New CTI Correction Method for the Spaced-Row Charge Injection of the Suzaku X-Ray Imaging Spectrometer

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Abstract

The charge transfer inefficiency (CTI) of the X-ray CCDs on board the Suzaku satellite (X-ray Imaging Spectrometers; XIS) has increased since the launch due to radiation damage, and the energy resolution has been degraded. To improve the CTI, we have applied a spaced-row charge injection (SCI) technique to the XIS in orbit; by injecting charges into CCD rows periodically, the CTI is actively decreased. The CTI in the SCI mode depends on the distance between a signal charge and a preceding injected row, and the pulse height shows periodic positional variations. Using in-flight data of onboard calibration sources and of the strong iron line from the Perseus cluster of galaxies, we studied the variation in detail. We developed a new method to correct the variation. By applying the new method, the energy resolution (FWHM) at 5.9 keV at March 2008 is ∼155 eV for the front-illuminated CCDs and ∼175 eV for the back-illuminated CCD.

Key words: instrumentation: detectors — techniques: spectroscopic — X-ray CCDs

1. Introduction

X-ray charge coupled devices (CCDs) have good spatial and energy resolution, and they have been the main detector for imaging spectroscopy in X-ray astronomy since the ASCA SIS (Burke et al. 1993). X-ray CCDs in orbit, however, suffer from radiation damage. The damage causes the increase of the charge transfer inefficiency (CTI), which results in the degradation of the energy resolution for two reasons: 1) the pulse height strongly depends on the position of an X-ray event, since the X-ray event loses more electric charges as the number of transfer increases, and 2) the loss of charge is a stochastic process, and thus there is a fluctuation in the amount of lost charge. In the case of the X-ray Imaging Spectrometer (XIS; Koyama et al. 2007) on board the Suzaku satellite (Mitsuda et al. 2007), the energy resolution at 5.9 keV was ∼140 eV (FWHM) at August 2005, and had degraded to ∼200 eV at August 2006.

The XIS is equipped with a charge injection (CI) structure (Prigozhin et al. 2004; Bautz et al. 2004; LaMarr et al. 2004; Prigozhin et al. 2008) which lies adjacent to the top row of the imaging area. The CI structure allows us to inject a commandable amount of charge in a nearly
2. Spaced-row Charge Injection

In the SCI mode of the Suzaku XIS, a charge is injected into every 54th row. The amounts of the injected charge into each pixel are equivalent to the X-ray energy of \( \sim 6 \) keV and of \( \sim 2 \) keV, for the front-illuminated (FI) and back-illuminated CCD (BI), respectively.

The terminologies and notations for the CCD, CTI, and CI are the same as Ozawa et al. (2009). To make clear for further descriptions of the SCI, relevant terminologies and notations are summarized in Table 1.

The CI in the SCI mode is assumed to consist of two components as CI1 and CI2 following Ozawa et al. (2009). The relation among readout pulse height \( PH' \), original pulse height generated by an X-ray of energy \( E \) \( (PH_o, at E) \), CTI1 \( (c_1) \), CTI2 \( (c_2) \), and transfer number \( i \) are formalized in equation 2 of Ozawa et al. (2009), where the detector coordinates are defined as ActX and ActY. The CCD consists of four segments (A, B, C, and D); each segment consists of 256 columns along ActX and has a dedicated read-out node.

In the SCI mode, a radiation-induced trap is filled with a probability \( p \) when a sacrificial charge passes through the trap. The filled trap does not capture a signal charge produced by an X-ray. However, the electron once filling the trap will be re-emitted with the time scale \( \tau \). Thus the probability of the trap holding the electron is proportional to \( p \cdot \exp(-t/\tau) \), where \( t \) is the time elapsed since the sacrificial charge passes the trap. Thus it is reasonable to assume that a pixel which is \( j \) rows away from its preceding charge injected row has the \( c_1 \) value proportional to \( 1 - p \cdot \exp(-\delta t \cdot j/\tau) \), where \( \delta t \) is time for one vertical transfer; \( \delta t \cdot j \) represents a time lag between the pixel and the charge injected row. We assume \( \delta t \cdot j/\tau \) is a small value, and hence \( 1 - p \cdot \exp(-\delta t \cdot j/\tau) \) is a linear function of \( j \) approximately. The charge is injected into every 54th row, and hence \( j = i \mod 54 \). We, consequently, can model the \( c_1-i \) relation of the SCI mode as,

\[
c_1(i) = c_{1t} + \frac{c_{1b} - c_{1t}}{54}, (i \mod 54).
\]

Equation 1 is a periodic sawtooth function as demonstrated in figure 1a. This \( c_1-i \) relation generates the \( PH' \)-i relation in figure 1b, and the shape is nicely reproduced by the ground experiments using the heavily damaged CCD as demonstrated in figure 15 of Tomida et al. (1997).

The sawtooth distribution is also found in the XIS in-orbit. We measured the \( PH' \)-i relations using the on-board calibration source data in October 2006 with an effective exposure time of 1 Ms, and show the results in figures 2a and b. Figure 2 shows that the sawtooth of the BI sensor is shallower than that of the FI sensors. The results based on the data in February 2008 are also shown in figures 2c and d. Compared with October 2006, the sawtooth became deeper. The pulse height just after the charge injected rows changed more in the case of the BI sensor than the FI sensors. This difference might be resulted in part from the smaller amount of charge injected in the BI sensor.

Our sawtooth CTI model can represent the complicated relation between \( PH' \) and \( i \), and make it possible to convert \( PH'(i) \) to \( PH_o \) with only three parameters, \( c_{1t}, c_{1b}, \) and \( c_2 \). Our goal is to convert \( PH'(i) \) to \( PH_o \) by deciding the three parameters.

3. CTI Measurement in Orbit

3.1. Calibration Data

To study the CTI in the SCI mode, we analyzed the data of the onboard calibration sources \(^{55}\text{Fe}\), the Perseus cluster of galaxies, and 1E 0102.2–7219, whose properties are summarized in section 4 of Ozawa et al. (2009).

XIS 2 suddenly showed an anomaly on November 9, 2006, and it has not been operated since then. Although there is no direct evidence, the micro-meteoroid impact might have caused the anomaly. Thus only the data of XIS 0, 1 and 3 are studied.

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1. The modular arithmetic \( i \mod 54 = j \) means that when \( i \) is divided by 54, it leaves \( j \) as the remainder, hence \( i-j \) is divisible by 54. For example, \( 111 \mod 54 = 3 \). Strictly speaking, charges are injected in rows of \( i = 54 \cdot n + 1 \) \((n = 0, \ldots, 18)\) and 1023 for full window mode. Thus \( j \) should be \((i+1) \mod 54 \). We nevertheless use this simplified description to avoid unnecessary confusion. We treated \( j \) properly for actual CTI measurement.

2. See http://www.astro.isas.jaxa.jp/suzaku/proposal/ao3/suzaku_td/.
Fig. 1. Our model of the “sawtooth” variation. We assume the $c_1$-$i$ relation shown in (a), and it generates the $PH'$-$i$ relation shown in (b).

Fig. 2. Pulse height of the Mn I Kα line from the onboard calibration source as a function of $i$: October 2006 (a and b) and February 2008 (c and d). We show the results of the segment A in XIS 0, 1 as typical examples. X-ray events of grade 02346 were analyzed. Black and red marks are data before and after our new CTI correction, respectively.
All data were acquired with the normal clocking mode and the full window option using the SCI. The editing data were corrected for the phenomenon based on the in-orbit changes the spatial extent of an X-ray event. All data pixel during the transfer. This charge-trail phenomenon of the charge in a pixel is left behind (trailed) to the next details of these modes.

The details about the charge-trail correction is shown in

\[ \text{Table 1. The list of notation.} \]

| Notation | Meaning |
|----------|---------|
| \( i \) | Transfer number. \( i = \text{Act}Y + 1 \); \( \text{Act}Y \) is a coordinate value where an incident X-ray generates a charge. |
| \( PHo \) | Original pulse height. |
| \( PH'(0) \) | Readout pulse height of a pixel at \( i = 0 \). It is equal to \( (1 - 1024 \cdot c2) \cdot PHo \). |
| \( PH'(i) \) | Readout pulse height of a pixel at \( i \). |
| \( j \) | Row number between a pixel and its preceding charge injected row. \( j = i \mod 54 \). |
| \( c1(i) \) | CTI 1 of Ozawa et al. (2009) for a pixel at \( i \). |
| \( c1t, c1b \) | The \( c1 \) values at the peak and valley of the sawtooth (see figure 1a). |
| \( c2 \) | CTI 2 of Ozawa et al. (2009). |
| \( -s(j) \) | Slope for a pixel with \( j \). It is equal to \( c1(i) \cdot PHo \). |
| \( -st \) | Slope for the tops of the sawtooth. It is equal to \( c1t \cdot PHo \). |
| \( -sb \) | Slope for the bottoms of the sawtooth. It is equal to \( c1b \cdot PHo \). |
| \( \beta \) | CTI depends on the pulse height as \( c1,2 \propto PHo^{-\beta} \). See Ozawa et al. (2009). |

As mentioned in Koyama et al. (2007), a small fraction of the charge in a pixel is left behind (trailed) to the next pixel during the transfer. This charge-trail phenomenon changes the spatial extent of an X-ray event. All data were corrected for the phenomenon based on the in-orbit data \(^3\), otherwise some X-ray events would be judged as grade 7, and the detection efficiency would decrease.

We used the archival trend data of the calibration source obtained between August 2006 and March 2008, and the total effective exposure time is about 23.7 Ms. The observations of the celestial objects are summarized in table 2.

3.2. Determination of the CTI Parameters

The procedures for the CTI determination are as follows:

- **Step 1:** deciding \( PHo \) at 5.895 keV and 6.56 keV.
- **Step 2:** measuring \( c2 \) for \( PHo \) at 6.56 keV.
- **Step 3:** measuring \( c1t \) and \( c1b \) for \( PHo \) at 5.895 keV or 6.56 keV.
- **Step 4:** deciding the CTIs for any \( PH' \) values.

In the case of the non-SCI mode, we can measure the CTI of each column by the checker flag CI (Nakajima et al. 2008; Ozawa et al. 2009). Since the checker flag CI is a complicated operation, we have not used this technique in the SCI mode. We, therefore, measured the averaged CTI of each segment.

In the normal analysis of the XIS data, both of single-pixel and multi-pixel events (grade 0 and 2346 events; see Koyama et al. 2007) are used. To determine the CTI, however, we analyzed only the grade 0 events; if we use the multi-pixel events, it is difficult to measure the CTI correctly, because the CTI depends on the amount of transferred charge, and the amounts of charge in each pixel comprising the multi-pixel event is different with each other. We will mention how to correct the data of grade 02346 events in step 4.

**Step 1:** \( PHo \) at 5.895 keV and 6.56 keV

We determined the \( PHo \) of the Fe XXV Kα line from the Perseus cluster by using the data of the first SCI observation on 29 August, 2006. Because it is impossible to measure the \( c2 \) value in August 2006, we assumed that value is equal to zero. Even if this assumption would not be reasonable, we can cover it by adjusting the \( PHo \cdot E \) relation. Then the \( PH' \) at \( i = 0 \) (\( PH'(0) \)) is equal to \( PHo \).

Since the statistics are limited, we divided each segment to four regions along the ActY axis, and obtained the center pulse height of the iron line from each region. An example of \( PH' \) as a function of \( i \) is shown in figure 3. By fitting the data with a linear function of \( i \), the \( PHo \) value was obtained as \( PH'(0) \).

For the segments A and D, we obtained the \( PHo \) value of the Mn I Kα line (5.895 keV) using the data of the calibration sources in August, 2006. We obtained the \( PH' \)-\( i \) relation, but in this case, the \( i \) values are limited at around 900 because the calibration sources irradiate

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\(^3\) The details about the charge-trail correction is shown in [http://xmm2.esac.esa.int/external/xmmwscn/icwg/presentations/Suzaku_XIS.pdf](http://xmm2.esac.esa.int/external/xmmwscn/icwg/presentations/Suzaku_XIS.pdf)
only the two far-end corners from the read-out node of the imaging area (Koyama et al. 2007). We extrapolated the relation to \( i = 0 \) by using a linear function, the slope of which was fixed to a value \( s_{\text{Mn}} \) calculated as follows. Because the slope represents an averaged \(-c_1 \cdot PH_o\), the slope should be proportional to \( PH_0^{1-\beta} \). Then we calculated \( s_{\text{Mn}} \) from the slope for the 6.56 keV data \( (s_{\text{Fe}}) \) as \( s_{\text{Mn}} = s_{\text{Fe}} \cdot (5.895/6.56)^{1-\beta} = s_{\text{Fe}} \cdot (0.90)^{1-\beta} \).

**Step 2:** \( c_2 \) for \( PH_o \) at 6.56 keV

We obtained the \( PH'(0) \) values for all data of the Perseus cluster (table 2) with the same method of step 1. The \( PH'-i \) relations are shown in figure 3. As is found in figure 3, \( PH'(0) \) is decreased with time; \( PH'(0) \) becomes different from \( PH_o \). We assumed the difference \( PH_o - PH'(0) \) is attributable to \( c_2 \). Assuming that \( c_2 \) is a linear function of time, the increasing rate of \( c_2 \) for \( PH_o \) (at 6.56 keV) is typically \( \sim 2 \times 10^{-6} \) yr\(^{-1}\) for the FI sensors and \( \sim 6 \times 10^{-6} \) yr\(^{-1}\) for the BI sensor.

**Step 3:** \( c_{1b} \) and \( c_{1b} \) for \( PH_o \) at 5.895 keV and 6.56 keV

For the segments A and D, we determined \( s_t \) and \( s_b \) for \( PH_o \) at 5.895 keV by using the data of the calibration sources. For the segments B and C, we measured those for \( PH_o \) at 6.56 keV by using the Perseus data. We fitted the \( PH'-i \) relation with the sawtooth function shown in figure 1b, and determined \( s_t \) and \( s_b \). In the fitting, we fixed the \( PH_o \) and \( c_2 \) to the values obtained in step 1 and step 2. Typical examples of the fitting are shown in figures 4 and 5. Using \( s_t \) and \( s_b \), we calculated \( c_{1b} \) and \( c_{1b} \).

In the case of the FI sensors, the \( c_{1b} \) and \( c_{1b} \) values for \( PH_o \) at 5.895 keV at August 2006 are typically \( <1 \times 10^{-7} \) and \( \sim 3 \times 10^{-6} \), respectively. The increasing rates are \( \sim 1 \times 10^{-6} \) yr\(^{-1}\) and \( \sim 5 \times 10^{-6} \) yr\(^{-1}\), respectively. In the case of the BI sensor, the parameters \( c_{1b} \) and \( c_{1b} \) at August 2006 are \( \sim 6 \times 10^{-6} \) and \( \sim 1 \times 10^{-5} \), and the increasing rates are \( \sim 5 \times 10^{-6} \) yr\(^{-1}\) and \( \sim 8 \times 10^{-6} \) yr\(^{-1}\), respectively. Typical examples of the time evolution of the \( c_1 \) values for \( PH_o \) at 5.895 keV are shown in figure 6.

The CTI of the BI sensor is larger, and increases more rapidly than that of the FI sensors. It might be the reason that the amount of the injected charge to the BI sensor is less than that of FIs.

**Step 4:** CTI for any \( PH' \) values

For an event of \( PH' \), we calculated the CTI with an equation of \( c_{1,2} \times \{PH'/(PH_o \text{ at 5.895 keV or 6.56 keV})\}^{-\beta} \). Here, we assumed the same \( PH_o-c_i \) relation as that of the non-SCI mode and used the same \( \beta \) (typically \( \sim 0.25 \); Ozawa et al. 2009).

Since we obtained the CTI for all pulse-height values, we can now correct the CTI of multi-pixel events (grade 2346 events). By using the Mn Kα line of the calibration sources or the FeXXV Kα line from the Perseus cluster, we examined the CTI correction for the grade 2346...
Fig. 5. Best-fitting result of the sawtooth function for the Fe XXV Kα line from the Perseus cluster. The result of the XIS 0 segment C in February 2008 is shown as a typical example. The white and black circles show the pulse height of regions with smaller and larger $j$ values, respectively. Only grade 0 events were used.

Fig. 6. Time history of $c_{1t}$ and $c_{1b}$ for $PH_0$ at 5.895 keV. The segment A of XIS 0 and 1 are shown as typical examples.

Fig. 7. Time history of the line centroid of Mn I Kα line. We show the result of the XIS 1 segment A as a typical example. The triangle and circle marks show the data of grade 0 and 02346 after the CTI correction with the parameters based on only the grade 0 events. The rectangle marks show the data of grade 02346 events after the CTI correction with the fine-tuned parameters as described in the text.

Fig. 8. Time history of the line centroid of O VIII Kα (0.653 keV). We show the result of the XIS 1 segment C as a typical example. The results are based on the grade 02346 events corrected with the fine-tuned CTI parameters as described in the text.

We then fine-tuned the parameters $c_{1t}$, $c_{1b}$, and $c_2$ by multiplying a common time-independent factor. We determined the factor of each segment so that the line center of the grade 02346 events becomes temporally constant. The factors are typically 0.9. Figure 7 also shows that the result of the grade 02346 data corrected with the fine-tuned CTI parameters. The adjusted pulse height becomes constant. However, as a result, the value becomes different from $PH_0$ measured in step 1. We regarded this adjusted pulse height as $PH_0$ at 5.895 keV, and determined the $PH_0$-$E$ relation.

To check the CTI correction in the low-energy band, we applied the fine-tuned CTI parameters to the grade 02346 data of 1E 0102.2$-7219$. We fitted the spectrum with the empirical calibration model. Figure 8 shows the pulse height of the O VIII Kα line after the CTI correction. We can see that the line centroid is constant, which supports the validity of our method.

4. Energy Scale Uniformity and Resolution in the SCI Mode

The pulse height of the Mn I Kα line after our new CTI correction is shown in figure 2. The sawtooth structure disappeared, and hence our new method greatly reduces the variation of the pulse height. Comparing between October 2006 and February 2008 shows that the CTI...
ation with time is also corrected properly.

The $PHo-E$ relation for each segment is assumed to be the same function form with a similar fine-tuning process of the absolute energy as Ozawa et al. (2009): a model of two slopes crossing at the energy of the Si-K edge (1.839 keV) with the same ratio of the two slopes as that obtained in the ground experiments (Koyama et al. 2007).

The time histories of the energy resolution of the corrected data are shown in figure 9. At the high energy (5.895 keV), the energy resolution of XIS 0 at March 2008 is improved from $\sim$160 eV to $\sim$155 eV by the sawtooth correction. On the other hand, the energy resolution of XIS 1 at March 2008 is not improved in spite of the sawtooth correction, and stays at $\sim$175 eV. At the low energy (0.653 keV), no clear effect of the sawtooth correction is seen in both FI and BI. The energy resolutions at March 2008 are $\sim$53 eV (XIS 0) and $\sim$62 eV (XIS 1) independently of the correction.

As we mentioned in section 2, the sawtooth of the BI sensor is shallower than that of the FI sensors. We think it causes the difference of the effect of the sawtooth correction between BI and FI. We speculate, at the low energy, the effect of the sawtooth correction was not seen because the original degradation of the energy resolution was small. In fact, the energy resolutions at O VIII Kα are almost same between the SCI and non-SCI mode.

The results of our new method to correct the sawtooth structure has been implemented to the software package released by HEASARC\(^5\) since HEAsoft version 6.3. Now, all of the XIS data of the SCI mode after the processing version 2.0 are corrected by the sawtooth method.

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\(^5\) http://heasarc.gsfc.nasa.gov/