed to measure CTE based on the analysis of non-saturating hot pixel defects from standard image telemetry.

Theory

The method proposed in this paper makes use of intrinsic hot pixel defects which are often distributed in a pseudo-random fashion throughout a typical 2-D array detector. The analysis is conceptually quite simple. Ideally, sharp, non-saturating single pixel defects are found in early reference images. These defects and the deferred charge in pixels immediately subsequent to the defects are then monitored over the life of the device. The 1-D CTE of the device can then be calculated independently for each transfer direction and defect using the following formula:

$$CTE = \sqrt[N_{tran}]{\frac{Q_{Defect}}{Q_{Defect} + \sum_i Q_{Deferred}}} \qquad 1.$$

where $Q\text{-}_{Defect}$ is the amount of charge in the defect pixel, S $Q_{Deferred}$ is the sum of the deferred charge in the trailing pixels of a particular direction, and N_{tran} is the total number of transfers in the direction being measured.

It is important that the background image be smooth in the vicinity of the pixel defect. A dark image is ideal for this method, but not necessary. If the background is a smoothly varying image, a high pass filter can be applied in the direction perpendicular to the transfer direction being analyzed in such a way as to remove any potential interference.

It is implicitly assumed in this model that the measured charge above the background level in the pixels trailing the defect pixel is due to CTI from the main charge packet. If the intrinsic dark current in a trailing pixel is disproportionately increased through radiation damage, this method will give erroneous results. A statistical measure of the expected error induced through this mechanism can be arrived at by propagating the measured dark current non-uniformity (DCNU) on a per pixel basis through the previous formula. The effects of read error can be minimized by averaging several readings. The effects of DCNU, however, cannot be easily disentangled.

Procedure

The first step in measuring CTE is to locate, in the image data, the necessary sharp non-saturating hot pixel defects. Sharpness is an important characteristic to enable an unambiguous CTE determination. A sharp defect is defined here as one in which a smoothly varying background level is exceeded by only a single pixel in a particular window of pixels. Defects which span multiple pixels can be used for qualitative analysis, but can introduce a large uncertainty into the quantitative measurement. Radiation-induced changes in the dark current levels could potentially alter the intrinsic carrier generation ratio between the pixels in a multi-pixel defect. Such an effect could easily be confused with a CTE change.

Exceptions to the sharpness criterion can be made if a CTE measurement in only a single direction is necessary. Defects which span multiple pixels in the horizontal direction can be used for quantitative measurement of vertical CTE and vice versa. If background smoothing is being done with a high-pass digital filter as described previously, an otherwise allowable multi-pixel defect may be affected in a non-linear fashion causing an error in the CTE determination.

In a similar manner, it is important for obvious reasons that non-saturating defects be selected if quantitative measurements are required.

To demonstrate this method, an EEV CCD25-20 was analyzed for suitable hot pixels and was then subjected to ~29kRad(Si) of 8MeV protons (estimated from the measured flat band voltage shift of ~3.5V[12]), corresponding to approximately 6.4Rad of non-ionizing energy loss (NIEL). This device is a 1152x768 pixel frame transfer back-illuminated device. The ROE was set at a vertical transfer rate of 333kHz/row and a horizontal transfer of 1MHz.

Figure 1 shows an example of the application of this method for various hot defects on a CCD both before and after proton irradiation at 263K. All defect pixels shown here pass the sharpness criterion as they consist of only a single pixel in the pre-irradiation image. The 273K image at the same integration time (not shown) appears to show the defect at 208,722 as a multi-pixel defect, but this is an illusion caused by blooming of the defect charge along the CCD column.

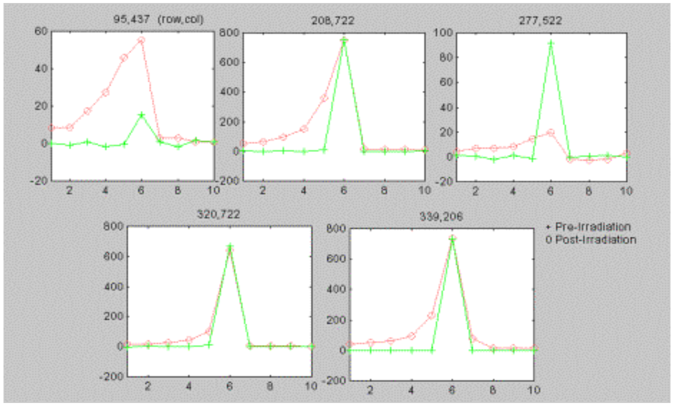

Figure 1.

Using equation 1 and summing the deferred charge over 5 trailing pixels, the results of this analysis for each acceptable defect are shown in table 1.

The uncertainty in this analysis is set by the read noise and DCNU of the device. After high-pass smoothing and removal of large outliers, the image standard deviation is found to be 1.6 counts in the pre-irradiation image and 2.1 counts in the post-irradiation image. Propagating these errors through equation 1 gives the respective CTE uncertainties as $<\pm 2.7\times10^{-4}$ and $<\pm 3.3\times10^{-4}$ based on the worst case signal to noise points (smallest packet size) in table 1. Each count corresponds to ~230 electrons.

Table 1. Results of Hot Pixel CTE Analysis

Pixel Coords.	Pre-Rad CTE	Post-Rad CTE	Packet Counts
277,522	1.0000	.99870	20
95,437	1.0002‡	.99898	55

320,722	.99997	.99966	641
339,206	1.0000	.99939	739†
208,722	.99998	.99929	751†

‡CTE levels >1.0 are unphysical and are errors caused by read noise and low signal.
†Absolute level was near saturation in non-linear regime for output circuit.

Figure 2 shows the effect of packet size on CTI. The background level varied linearly from ~2800 - 6400 electrons/pixel from the readout row at coordinates (520,x) to the top of the image at (0,x). As expected from theory, the defects with larger signal levels show less CTE degradation. This is because the number of radiation-induced charge traps seen by a particular charge packet does not scale linearly with the size of that packet. As a result, smaller charge packets have a much larger percentage of their charge deferred to trailing packets.

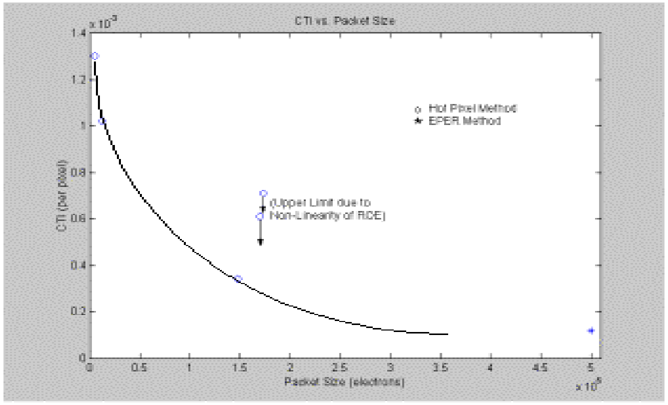

Figure 2

This device was later measured using the EPER method at a similar transfer rate and ~80% full well. Under these somewhat altered conditions, it was found to have a CTE of 0.99988 (shown in figure 2). This is also in keeping with expectations as bright field measurements like EPER are known to give better results than dark field measurements due to the 'fat zero' effect. This effect is due to passivation of charge traps by the increased number of background charges.

Figure 3 shows similar research on other EEV CCDs with similar pixel pitch at a much lower proton fluence corresponding to ~1Rad NIEL. Scaling the CTI linearly with NIEL gives an excellent comparison. The 16,000 electron background line would fall at a scaled up CTI of ~5.5x10^{-4}, while the curve at a background of 2,000 electrons has a scaled CTI intercept at ~1.7x10^{-3}, neatly encompassing the results of this study which were taken at an intermediate background level. The interesting thing to note here, is that the measured CTI at higher packet levels falls below the scaled high background assymptote defined by CTI = 5.5x10^{-4} at packet levels greater than ~80,000 electrons. In fact, the assymptotic value of the CTI at high packet levels appears to be identical to that of the previous study at ~1x10^{-4}.

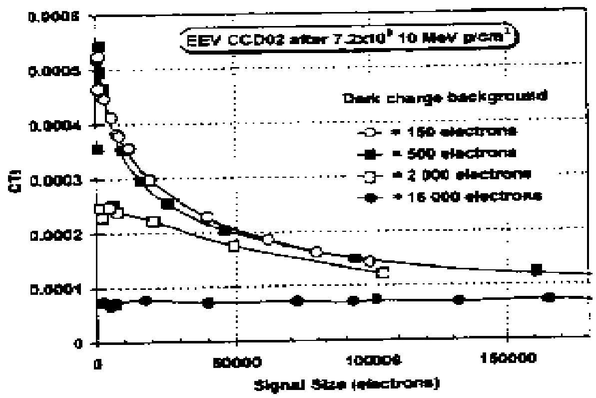

Figure 3

Conclusions

A simple new method of measuring CTE degradation has been demonstrated which relies on the monitoring of non-saturating, sharp hot-pixel defects detected in BOL CCD image telemetry. The results from this method compare well with commonly accepted measurement methods, following the expected functionality with respect to packet size.

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