

Modelling Charge Transfer on the STIS CCD

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Abstract. The Calibration Enhancement effort for the Space Telescope Imaging Spectrograph (STIS) aims to improve data calibration via the application of physical modelling techniques. We describe here a model of the Charge Transfer process during read-out of modern Charge Coupled Devices, and its application to data from STIS. The model draws upon previous investigations of this process and, in particular, the trapping and emission model developed by Robert Philbrick of Ball Aerospace.

Early comparison to calibration data is encouraging. Essentially, a physical description of the STIS CCD combined with the physics of known defects in the silicon lattice expected to arise in a hostile radiation environment, is enough to yield results which approximately match real data. Uncertainties remain, however, in the details of the model and the physical description of STIS.

1. Introduction

The STIS CCD is known to have a steadily declining Charge Transfer Efficiency, CTE, which is normal for a CCD in a hostile radiation environment (Cawley et al. 2001). Consequently, charge is lost or deferred as it is read out to the on-chip amplifier from the pixel where it was collected during the exposure.

The CCDs in *HST* instruments represent a rather unusual problem:

- *HST* orbits in a hostile radiation environment
- By contrast, ground based astronomical CCDs are not subject to bombardment from high energy radiation
- Expensive servicing mission are required to replace *HST* hardware
- CCDs used in medical imaging, X-ray crystallography, etc., can be replaced at relatively low cost when they degrade
- *HST* continues to acquire data from its CCDs which is, in all other senses, of the highest quality.
- Few other space based missions have enjoyed this longevity

Consequently, the *HST* CCDs provide an incentive for an accurate correction of CCD readout effects which does not arise in other CCD applications.

The simplest correction applicable to data suffering significant effects of poor CTE is to apply an empirically derived function relating pixel position, epoch and signal level to lost charge (Goudfrooij 2002). However, in reality charge trapping and deferral lead to more complex effects which can only be well understood by considering the transfer of charge through each pixel and potential trapping site. We discuss here an attempt to model the transfer of every electron through every pixel electrode on the STIS CCD during read out.

2. The Model

The model began as a “toy model” to help us understand the processes involved. Encouraged by the ease with which CTE phenomena were qualitatively reproduced by this model, we sought to replace our initial ad-hoc trapping and emission simulation with a more accurate representation of the physical processes involved. We were greatly assisted in this by Rob Philbrick of Ball Aerospace who had developed such a model for the Kepler mission, which will use similar CCDs to STIS (though provided by STA and E2V Technologies). Indeed Philbrick used STIS calibration data in his testing. This provided us with an emission and trapping model derived from the physics of known bulk state traps.

This modelling approach is by no means unique, however we bring together a number of features:

- Emission and capture is via the known bulk state traps summarized in the table:

Name/Description	Energy (MeV)	Capture Timescale τ_{cn} (μ s) at -83° C	Emission Timescale τ_{en} (μ s) at -83° C
P-V (Si-E)/Phosphorus Vacancy Complex	0.44	0.65	1.3E+06
O-V (Si-A)/Oxygen Vacancy complex	0.168	0.91	0.065
V-V/Divacancy	0.3	0.91	80

- The density of the traps is determined from the estimated Non-ionizing Energy Loss (NIEL) experienced by STIS appropriate for the length of time on orbit (Philbrick 2001, Robbins 2000).
- Time scales for trapping and emission for each trap type are related to their energy levels and the operating temperature.
- The state of all traps is tracked throughout the readout simulation. The initial distribution on the chip may be specified.
- The charge loss for each transfer is a function of the charge packet and the instantaneous state of the traps. There is no assumption of constant fractional charge loss.
- Electrons are treated as indivisible entities and capture and emission is modelled in a Monte-Carlo fashion (e.g., there is no floating point averaging assumption).
- Transfer of charge packets between every electrode is modelled.
- Output includes fits images of CTE degraded data, difference images and statistics of the capture and emission history of traps under every electrode.
- Other detectors suffering poor CTE may be modelled simply by specifying appropriate CCD parameters.

The implementation of these features is described in detail in Bristow & Alexov (2002).

3. Early Results

The *Sparse Field* technique makes use of the ability of the STIS CCD to read out to registers on opposite sides of the array. A sequence of nominally identical exposures is taken, alternating the readout between the registers. The observed differences between the results obtained from the two registers can be fit to a simple CTE model. Calibration data have been obtained at STScI for two tests based upon this idea.

The *internal* sparse field test uses slit images from a flat field lamp placed at various positions across the detector and read out through opposite registers (below these are the registers corresponding to the B amplifier and D amplifier). The ratio of the line of the signal readout from the slit image from the two amplifiers allows the calculation of the CTE (Kimble et al. 2001). The *external* sparse field test makes use of exposures of the outer regions of globular clusters, once again read out through opposite registers.

We take advantage of the plentiful internal sparse field data available from the STIS archive. These datasets contain slit images of varying intensity and varying distances from the amp used for readout. We choose a dataset in which the slit image is very close to the readout register so that CTE effects are likely to be small. This assumption is not critical; all that matters is that we have a slit image to use as our reference. If it has some small distortion to its shape due to *real* CTE effects this will be effectively divided out in the analysis below. We then use this as our input slit image and simulate the read out as if this line was placed at varying distances from the register. The background is also that from the real data.

In this way we are able to produce plots equivalent to those of Kimble et al. (2000). To calculate Kimble et al.’s “Amplifier B signal \div Amplifier D signal,” $\frac{B_{\text{signal}}}{D_{\text{signal}}}$, we divide the signal from a read out over y rows by another from a read out over $1024 - y$ rows. Of course our results will necessarily have the property $\left[\frac{B_{\text{signal}}}{D_{\text{signal}}}\right](y) = \left(\left[\frac{B_{\text{signal}}}{D_{\text{signal}}}\right](1024 - y)\right)^{-1}$ and in particular $\left[\frac{B_{\text{signal}}}{D_{\text{signal}}}\right](y = 512) = 1.0$. Here, y is the number of rows from the slit image to the register of the B amplifier. Indeed, deviations from this in the real results indicate either non-uniformity in the trap distribution or a difference in behavior of the readout amps.

Figure 1 top and bottom show our results plotted along with Kimble et al.’s Figures 5a and c respectively. For the lower signal level (top) the agreement is not bad for higher values of y , especially given that the loss over 512 rows is almost identical. As discussed above, the data points for $y = 512$ and below from Kimble et al. are anomalous. Also in good agreement is the centroid shift for this data, measured at 0.38 pixels in the simulation results compared to ~ 0.35 (read from Figure 6b of Kimble et al.) for the real data.

For the higher signal level (bottom) the simulation results appear to underestimate the effect of degraded CTE. The centroid shift in the simulation output is also about 40% lower than in the real data.

We have not chosen to include error bars in the simulated results. This is because uncertainty arises, at least in part, from the validity of the model itself, which is difficult to quantify and in any case this is what we are trying to ascertain with this test. Uncertainty also stems from the physical parameters of the STIS CCD. If this uncertainty was represented by error bars then the dominant contribution would come from our lack of knowledge of the exact dimensions and effectiveness of the STIS mini-channel (this is discussed in somewhat more detail by Bristow & Alexov 2000).

A more accurate fit to the real data is always possible by arbitrarily fixing trap densities and trapping and emission constants, but we have plotted the values for the theoretical values of these parameters only.

4. Conclusions

We have developed a simulation of the CCD read out process that attempts to reproduce quantitatively the effects of poor CTE in realistic astronomical data. This approach is by no means unique, but we attempt to build upon recent progress in the understanding of the underlying processes. The simulation has been customized to the STIS CCD, but is, in principle, portable to other space based instruments. Moreover, the model is adaptable to differing operating conditions, illumination patterns and levels of radiation damage.

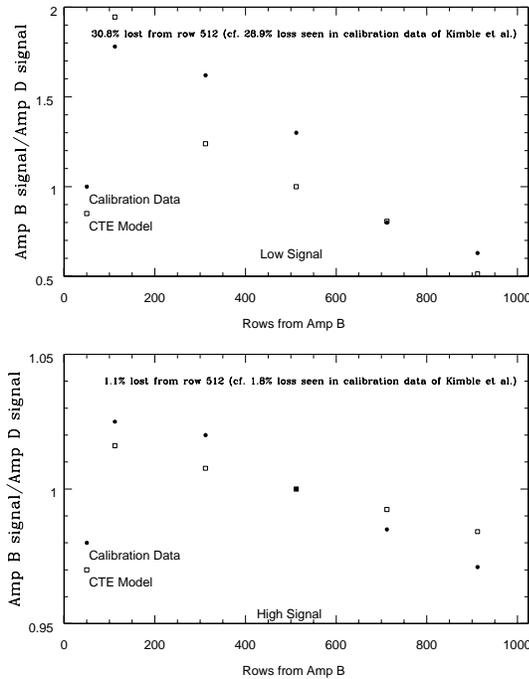


Figure 1. Top: Signal per column for 60e⁻ (cf. Kimble et al. 2000, Figure 5a).
Bottom: Signal per column for 3400e⁻ (cf. Kimble et al. 2000, Figure 5c)

The simulation gives an insight into the processes involved and serves as a useful tool for better understanding CTE. It reproduces qualitatively, known degraded CTE phenomena. Preliminary quantitative results are encouraging. Without any empirical tweaking of the models physical parameters we are able to get an approximate match to various values of CTE measured in orbit. These comparisons now need to be extended to a wider range of data, CTE measurement techniques and radiation damage levels. Simultaneously we intend to improve the physical model by reducing the uncertainty in some parameters and better understanding some processes. It will be interesting to see if this brings the results into closer agreement with the data.

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