The onboard calibration for the spaced-row charge injection of the Suzaku XIS

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ABSTRACT

The energy resolution of the X-ray CCDs onboard the Suzaku satellite (X-ray Imaging Spectrometer; XIS) has been degraded since the launch due to radiation damage. To recover from this, we have applied a spaced-row charge injection (SCI) technique to the Suzaku XIS in orbit. By injecting charge into CCD rows periodically, the energy resolution 14 months after launch is improved from 210 eV to 150 eV at 5.9 keV, which is close to the resolution just after the launch (140 eV). Additional information on these results is given in a companion paper by the XIS team. In this paper, we report the details of CCD charge transfer inefficiency (CTI) in the SCI mode, the correction method, and the implementation of it in ground analysis software for XIS data. In the SCI mode, CTI depends on the distance of a charge packet from the nearest charge-injected row, and the gain shows a periodic non-uniformity. Using flight data obtained with the onboard calibration sources, as well as a cosmic source (the Perseus cluster of galaxies), we studied the non-uniformity in detail. We developed a method to correct for the non-uniformity that will be valuable as the radiation damage progresses in future.

Keywords: X-ray, CCD, Charge Injection, Suzaku satellite

1. INTRODUCTION

The Charge Coupled Device (CCD) has been the main detector for imaging spectroscopy in X-ray astronomy since the ASCA/SIS\textsuperscript{1} because of its high positional and energy resolution. However, a drawback of an X-ray CCD in orbit is the degradation of the gain and energy resolution due to the increase of the charge transfer inefficiency (CTI). CTI is defined as the ratio of lost charge to transferred charge in one pixel by one transfer. CTI causes gain to depend on the position of an X-ray event within the detector because more charge is lost from pixels farther from the readout node. If uncorrected, the positional dependence of the gain degrades the energy resolution. The main origin of CTI is the increase in the number of charge traps. Radiation damage in orbit generates defects in silicon that can trap transferred charge. Measuring the CTI accurately and correcting the amount of the lost charge with ground software, especially using the column-to-column CTI correction method,\textsuperscript{2} can greatly reduce the positional dependence of the gain and improve the energy resolution to some extent. The

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energy resolution, however, inevitably becomes worse in spite of the CTI correction because charge trapping is a random process and the number of trapped charges fluctuates, and so cannot be perfectly corrected.

The X-ray Imaging Spectrometer was launched aboard Suzaku, the 5th Japanese X-ray satellite. The XIS had high-energy resolution, \(~140\) eV (FWHM) at \(5.9\) keV, in August 2005, just after first light. However, the gain and energy resolution have gradually degraded due to the increase of the CTI during transits through the South Atlantic Anomaly. The energy resolution had degraded to \(\sim 210\) eV (FWHM) by August 2006. The XIS is equipped with a charge injection structure which can inject a commandable quantity of charge in a nearly arbitrary spatial pattern. The charge injection (CI) can be used to mitigate the effect of in-flight radiation damage in two ways. First, the CI can measure the CTI accurately, column by column. The second method is one we call the spaced-row charge injection (SCI) technique. In the SCI technique, charge is injected into the CCD rows periodically. The injected charge fills the radiation-induced traps as "sacrificial charge", and thus prevents some of the traps from capturing signal charge produced by X-ray events. The result is lower CTI and improved energy resolution. Results from ground experiments using the SCI technique with radiation-damaged CCDs have been reported but no in-orbit experiment had been done. The Suzaku XIS operated the SCI technique in orbit for the first time in August 2006 and verified the improvement of the energy resolution from \(\sim 210\) eV to \(\sim 150\) eV at \(5.9\) keV. These results are described in a companion paper by the XIS team. On the other hand, since the in-orbit experiment showed that in the SCI mode CTI depends on the distance from the charge-injected rows, the gain has periodic non-uniformity. This means a new CTI correction method for the SCI mode is needed. This paper reports the study of CTI in the SCI mode and presents a new CTI correction method. In this paper, all errors are \(1\sigma\) unless otherwise described.

2. IN-ORBIT EXPERIMENT

2.1 Suzaku XIS

Koyama et al. have provided details on the XIS and its CCDs (MIT Lincoln Laboratory model CCID41). Here, we briefly summarize relevant instrument characteristics. The CCDs are of the three-phase frame-transfer type and (with the exception of the charge injection capability) have basically the same structure as those of Chandra/ACIS. A schematic view of the XIS CCD is shown in Fig.1. The upper half of the CCD contains the imaging area, and the lower half the frame-store region. Each region has \(1024 \times 1026\) pixels. The signal charge is transferred down in Fig.1. We define coordinate axes on the detector as shown in Fig.1: ACTY is parallel to the transfer direction, and ACTX is perpendicular to ACTY. Each CCD chip has four segments (A through D), and each segment has one readout node. \(^{55}\)Fe calibration sources, which irradiate the upper edge of segments A and D, are used to monitor the gain, CTI, and energy resolution in orbit. There are four CCDs onboard Suzaku. Three of them are front-illuminated (FI) chips, while the other is a back-illuminated (BI) device. Since the front side of the CCD bears a gate structure made of thin Si and SiO\(_2\) layers, the BI CCD is more sensitive than the FI CCD to soft X-rays. The thickness of the depletion layer in the FI chips is \(\sim 65\) \(\mu\)m, while that of the BI chip is \(\sim 42\) \(\mu\)m. The charge injection structure lies adjacent to the topmost row of the imaging area. A detailed description of the charge injection structure and its electrical performance are presented in Prigozhin et al.\(^5\) It can inject charges from \(\sim 50\) e\(^-\) to \(\sim 4000\) e\(^-\) per pixel; the equivalent X-ray energies range from \(\sim 300\) eV to \(\sim 15\) keV.

2.2 Data Acquisition

As in-orbit experiments with SCI, we observed the Perseus cluster and onboard calibration sources (\(^{55}\)Fe). All the data were acquired with the normal clocking, full window mode and the \(3 \times 3\) or \(5 \times 5\) editing modes. In the normal clocking mode, the exposure time is 8 sec, and the signal charge is transferred and read out in 8 sec. In the full window mode, all the pixels of the imaging area are read out. Koyama et al.\(^3\) provide details of these modes.

In the SCI mode, we injected charge into all pixels in every 54th row. The quantity of charge injected in each pixel was equivalent to the X-ray energy of \(\sim 6\) keV (FI) and of \(\sim 2\) keV (BI).

The Perseus cluster of galaxies is one of the X-ray brightest clusters in the sky; its redshift \(z=0.0176\). It has the X-ray spectrum of thermal plasma with strong K\(_\alpha\) lines of Fe XXV. Its radius is about \(15'\) and the
temperature of the plasma changes smoothly from $k_B T \sim 4$ keV to $\sim 7$ keV toward the outer region. The XIS combined with the X-Ray Telescope (XRT) onboard Suzaku has a FOV of $18' \times 18'$ on the sky, which can cover most of the Perseus cluster. The line center energy of the Fe XXV Kα triplet is almost constant ($\sim 6.56$ keV at $z=0.0176$) for plasma temperatures between $k_B T \sim 4$ keV and 7 keV. So this source is suitable to measure the positional dependence of the gain caused by CTI. We observed the Perseus cluster on August 29th 2006 with both the SCI and no-SCI modes. After removing the epoch of a low Earth elevation angle and South Atlantic Anomaly (SAA), the effective exposure is about 50 kilo-seconds total.

The onboard calibration source $^{55}$Fe produces the Kα line of Mn I. The center energy is 5.895 keV and the line width is negligible for our purposes. (Strictly speaking, since this line is a blend of Mn K I $\alpha_1$ 5.888 keV and $\alpha_2$ 5.8899 keV, its actual width is a few eV). Thus the observed line width directly reflects the energy resolution of the XIS. We used the archival trend data from the calibration source, which was distributed by the Data Archives and Transmission System (DARTS)* of ISAS/JAXA. The data were obtained between April 10th 2007 and May 2nd 2007, and the effective exposure is about 1 mega-seconds.

2.3 Observed Positional Non-uniformity of the Gain and CTI
First, we studied how the SCI improved CTI by analyzing the data from the Perseus cluster. We divided data from each CCD segment into six regions along ACTY, extracted the X-ray events from them and made spectra. We used only single-pixel events, in which all charge produced by an X-ray photon in the Fe XXV Kα line was collected in one pixel. If we use multi-pixel events, it is difficult to measure CTI correctly because CTI depends on the quantity of transferred charge, and the amplitudes of the various pixels comprising a multi-pixel event are different. The spectra were fitted with gaussians-plus-power-law model to measure the Fe XXV Kα line centroid. The positional dependence of the Fe XXV Kα line centroid in both the SCI and no-SCI modes is shown in Fig.2. The centroid is described in units of pulse height (PH) channel, which is directly proportional to the charge amplitude read out. In the no-SCI mode, the centroid channel of Fe XXV Kα line depends on ACTY. In the SCI mode, the dependence is much smaller. This shows that the SCI decreased CTI. Indeed, the slope in Fig.2 is proportional to CTI, and the ratio of the slope of the SCI data to that of the no-SCI data shows that the CTI became $\sim 30\%$ by the SCI. The calibration source data taken during the observation of the Perseus cluster shows that SCI improve the energy resolution from $\sim 210$ eV to $\sim 150$ eV by the SCI. Details of these results are given in a companion paper by the XIS team.

*http://darts.isas.jaxa.jp/index.html.en
Figure 2. The positional dependence of the Fe XXV Kα line centroid from the Perseus Cluster in both SCI and no-SCI modes. We show the dependence of the XIS 0 Segment D as a typical example.

Figure 3. The positional dependence of Mn I Kα line in the ground experiment by Tomida et al. It was measured by illuminating a proton-damaged CCD with an 59Fe calibration source. This figure is adapted from Tomida et al.

Next, we analyzed the archival trend data from the calibration source to study the positional dependence of the gain on a smaller spatial scale. Tomida et al. conducted a ground experiment involving SCI using a severely proton-damaged CCD and reported that the gain degraded with increasing distance from the preceding CI row and recovered again at the next CI row. Thus the gain positional dependence showed a periodic "saw-tooth" structure, as illustrated in Fig.3. Clearly a pixel nearer to a CI row benefits more from the SCI, and its CTI is improved more. Using the calibration source data, we checked whether such a gain variation occurred in orbit.

We divided the X-ray events between a pair of successive CI rows into three groups: the nearest to the preceding CI row, the middle and the farthest. Then we extracted single-pixel events, made spectra from them and measured the Mn I Kα line centroid. The positional dependence of the Mn I Kα line centroid is shown in Fig.4. The line centroids farther from the preceding CI row are lower. We can see clearly the periodic saw-tooth non-uniformity of the gain appeared in orbit. This non-uniformity of the gain can degrade the energy resolution.
Figure 4. The positional dependence of the Mn I Kα line centroid of the in-orbit calibration source data in the SCI mode. The circles are the observed data. The broken line shows the result of fitting the data with the ”saw-tooth” function. We show the dependence of the XIS 0 Segment D as a typical example.

We therefore developed a new CTI correction method for the SCI mode to reduce this non-uniformity.

3. CTI CORRECTION FOR SCI MODE

3.1 CTI Correction Method for SCI Mode
In this section, we explain the new CTI correction method for the SCI mode we developed. First, we define terms and notation. Q₀ and Q’ are the amount of the readout charge produced by an X-ray photon of certain energy at ACTY=0 and another ACTY, respectively. The relation between Q₀, Q’, CTI and ACTY is

\[ Q' = (1 - CTI)^{ACTY} \cdot Q_0 \approx (1 - CTI \cdot ACTY) \cdot Q_0. \] (1)

Since the CTI is typically of the order of \(\sim 10^{-5}\), we can use the above approximation. If the CTI is independent of ACTY, the relation of ACTY and Q’ is linear. Actually we have corrected no-SCI mode data for CTI effects using such linear functions. In the SCI mode, the relation between ACTY and Q’ is not linear (see in Fig.4). To account for the dependence of CTI on ACTY, we assumed the CTI was a function of the distance from the nearest preceding CI row, \(\Delta ACTY\), not ACTY itself, because we thought the effect of the nearest preceding CI row was largest and that of other CI rows (e.g. the second nearest preceding CI row) was negligible. We also assumed the CTI dependence on Q₀ in the SCI mode was the same as that in the no-SCI mode. In the no-SCI mode, the CTI is proportional to \(Q_0^{\text{ctipow}}\); here ctipow is a constant measured for each sensor. We used values for ctipow measured by Nakajima et al.;² typically ctipow \(\sim 0.3\). We assumed the CTI is the function of the following form:

\[ \text{CTI}(\Delta ACTY, Q_0) = \text{CTI}_{\text{NORM}}(\Delta ACTY) \cdot Q_0^{-\text{ctipow}}, \] (2)

where CTI_{\text{NORM}} is the functions of \(\Delta ACTY\).

Then we modeled the non-uniformity of the gain shown in Fig.4 using the ”saw-tooth” function shown in Fig.5. We note that the form of the function CTI_{\text{NORM}}(\Delta ACTY) is determined physically by the de-trapping time constants of the radiation-induced traps, and by the CCD readout timing. In principle, CTI_{\text{NORM}} could be any non-decreasing function of \(\Delta ACTY\), but for simplicity, and given the limitations of the available data, we assume a linear form. The function in Fig.5 is specified uniquely if values of three parameters, CTI_{\text{NORM}}^U, CTI_{\text{NORM}}^L and Q₀ are given. CTI_{\text{NORM}}^U and CTI_{\text{NORM}}^L are equal to the CTI_{\text{NORM}} of the pixel
nearest to the preceding CI ($\Delta$ACTY=0) and the pixel farthest from it ($\Delta$ACTY=54), respectively. CTI NORM for arbitrary $\Delta$ACTY is described in the following expression with CTI NORM_U and CTI NORM_L:

$$\text{CTI NORM}(\Delta \text{ACTY}) = \frac{\text{CTI NORM}_U \cdot (54 - \Delta \text{ACTY}) + \text{CTI NORM}_L \cdot \Delta \text{ACTY}}{54}. \quad (3)$$

From Eq.(1), (2) and (3), $Q'(\text{ACTY})$ is described as

$$Q'(\text{ACTY}) = [1 - \text{ACTY} \cdot \frac{\text{CTI NORM}_U \cdot (54 - \Delta \text{ACTY}) + \text{CTI NORM}_L \cdot \Delta \text{ACTY}}{54} \cdot Q_0^{\text{ctipow}}] \cdot Q_0. \quad (4)$$

Using this function, we correct the CTI as follows. First, fit the ACTY-PH dependence (PH $\propto Q'$) in the SCI mode, such as Fig.4, with Eq.(4) and obtain the parameters, CTI NORM_U, CTI NORM_L and $Q_0$. CTI NORM_U and CTI NORM_L specify CTI(ΔACTY, Q) from Eq.(2) and (3). Then use the following expression to obtain $Q_{\text{corrected}}$ from arbitrary $Q'$ and ACTY:

$$Q_{\text{corrected}} = [1 + \text{CTI}(\Delta \text{ACTY}, Q') \cdot \text{ACTY}] \cdot Q'. \quad (5)$$

This is an approximate solution of Eq.(4). As of the writing of this paper, the CTI of the SCI data is small, and $Q_0 \sim Q'$. 

### 3.2 Result of the New CTI Correction Method

We fitted the ACTY-PH dependence of Fig.4 with Eq.(4) (shown in Fig.5) and obtained CTI NORM_U, CTI NORM_L and PH_0 ($\propto Q_0$). The fitting result is shown in Fig.4. Then, using these values of CTI NORM_U, CTI NORM_L and Eq.(5), we corrected the calibration source data. After the correction, we measured the ACTY-PH dependence again, and show the result in Fig.6. The corrected PH shows little dependence on ACTY, thus confirming that this CTI correction method, which we call the "saw-tooth" correction, greatly reduces the non-uniformity of the gain. We note that the gain non-uniformity at 5.9 keV is reduced from about 0.5% to about 0.1%. This improvement is significant given that the target gain calibration accuracy is roughly 0.3%.

We also checked the effect of this CTI correction on the energy resolution and show the uncorrected and corrected spectra in Fig.7. These spectra include both single-pixel and multi-pixel events. The energy resolution at 5.9 keV (FWHM) was improved slightly from 151 eV to 148 eV. The effect on the energy resolution of
the correction is not large now but this correction will be more significant when the CTI increases the energy resolution becomes worse in the future. In fact, CTI NORM U and CTI NORM L are increasing with time. Using data from the calibration source from XIS 0 segment D, CTI NORM U and CTI NORM L in August 2006 were < 10^{-5} and ~ 5.1 \times 10^{-5}, respectively. Corresponding values April 2007 are ~ 1.0 \times 10^{-5} and ~ 9.8 \times 10^{-5}.

We assumed the CTI dependence on Q in the SCI mode was the same as that in the no-SCI mode and used the same ctipow parameters. We checked this assumption by comparing with Q_{corrected} of single-pixel events and that of multi-pixel events. Since the amount of charges per pixel in multi-pixel events is smaller than that of
single-pixel events, Q_{corrected} of single-pixel events and multi-pixel events will differ if the CTI dependence on Q is different. For the FI sensors, this assumption seemed good because Q_{corrected} of multi-pixel events was roughly the same as that of single-pixel events. However, for the BI sensor, Q_{corrected} of multi-pixel events was larger than that of single-pixel events. This means the assumption was not valid for the BI sensor and we corrected too much. We are studying the CTI dependence on Q of the BI sensor in more detail now.

3.3 Current Status of the Software and the Calibration for SCI Mode
The "saw-tooth" CTI correction has been built into xispi, part of the FTOOLS software package released by HEASARC¹, beginning with HEASoft version 6.3. A calibration database, which includes the correction parameters for SCI, such as CTI\_NORM\_U and CTI\_NORM\_L, has also been released. At this writing, in July 2007, the SCI parameters are calibrated well for the data from the FI sensors obtained at the end of August 2006 in the energy range around 6 keV. We are studying the time dependence of the parameters, the gain in the low energy range, and the CTI dependence on Q for the BI sensor now. The results will be included in the calibration database and released soon.

4. SUMMARY
The Suzaku XIS demonstrated the SCI technique in orbit for the first time. We studied the positional dependence of the gain in the SCI mode and found it showed the saw-tooth like non-uniformity. We developed the "saw-tooth" CTI correction to resolve this non-uniformity. We applied this correction to flight data from the calibration source and confirmed this correction worked well. The correction reduces the gain non-uniformity significantly (from 0.5% to 0.1%) but at this time adds little to the resolution improvement already provided by charge injection. The CTI dependence on Q of the BI sensor in the SCI mode seems different from that in the no-SCI mode. The "saw-tooth" CTI correction has been built into xispi of FTOOLS. The calibration database for SCI mode is being updated now.

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REFERENCES

¹http://heasarc.gsfc.nasa.gov/
