
STIS Model Based Charge Transfer Inefficiency Correction

Example Science Case 1: Proper Motions of Dwarf Galaxies

P. Bristow

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Abstract

The STE-CF Calibration Enhancement effort for the Space Telescope Imaging Spectrograph (STIS) aims to improve data calibration via the application of physical modelling techniques. As part of this effort we have developed a model of the STIS CCD readout process that is able to correct STIS data for charge transfer inefficiency (CTI). The model itself is described in some detail in earlier ISRs. Here we give an example of a science case utilizing STIS data, which would be enhanced by this CTI correction: the measurement of the proper motion of Galactic dwarf spheroidal galaxies undertaken by Piatek et al.

Without reproducing the entire detailed and thorough analysis involved in the published science case, we demonstrate that apparent centroid shifts introduced by CTI can be as much as ~ 25 mas/century, which is of the order of the proper motion measured by the authors. Moreover the apparent shifts are a function of epoch and position on the CCD detector as well as being aligned within a given dataset. It is unlikely that the proper motion measured by Piatek et al is solely a manifestation of CTI, indeed over the various datasets which they used the CTI induced shifts may, to some extent, cancel out, particularly in cases where the QSO is close to the centre of the chip. However, the true influence of CTI in Piatek et al's data can only be ascertained by applying their analysis to the CTI corrected datasets, now available for STIS using our CTI pre-processor.

1.Introduction

Charge Coupled Devices (CCDs) operating in hostile radiation environments suffer a gradual decline in their Charge Transfer Efficiency (CTE, or an increase in charge transfer inefficiency, CTI). STIS and WFPC2 on HST have both had their CTE monitored during their operation in orbit and both indeed show a measurable decline in CTE which has reached a level which can significantly affect scientific results (e.g. Cawley et al 2001, Heyer 2001, Kimble, Goudfrooij and Gililand 2000).

Instead of seeking empirical corrections, as derived by Guodfrooij and Kimble (2002), we have chosen to construct a physical model that allows us to correct the effects of poor CTE in STIS data. Detailed discussion of the model development and the physics involved can be found in Bristow & Alexov et al. (2002) and Bristow (2004b). Bristow (2004a) provides an overview of the beta pipeline pre-processor that applies the model-derived corrections to STIS datasets. Testing and validation of the model for STIS imaging data is described in Bristow 2003.

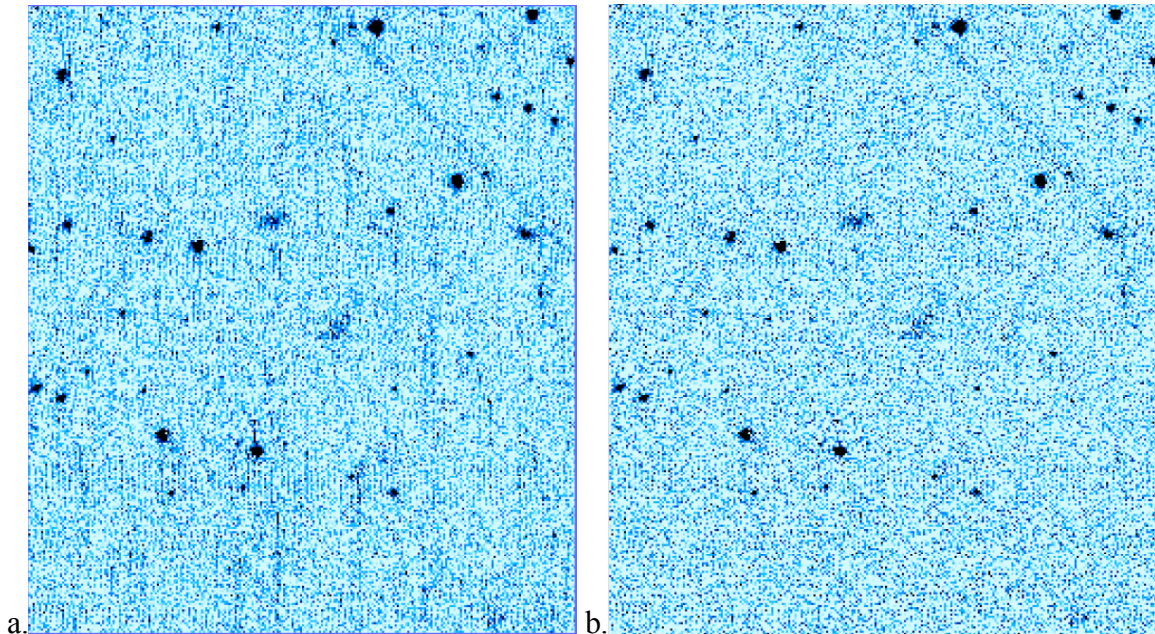
The model-based approach offers several advantages over empirical corrections that are restricted to correcting only the total flux and only for isolated point sources on a smoothly varying background. Moreover empirical corrections require calibration for differing signal strength, background, epoch and position on the CCD and mode (imaging vs. spectroscopic). The model we have developed is able to account for the variations in CTE with these parameters. In addition the model allows correction of the flux distribution itself so that the morphology and astrometry are corrected as well as the photometry.

In this paper we give an example of a published STIS science case that could benefit from the application of the model-based CTI correction. Piatek et al. 2002 and Piatek et al. 2003 (hereafter P03) set out to detect and measure the motions of dwarf spheroidal galaxies (dSph) in the neighbourhood of the Milky Way Galaxy by comparing the relative positions of constituent stars to a QSO(s) along the line of sight at several epochs spanning several years using STIS imaging data and WFPC2 PC data. The accuracy of the astrometry required to make such measurements pushes even HST's instruments to their limits. Exactly the sort of measurement, in fact, that would be sensitive to the very small systematic offset of centroids introduced by CTI. Piatek et al's analysis employed dithered exposures to better sample the PSF, a rigorous determination of the effective PSF, strict selection criteria for the stars considered and took proper account of effects such as geometric distortion. There is however no mention given to the possible effects of CTI, perhaps not surprising as until now there has been no method available for correcting anything more than average flux in point sources.

Piatek et al's analysis is far too detailed for us to reproduce in its entirety. Instead we simply illustrate how the centroids of stars in Piatek et al's STIS data will be affected by CTI in a systematic way as a function of signal, epoch and position on the CCD detector. We restrict ourselves to consideration of the STIS data, as we do not yet have an implementation of the CCD readout model for WFPC2, however WFPC2 PC data is likely to be effected in a very similar way.

2.CTI Induced Shifts

Imperfect charge transfer results in some fraction of the charge contained in large charge packets being left behind as the charge packet is transferred out across the chip. The charge left behind is likely to then join a subsequent, smaller, charge packet (e.g. Janesick 2001). This causes the familiar CTI trails seen in CTI affected data in which the flux of bright sources has a trail in the direction away from the readout register. Figure 1a is an example of this phenomenon as seen in one of the datasets used in the proper motion study we are concerned with here. Figure 1b shows the same data after our model based CTI correction has been applied. In these figures, and in all of the following discussion, the readout direction is upwards towards the upper STIS register and the D amplifier. This redistribution of charge/flux has several consequences. The apparent total flux of the source is reduced (some flux is redistributed outside of the measured isophotes), the peak intensity is reduced, the morphology is altered and the centroid is shifted in the direction away from the readout register. Until now only the former could be corrected, by the application of empirical corrections. The effect upon morphology and centroid are relatively small, but where STIS astrometry is pushed to its limit, as in the case considered here, it is not negligible.



• Figure 1: a) Section of the dataset o6d905040 showing CTI trails (vertical streaks). b) The same section after application of the model based CTI correction. The readout direction is upwards. Both sections have had the standard CALSTIS pipeline applied and are the result of combining multiple exposures.

Analysis of CTI affected data has revealed that the flux loss from sources is a function of position on the chip (distance from the read out register), background, signal strength and epoch (e.g. Kimble et al. 2000). This can be understood if we consider a population of charge traps on the detector that are produced by radiation damage. The epoch dependency reflects the increasing radiation damage suffered with time on orbit. Larger charge packets have a greater cross-sectional area and therefore encounter more traps. Higher background signals will fill traps leaving less empty traps to be filled by signal from the source. Clearly the greater

the distance from the readout register the more transfers are needed and more chances for trapping exist. This is reflected in the empirical corrections available for CTE (Goudfrooij, Dolphin 2002) and is reproduced by our readout model (Bristow 2003a).

The magnitude of centroid shift has not been so precisely parameterised but will clearly be dependent upon the same factors. Moreover the centroid shifts will always be in the same direction, aligned with the parallel axis and away from the readout register (we are ignoring the very small serial CTI effect which in theory contributes a component along the serial axis, but will be extremely small). Therefore within each STIS field the centroids of sources will have been shifted downwards by an increasing amount with increasing distance from the readout register (at the top) and with some variation according to the flux of the individual sources. The effect will be larger in more recent datasets (more radiation damage) and will also show some dependence upon the varying sky backgrounds between the frames.

3. Corrections to datasets

Crucial to Piatek et al's study is the centroid shift of the quasar relative to the stars in the Galactic dSph Carina. The readout model enables us to correct raw data sets for CTI and compute the centroid shift between sources (stars in the dSph Carina and the quasar itself) in the fully reduced frames with CTI correction and their counterparts in fully reduced frames without CTI correction.

We restrict ourselves to a study of just two of the datasets used in P03

O5BL05010 10th April 2000

O6D905040 6th April 2002

They are observations of the same field, **Car J0640-5055** (centred on R.A. 06 40 59.20 Decl -50 55 41.00 J2000.0), each consisting of three 207 second CR-split sub-exposures. P03 there considered a further 21 STIS exposures of this field at different dither positions at each epoch and an intermediate epoch (April 2001). In addition P03 utilised a similar set of WFPC2 PC exposures of a nearby field in the Carina dSph that also contains a QSO. The proper motion Piatek et al derive from these observations is approximately 25 mas/century, or 0.015 pixels over 2 years .

The CTI correction must be applied to the raw data (see Bristow 2003c). We did this for the datasets in Table 1 and then ran the standard CALSTIS reduction pipeline. We also applied CALSTIS to a copy of the raw data that had not had the CTI correction. Source detection was then carried out on both versions of the calibrated data using using SExtractor (Bertin 2003) and applying the same correction criteria as P03. That is sources must contain a central grid of 5x5 pixels for which:

$$S/N = \frac{\sum_{i=1}^{25} v_i}{\left(\sum_{i=1}^{25} u_i^2\right)^{1/2}}$$

is more than 15. Here v_i is the signal in a pixel (corrected for the sky) and u_i is the uncertainty

in v_i . Both sums include only those pixels whose data quality flags equal zero. In addition the central 3×3 pixels must all have data quality flags equal to zero. Sources that were clearly not stars were also excluded.

The source lists for the CTI corrected and CTI uncorrected datasets were matched and a number of difference and ratio parameters derived. Some of the more useful parameters are plotted in figures 2 and 3 for the datasets considered.

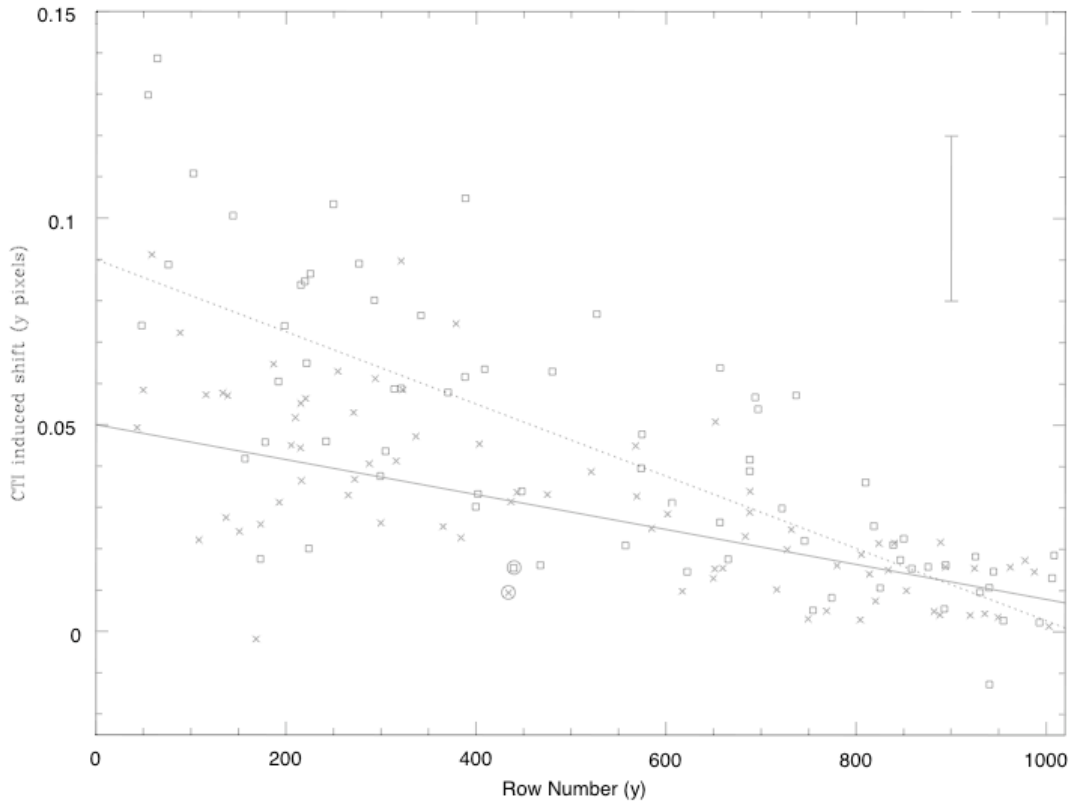


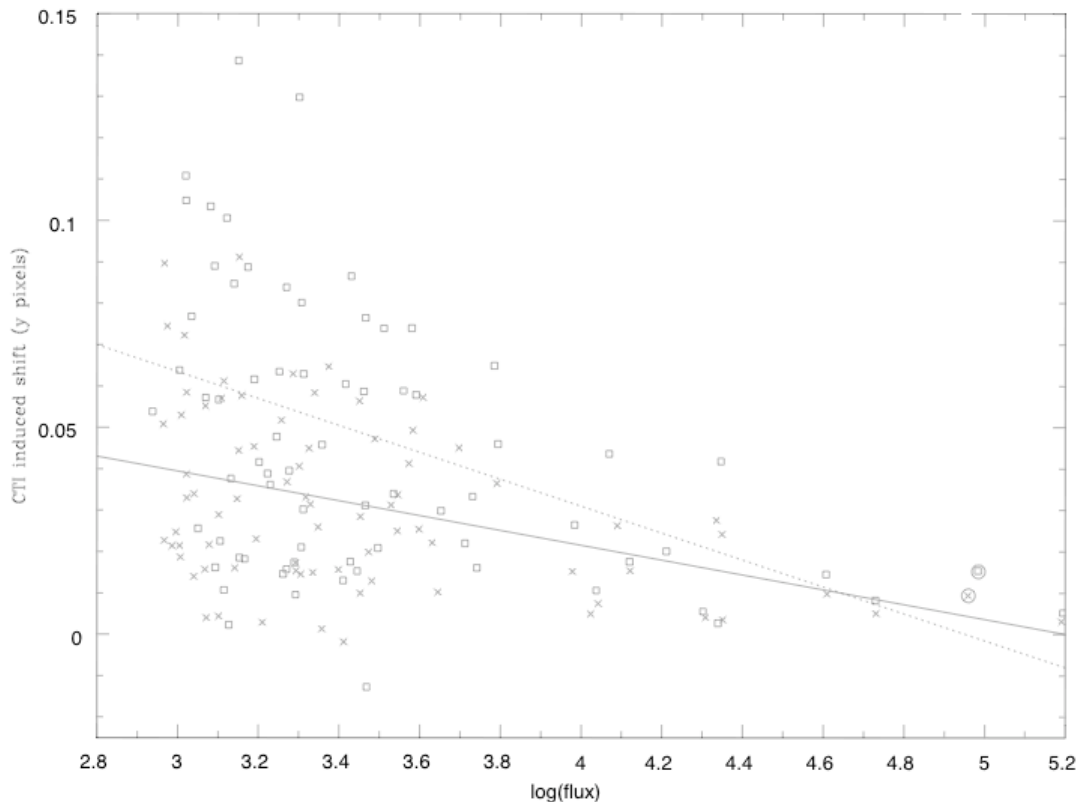
Figure 2 CTI induced centroid y -shift for sources in the earlier epoch O5BL05010 (crosses) and later epoch O6D905040 (squares) datasets. The solid and dotted lines are linear fits to the O5BL05010 and O6D905040 data respectively. The QSO, as it appears in each image, is ringed. For comparison the error bar represents the scatter in centroid differences for sources from different epochs when put into the same reference frame in P03.

Figure 2 shows the y shift in the centroid of the central 5×5 pixels of sources, selected as above, caused by CTI as a function of row number (y) for data from 2 epochs. A positive shift is here defined as the true centroid being above the centroid in CTI degraded data, i.e. higher (positive) shifts mean that CTI has caused the apparent centroid to shift further down the image array. The crosses, from the 2000 O5BL05010 dataset, clearly have a weaker dependence upon row number than the squares, from the 2002 O6D905040 dataset. The two linear fits, solid and dotted for crosses and squares respectively emphasize this. The difference between the two linear fits gives an idea of the mean relative CTI induced y shift between the two epochs as a function of row number.

It may seem strange that this row dependency didn't show up in the analysis of P03, however, it may have been hard to detect given the uncertainty introduced in trying to match the centroids of stars as they appeared in several different pointings. Also shown in figure 2 is an error bar representing the scatter in centroid differences for sources from different epochs (see e.g. P03 figure 14). This uncertainty, deriving presumably from shot noise in the sources, contamination from Galactic stars and proper motion amongst Carina's stars, could easily be enough to mask the difference between the two linear fits in 2.

The QSO, as it appears in each dataset, is ringed. It appears, in both cases, to have suffered relatively little CTI induced y shift for its row number. This is likely due to the fact that it is a relatively bright source and it is in an area of relatively high background due to the halo of the nearby bright star.

We also expect the CTI induced shift to depend upon the source flux. Figure 3 is a plot of the y shift, as in figure 2, as a function of source flux for data from the two epochs. As we would expect, the shift is smaller for higher fluxes. Once again we see that the dependency is stronger for the later epoch (squares, dotted line), the average shift is greater for the later epoch and the quasar (ringed) suffers relatively little CTI induced y shift in both epochs.



• Figure 3 The CTI induced centroid y -shift as a function of the log of the source flux. The symbols are as in figure 2.

Once again it is the difference between the two linear fits that is interesting. For a given flux,

the difference in CTI induced y -shift is the difference between the lines at that flux. Most stars would suffer a greater CTI induced y -shift than the QSO, more so at the later epoch than the earlier epoch.

We also expect the strength of CTI effects to depend upon the background signal. Within a given dataset the background does not vary a great deal and this trend is not clear. However, by chance, the average background is lower in the more recent dataset, this will also lead to stronger CTI effects in addition to the greater radiation damage present on STIS at the later epoch.

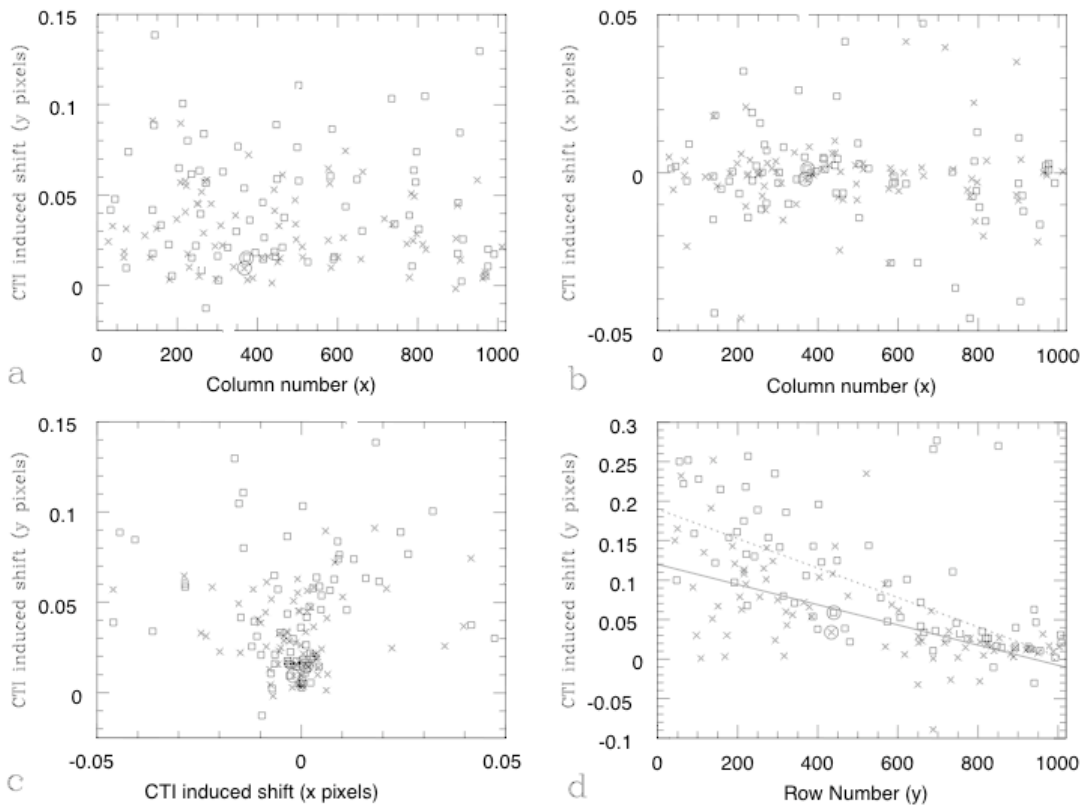


Figure 4 All symbols are as in figure 2 a) CTI induced centroid y -shift as a function of column number, x . b) x -shift as a function of column number, x . c) x shift versus y shift d) As figure 2 but here the y -shift is calculated from the centroids measured for the entire object by SExtractor.

Figure 4 contains several plots that are essentially sanity checks. Figure 4a demonstrates that there is no dependency of y -shift upon the column (x co-ordinate). Similarly, 4b demonstrates that the small x -shifts seen between CTI corrected and CTI un-corrected data are not correlated with x position. Figure 4c shows the distribution of shifts in x and y space. Finally Figure 4d is similar to Figure 2 except that we have used centroids measured by SExtractor for the entire spatial flux distribution in each object as opposed to the central grid of 5×5 pixels to derive the shifts. The result is much the same

4. Possible impact upon the determination of Carina's proper motion

The analysis presented in Piatek et al (2002 & 2003) is extremely thorough and overcomes many of the potential complications inherent in making such precise astrometric measurements over a long time baseline. Indeed, it is because this study *is* so meticulous and leaves nothing to chance, that it is worth considering if the, until now, insoluble problem of CTI distortions to centroid positions may compromise the results. After all, it would now be possible to reproduce the analysis with CTI corrected STIS data.

A simple estimate as to the impact of CTI upon the proper motion measured can be made by considering Figure 2. Here we see that, on average the centroid of the Carina stars has been shifted down the detector in the later epoch data by 0.02 pixels relative to the earlier epoch data. On the other hand the QSO has been shifted down the detector in the later epoch data by at most 0.005 pixels relative to the earlier epoch data. This would appear as a proper motion of 0.015 pixels over 2 years or 0.5 pixels/century (~ 25 mas/century), which is of the same order as the proper motion derived P03.

Of course this ignores the differential shifts of the sources within the detector field. Moreover Piatek et al's analysis of the Carina cdSph involves two fields imaged with two different detectors with different CTI properties. The relative shift of the QSOs in each field depends upon their positions and brightness relative to the stars of the Carina dSph sampled. The different detectors have different CTI properties which each have their own dependence upon epoch. The extent to which CTI effects may cancel out is therefore very difficult to estimate, but it would seem very unlikely that the measured proper motion was purely a manifestation of CTI.

CTI may also impact Piatek et al's analysis in a more subtle way than just the systematic centroid shifts. The analysis depends upon transforming the positions of centroids imaged at different epochs onto a single co-ordinate system. As noted in P03:

To ameliorate the impact of the small number of stars on the accuracy of the [effective]PSF, we use all of the dither images available for a field at a given epoch to generate a single esp. This procedure effectively increases the number of stars contributing to the ePSF, at the cost of assuming that the ePSF neither varies among the images at one epoch or within the images.

However, it is clear from the CTI model is that, even if the PSF were consistent across the images in the absence of CTI, it will not be in reality. We find that, for the O6D905040 data, the sources imaged at the bottom of the CCD have, on average, had their isophotal areas increased by more than 15% due CTI, whereas those imaged at the top of the CCD experience no such effect. FWHM and elongation show similar dependence upon the position on the chip.

With the current simple analysis, it is not possible to be more precise about the impact of CTI upon Piatek et al's results. The way in which the differential shifts of individual sources feeds through to the final result is somewhat convoluted. Clearly the only way to fully understand the impact of CTI upon Piatek et al's analysis would be to redo their analysis with the CTI corrected image data, which is now available (cf. CTI pre-processor for CALSTIS (Bristow 2004a)

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