Sacrificial Charge and the Spectral Resolution Performance of ACIS CCDs

Catherine E. Grant, Gregory Prigozhin, Beverly LaMarr, Mark W. Bautz
MIT Center for Space Research

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Abstract

Soon after launch, the Advanced CCD Imaging Spectrometer (ACIS), one of the focal plane instruments on the Chandra X-ray Observatory, suffered radiation damage from exposure to soft protons during passages through the Earth’s radiation belts. The ACIS team is continuing to study the properties of the damage with an emphasis on developing techniques to mitigate charge transfer inefficiency (CTI) and spectral resolution degradation. A post-facto CTI corrector has been developed which can effectively recover much of the lost resolution (Townsley et al. 2000). Any further improvements in performance will require knowledge of the location and amount of sacrificial charge - charge deposited along the readout path of an event which fills electron traps and changes CTI. We report on efforts by the ACIS Instrument team to characterize which charge traps cause performance degradation and the properties of the sacrificial charge seen on-orbit. We also report on early attempts to correct for the presence of sacrificial charge.
1 ACIS Radiation Damage

A symptom of radiation damage in CCDs is an increase in the number of charge traps. When charge is transferred across the CCD, some portion can be captured by the traps and re-emitted later. If the original charge packet has been transferred away before the traps re-emit, the captured charge is “lost” to the charge packet. This process is quantified as charge transfer inefficiency (CTI), the fractional charge loss per pixel. The front-illuminated ACIS CCDs suffer from radiation damage from low energy protons, so only the imaging region of the CCD is affected. The charge loss occurs as photons are transferred from the image array to the framestore along the CHIPY direction. Four flavors of charge trap have been identified on the ACIS FI CCDs. The estimated fractional abundances and emission time constants measured at -120°C are of order 4% with 60 μs, 46% with 400 μs, 26% with 2 msec, and 24% with > 3 sec (Bautz et al. 2001).

2 Sacrificial Charge

Measured CTI is a function of fluence or, more specifically, the amount of charge deposited on the CCD. As the fluence increases, traps filled by one charge packet may remain filled as a second charge packet is transferred through the pixel. The second charge packet sees fewer unoccupied traps as a result of the previous “sacrificial charge” and loses less charge than it would have otherwise.

Since each X-ray event sees traps with different charge histories, the measured pulseheight for each event can be substantially higher or lower than the average. The importance of sacrificial charge to the overall performance is determined by the emission time constants of the charge traps and the frequency of sacrificial charge deposition. During a typical calibration source run, an average of 2% of the pixels have more than 40 ADU of charge - much of that due to cosmic rays. On average an X-ray event will encounter sacrificial charge of at least this magnitude every 60 rows as it is transferred to the framestore. One of the ACIS traps has a time constant similar to the average time between sacrificial charge events (~ 2 msec = 50 rows), so the traps encountered by each event can be in a wide range of occupancy states, which is a source of spectral resolution degradation.

Figure 1 illustrates how detrapping time constants and sacrificial charge frequency interact. The idealized input charge distribution fills the charge traps every 200 transfer pixels. The charge is drained away exponentially with a time constant of 100 μsec (blue), 1 msec (green) or 1 sec (red). The millisecond trap spends much of the time in intermediate states, while the shortest and longest traps are either empty or full.

3 CTI Correction

Since the charge loss process can be modeled, it is possible to apply a post-facto correction algorithm to replace the lost charge and recover some of the detector’s spectral resolution. Townsley et al. (2000) describe a CTI correction algorithm in which a position and pulseheight dependent correction is made to each pixel in the event island. Their model also accounts for sacrificial charge shielding and charge trailing within the event itself. A similar but not identical algorithm is being implemented by the Chandra X-ray Center as part of acis_process_events. Charge loss in this algorithm is parameterized as a power law function of energy with a power law index, α, close to 0.5. CTI correction removes the position dependence of pulseheight and provides substantial improvement in spectral resolution. While a CTI corrector can be calibrated to match charge loss
induced by differing global levels of sacrificial charge, the spectral resolution degradation caused by sacrificial charge remains.

4 Data

Because most of the sacrificial charge deposited on the CCD is from cosmic rays that are rejected by on-board event processing, standard ACIS event lists are insufficient for this study and raw data are required. Since May 2001, ACIS has periodically been taking External Calibration Source data in a special telemetry format that packs raw data such that many consecutive data frames can be telemetered (Primary spectral features are Al-K at 1.5 keV, Ti-Kα at 4.5 keV and Mn-Kα at 5.9 keV). Only a 16-column wide strip of I3 node 3 is telemetered. The data used in this study represent approximately 200 ksec taken over 10 months immediately before and after radiation belt passages. The focal plane temperature was -120°C. The raw frames were processed to select events, much like on-board, and to record the distance and pulseheight to each of the precursor charges for each event. Only precursors that have more charge than any preceding precursors are included.

5 Sacrificial Charge Correction

We are attempting to develop algorithms to correct X-ray event pulseheights based on their sacrificial charge history. For each X-ray event $X$, we define $Z_X$, which represents the sacrificial charge history of the event as an equivalent difference in transfer distance induced by the presence of sacrificial charge.

$$Z_X = \sum_{i=1}^{N} \left[ \left( \frac{p_i}{p_X} \right)^{\alpha} - \left( \frac{p_i-1}{p_X} \right)^{\alpha} \right] (y_X - d_i) e^{-d_i/\tau}$$

where,
\((p_X, y_X)\) are the pulseheight and CHIPPY of the X-ray event \((p_0 \equiv 0)\)

\((p_i, d_i)\) are the pulseheight and distance to precursor charge \(i\)

(if \(p_i > p_X\) then \(p_i = p_X\))

\(\alpha\) is a power law index such that \(p^\alpha\) is proportional to the volume occupied by charge \(p\) \((\alpha \sim 0.5)\)

\(\tau\) is the time constant of the charge traps expressed in rows

(1 row = 40 \(\mu\)s, \(\tau \sim 25\) rows)

Events with large values of \(Z\) are most influenced by sacrificial charge. Figure 2 demonstrates the dependence of pulseheight on \(Z\) at 5.9 keV. At high \(Z\), the pulseheight is nearly a linear function of \(Z\), while at very small values of \(Z\) the dependence has been modeled as an exponential function. The line is a fit to the data of a linear plus an exponential function. Our preliminary precursor correction uses this function to correct the pulseheight of each event and, as seen in the performance comparison figures, does improve the spectral resolution.

![Pulseheight dependence of Z at 5.9 keV](image)

Figure 2:

6 Performance Comparison

Figure 3 shows the pulseheight of each X-ray event versus its row number.

**Top panel - Uncorrected data** The pulseheight of each spectral line drops with increasing transfer distance. The spectral resolution is also a function of position and degrades with increasing transfer distance. Near the framestore, at low row numbers, the performance of the device is essentially the same as before the radiation damage.

**Middle panel - CTI corrected data** A position and pulseheight dependent correction has been
Figure 3: This figure shows the pulseheight of each X-ray event versus its row number for data that is uncorrected (top), has been corrected for CTI (middle) and has been corrected for CTI and precursor charge (bottom)
made to each pixel in the event island. The pulseheight of each spectral line is now independent of row. The spectral resolution is improved, although some position dependence remains.

**Bottom panel - CTI and precursor corrected data** After a standard CTI correction, the event pulseheights have been further corrected for the presence of precursor charge along the transfer direction. This further improves the spectral resolution as a function of row which can best be seen by the better separation of the Mn and Ti K-α and K-β lines.

![Energy vs Counts for ACIS-I3, CHIPY > 800, T = -120C, G02346](image)

Figure 4: Figure 4 compares the pulseheight spectra at 5.9 keV for data above row 800. **Green** - Uncorrected data, **Blue** - CTI corrected data, **Red** - CTI and precursor corrected data

Figure 4 shows the pulseheight spectra at 5.9 keV for data above row 800 (The I3 aimpoint is at row 964). An offset has been added to the uncorrected pulseheights to account for the position dependent gain. The precursor correction removes the high energy shoulder of the response and clearly improves the separation of the Mn-Kα and Kβ lines.

Figure 5 shows the FWHM of the spectral lines at 5.9 keV and 1.5 keV as a function of row number (The I3 aimpoint is at row 964). Applying the precursor correction as well as the CTI correction improves the FWHM by up to 12% at 5.9 keV and up to 9% at 1.5 keV. At the highest row bin, the FWHM at 5.9 keV improves from 386 ± 6 eV with no corrections, to 277 ± 3 eV with CTI correction alone, and to 247 ± 3 eV with CTI and precursor correction. The improvement is smaller at 1.5 keV, even though one might expect that sacrificial charge would become more important at lower energies.

### 7 Discussion and Future Improvements

While our preliminary sacrificial charge correction algorithm does offer some improved performance, we believe that a more substantial improvement may be possible. It may also prove possible to define a filter in $Z$ which removes the events most affected by sacrificial charge without significantly degrading the detection efficiency. Future improvements may include the following.
Figure 5: This figure shows the FWHM of the spectral lines at 5.9 keV and 1.5 keV as a function of row number. **Green** - Uncorrected data, **Blue** - CTI corrected data, **Red** - CTI and precursor corrected data

- More accurate values for $\alpha$, the charge volume power law index, and $\tau$, the trap time constant.
- Re-examination of the parameterization of $Z$.
- Better parameterization of the energy dependence. Current correction is calibrated at 5.9 keV and scaled to apply to all energies; better results at low energies may be possible by a different energy scaling.
- Consideration of sacrificial charge in all three columns of the event island; currently only sacrificial charge in the center column is included.

If a correction or filtering scheme does provide significant performance improvement, its implementation will require changes to the flight software to telemeter additional information about the precursor charge with each event without making a significant impact on telemetry saturation. Such a patch is under development by the ACIS team.

**References**
