Astronomical Data Analysis Software and Systems XIII
ASP Conference Series, Vol. 314, 2004
F. Ochsenbein, M. Allen, and D. Egret, eds.

Maintaining Software for Active Missions: a Case Study of Chandra's CTI Problem

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Abstract. During early flight operation, the Chandra X-ray Observatory's Advanced CCD Imaging Spectrometer (ACIS) suffered degradation of charge transfer inefficiency (CTI) due to radiation induced charge trapping. The ACIS front-illuminated detector CTI has significantly degraded over time with respect to the intrinsic energy resolution of the chips. In this presentation we use the degradation of CTI in the ACIS camera as an example of how software was adapted to fix a significant and unforeseen post-launch problem in on-board hardware. We will discuss the impact of CTI on events, RMF and gain files. Then, we will discuss the software updates necessary to alleviate the degradation effects and to improve spectral resolution. Finally, we will highlight other ACIS hardware problems and their corresponding software solutions.

1. Introduction

As hard as engineers may try to foresee and hardware problems leading up to the launch of a space-based telescope, these problems are nearly impossible to prevent. For an unserviceable mission such as the Chandra X-Ray Observatory, the issue of hardware problems takes on greater significance for the success and ultimate fate of the mission. Even for serviceable missions, to fix a problem with software is usually more cost effective than replacing or repairing on-board hardware.

CTI and Chandra When either X-rays or cosmic rays deposit charge in an ACIS CCD, the deposited charge is read out from one of four sets of read-out nodes (256 x 1024 pixels). Because charge is read out at only one location on a node, the charge at all other locations must be moved to the read-out. Charge is moved both vertically (i.e. in the negative CHIPY or "parallel" direction) and horizontally (i.e. in the positive or negative CHIPX or "serial" direction). As charge is moved, some may be lost to charge traps that are distributed across the detector. The mean fractional amount of charge lost per pixel transferred is called the charge transfer inefficiency (CTI).

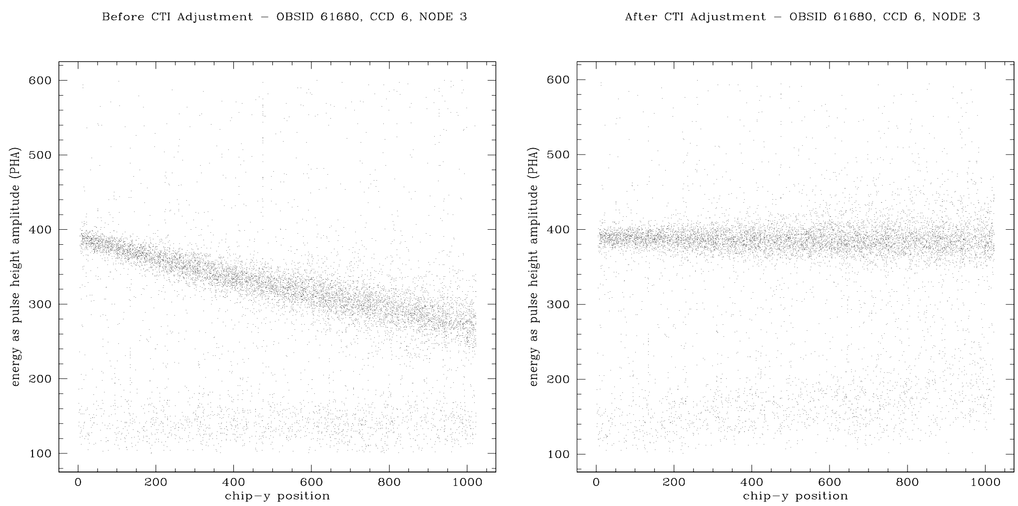

Figure 1. Energy plots across a CCD before (left) and after (right) the CTI correction.

Shortly after the launch of the Chandra Observatory, the ACIS detector (one of two primary science instruments) suffered severe degradation to its charge transfer inefficiency due to soft proton damage, resulting in loss of energy resolution and the elimination of some events that would otherwise be considered good.

2. Data Impact of CTI

The increase in CTI had a significant impact on the quality of Chandra science data. Listed below are some of the effects and how they were caused by CTI.

Grade Migration When charge is captured by a CCD the energy is divided within an "event island", usually 3 pixels by 3 pixels. The distribution of charge within the island determines the GRADE of the event. When the event is read out across the detector, its charge is "smeared out" in the read-out direction due to the effects of CTI. This smearing redistributes some of the charge and may change the GRADE of some events.

Detection Efficiency When event GRADEs with "good" values change to "bad", the result is that the events are excluded from Level 2 event files and there is an apparent reduction in the detection efficiency of a CCD.

Gain Shift The amount of charge read out from an event will be less than the amount of charge deposited on the detector. The difference in charge will depend on the number of pixels crossed before reaching the read-out node. Thus, the loss of charge at the top of the chip will be greater than when charge deposited near the read-out node. The pulse-height distribution for a source will be shifted to lower energies and result in an apparent gain shift.

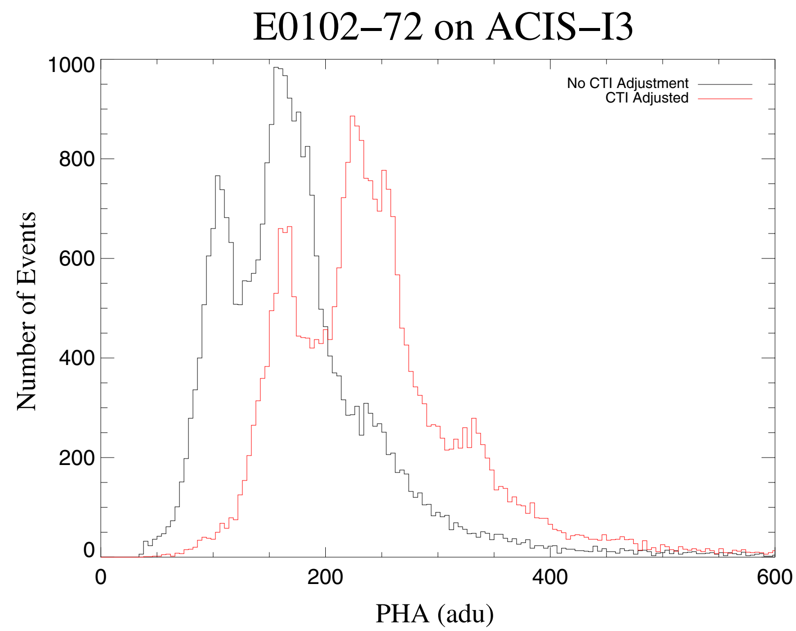

Figure 2. An energy spectrum before and after the CTI adjustment.

Spectral Resolution CTI also causes degradation in the energy resolution of a CCD. The pulse-height distribution of line features is broadened. This spectrum shift is also spatially dependent, being greatest at the furthest point from the read-out node.

3. Software Impact of CTI

In order to resolve the impact of CTI on data, software changes were made in several areas of the Chandra data processing system.

Tools The core event processing tool that computes energies and performs coordinate transformations was changed in order to incorporate a correction algorithm developed by teams at Penn State and MIT. The algorithm estimates the amount of charge deposited on a CCD for an event based on the amount of charge read out and the location of the event on the detector. New parameters were added to the tool to make use of new calibration files and for controlling when to implement the algorithm. The CTI adjustment reverses nearly all of the apparent gain shift and can significantly improve the energy resolution of a detector. The grating event processing tool also had minor updates to handle new calibration files.

Calibration The calibration changes were a major portion of the CTI correction effort. In particular, the Redistribution Matrix File (RMF) and gain tables needed to be re-calibrated to use the CTI-corrected data. The updates for RMFs alone involved dramatically increasing the number of input Fits Embedded Function (FEF) files, changing the format of the FEF to handle regions within a node, creating weighted RMFs as input for extended sources, and developing a new method to produce PI-RMFs to save time.

Pipelines Ultimately all of the software changes were destined for the standard processing pipelines. Updating the pipelines meant using the new calibration database and performing many regression tests to verify that the correction was working well in the context of an automated processing environment. The software correction for CTI became available to the Chandra user community through standard data processing on March 6, 2003.

4. Examples of Other ACIS Hardware Issues

CTI is one issue affecting the quality of science data produced the the Chandra X-Ray Observatory. Listed below are several other hardware problems that have been or will be fixed by software.

Horizontal streaks Some ACIS CCDs, the S4 chip of the S-array in particular, were found to have spurious horizontal streaks. The streaks were not removed by standard grade, status, or bad pixel filtering. A tool was created to remove these streaks without affecting the scientific significance of the data.

Vertical streak with bright source While ACIS reads out, it is still taking data. Photons detected during the read-out are clocked out in the wrong row and so have incorrect CHIPY values. For a bright source, a streak appears all along the column (on both sides of the source, since some events are from the previous exposure).[1]

A software tool was developed to remove the streak from the image for cosmetic reasons and so that it doesn't affect source detection. The tool also retains the streak photons, which have more accurate timing information and are not affected by pile-up.

Quantum Efficiency (QE) at low energies The optical filter above the ACIS camera has experienced a gradual increase of a contaminant resulting from the out-gassing of solid adhesives within the telescope since launch. As a result, the sensitivity of ACIS has gradually decreased at low energies. Most likely in the near future, the instrument will be heated to "bake-off" the contaminant, then brought back to the lower operating temperature. There have been and will continue to be software changes to ameliorate this problem.

Acknowledgments. This work was supported by NASA contract NAS8-39073.

References

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[1] http://cxc.harvard.edu/ciao/threads/acisreadcorr/