Energy-Scale Calibration of the Suzaku X-Ray Imaging Spectrometer Using the Checker Flag Charge-Injection Technique in Orbit

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Abstract

The X-ray Imaging Spectrometer (XIS) aboard the Suzaku satellite is an X-ray CCD camera system that has superior performance, such as a low background, high quantum efficiency, and good energy resolution in the 0.2–12 keV band. Because of radiation damage in orbit, however, the charge-transfer inefficiency (CTI) has increased, and hence the energy scale and resolution of the XIS has been degraded since the launch in 2005 July. The CCD has a charge-injection structure, and the CTI of each column and the pulse-height dependence of the CTI are precisely measured by a checker flag charge-injection (CFCI) technique. Our precise CTI correction improved the energy resolution from 230 eV to 190 eV at 5.9 keV in 2006 December. This paper reports on CTI measurements with the CFCI experiments in orbit. Using the CFCI results, we have implemented the time-dependent energy scale and resolution to the Suzaku calibration database.

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

1. Introduction

After the first successful space flight use of the X-ray charge coupled device (CCD) of the SIS (Burke et al. 1993) aboard ASCA, the CCD has been playing a major role in imaging spectroscopy in the field of X-ray astronomy. However, the charge-transfer inefficiency (CTI) of X-ray CCDs increases in orbit due to radiation damage; the CTI is defined as the fraction of electrons that are not successfully moved from one CCD pixel to the next during the readout. Since the amount of charge loss depends on the number of transfers, the energy scale of X-ray CCDs depends on the location of an X-ray event. Furthermore, there is a fluctuation in the amount of the lost charge. Therefore, without any correction, the energy resolution of X-ray CCDs in orbit gradually degrades. In the case of the X-ray Imaging Spectrometer (XIS) (Koyama et al. 2007) aboard the Suzaku satellite (Mitsuda et al. 2007) launched on 2005 July 10, the energy resolution in full width at half maximum (FWHM) at 5.9 keV was ~140 eV in 2005 August, but had degraded to ~230 eV in 2006 December.

The increase of the CTI is due to an increase in the number of charge traps at defects in the lattice structure of silicon made by radiation. Since the trap distribution is not uniform, it would be best if we could measure the CTI of each pixel as Chandra ACIS (Grant et al. 2004). In the case of the XIS, however, it is impossible to measure the CTI values of all the pixels, mainly because the onboard calibration sources do not cover the entire field of view of the XIS. Therefore, we use the CTI of each column to correct the positional dependence of the energy scale.

The XIS is equipped with a charge-injection structure (Prigozhin et al. 2004; Bautz et al. 2004; Lamarr et al. 2004; Prigozhin et al. 2008) that can inject an arbitrary amount of charge in arbitrary positions. Using this capability, we can precisely measure the CTI of each column (Nakajima et al. 2008). By applying the column-to-column CTI correction, the positional dependence of the CTI corrected energy scale is greatly reduced, and the over-all energy resolution is also improved (Nakajima et al. 2008).

In Nakajima et al. (2008), the results of the CTI correction were mainly based on ground-based charge-injection experiments. In-orbit measurements were limited to within one year after the launch. This paper reports on more comprehensive and extended in-orbit experiments up to two years after the launch. The results are based on data with the normal full window mode (Koyama et al. 2007) without a spaced-row
2. X-Ray CCD with the Charge Injection Capability

2.1. Checker Flag Charge Injection

The XIS is a set of four X-ray CCD camera systems. Three sensors (XIS 0, 2, and 3) contain front-illuminated (FI) CCDs and the other (XIS 1) contains a back-illuminated (BI) CCD. The XIS 2 sensor became unusable on 2006 November 9. Therefore, there are no data for XIS 2 after that day.

The detailed structure of the CCD is provided in Koyama et al. (2007). In this paper, we define a “row” and a “column” as a CCD line along the ActX and ActY axes, respectively (see figure 3 in Koyama et al. 2007). In the imaging area, the ActX value runs from 0 to 1023 from segments A to D, while the ActY value runs from 0 to 1023 from the readout node to the charge-injection structure.

The charge-injection structure lies adjacent to the top row (ActY = 1023) in the imaging area. We can inject charges from ~50 e⁻ to ~4000 e⁻ per pixel; the equivalent X-ray energy ranges from ~0.2 keV to ~15 keV.

A charge packet generated by an incident X-ray is transferred to the readout node, and is then converted to a pulse-height value. We define PHo to be the original pulse height generated by an X-ray. In the real case, the readout pulse height of the packet (PH') is smaller than PHo, because some amount of charges is lost during the transfer. To measure the charge loss, we have to know both PHo and PH'. However, we can usually measure only PH', and hence it is difficult to obtain PHo.

Prigozhin et al. (2004) and Prigozhin et al. (2008) reported a technique to solve this problem by the charge-injection method, and Nakajima et al. (2008) applied this technique to the XIS. We briefly repeat by referring figure 3 in Nakajima et al. (2008). First, we inject a “test” charge packet into the top CCD row (ActY = 1023). Then, after a gap of a few rows, five continuous packets are injected with the same amount of charge of the test packet. The former four packets are called “sacrificial” charge packets, while the last one is called a “reference” charge packet. The test packet loses its charge by charge traps. On the other hand, the reference packet does not suffer from any charge loss, because the traps are already filled by the preceding sacrificial packets. Thus, we can measure the charge loss by comparing the pulse-height values of the reference charge (PHref) and the test charge (PHtest). The relation between the sacrificial charge packets and the reference charge packets is described in Gendreau (1995). We can obtain a checker flag pattern by these injected packets in the X-ray image (right panel of figure 3 in Nakajima et al. 2008), because of the onboard event-detection algorithm (Koyama et al. 2007). Therefore in this paper, we call this technique a “checker flag charge injection (CFCI).”

2.2. Formulation of the CTI

A charge packet in the XIS loses its charge during (a) fast transfer (24 μs pixel⁻¹) along the ActY axis in the imaging area, (b) fast transfer along the ActY axis in the frame-store region, (c) slow transfer (6.7 ms pixel⁻¹) along the ActY axis in the frame-store region, and (d) fast transfer to the readout node along the ActX axis. The CTI depends on many parameters such as the transfer speed and the number density of the charge traps (Hardy et al. 1998). The frame-store region is covered by a shield, and is not exposed to radiation directly. Furthermore, the pixel size of the frame-store region (21 μm × 13.5 μm) is different from that of the imaging area (24 μm × 24 μm). Thus, the number of traps per pixel may be different between the imaging area and the frame-store region. We then assumed that the four transfers have different CTI values. We examined the transfer (d) by using the calibration source data taken in 2007 April, and found no significant decrease of the pulse height along the ActX axis. We, therefore, ignore the charge loss in the transfer (d).

We define that i is the transfer number in the imaging area (i = ActY + 1; here, ActY is a coordinate value where an incident X-ray generates a charge packet). Then the relation between PH' and PHo is expressed as

\[ PH'(i) = PHo(1 - c_o)^i(1 - c_b)1024-i(1 - c_c)^i, \]

\[ \sim PH_o[1 - i(c_o - c_b + c_c) - 1024c_b], \]

where c_o, c_b, and c_c are the CTI values in transfers (a), (b), and (c), respectively. Here, we used the fact that the CTI values are much smaller than 1. Thus we can separate the charge loss into an i-dependent component [the second term in the right-hand side of equation (1)] and an i-independent component (the third term). We therefore substitute the CTI with CTI1 (the former component) and CTI2 (the latter component), which have CTI values of \( c_1 = c_o - c_b + c_c \) and \( c_2 = c_b \), respectively. Then, equation (1) can be written as

\[ PH'(i) \sim PH_o(1 - ic_1 - 1024c_2). \]

Since the CTI values depend on the amount of transfer charge, which is proportional to the pulse height, we assume the CTI is described by a power function of the pulse height (Prigozhin et al. 2004), and expressed as

\[ c_1 = k_1(PH_o)^{-\beta} \quad \text{and} \quad c_2 = k_2(PH_o)^{-\beta}, \]

where \( k_1 \) and \( k_2 \) are scale factors for the CTI1 and CTI2, and the index \( \beta \) is common to CTI1 and CTI2.

3. Measuring the CTI with the CFCI

We conducted CFCI experiments six times in orbit. The effective exposure time for each experiment ranged from a few to ~20 ks. The equivalent X-ray energy of the injected charge packets ranged from ~0.3 keV to ~8 keV. Since 2006 June, we injected various amounts of charge in one experiment. The log is summarized in table 1.

In the CFCI experiments, the test charge was injected to the row at ActY = 1023 (i = 1024), and hence \( PH'(1024) = PH_{test} \). The reference charge should be equal to the original charge, which does not suffer from any charge loss, and hence
Table 1. Log of the checker flag charge injection experiments in orbit.

| Log number | Date           | Exposure (ks) | XIS 0 | XIS 1 | XIS 2 | XIS 3 |
|------------|----------------|---------------|-------|-------|-------|-------|
| 1          | 2006/1/17–20   | 3.7           | —     | 7.1   | —     | 4.6   |
| 2          | 2006/5/20–21   | 1.2           | 4.2   | —     | 3.9   | —     |
| 3          | 2006/6/26–27   | 4.9           | —     | 0.3/7.1 | —     | 0.5/4.5 |
| 4          | 2006/7/17      | 5.7           | 0.6/4.2/8.0 | —     | 0.6/3.9/7.8 | —     |
| 5          | 2006/8/25–26   | 4.9           | —     | 0.3/7.1 | —     | 0.5/7.0 |
| 6          | 2007/9/28      | 25.3          | 0.6/4.1/7.9 | 0.4/7.2/7.9 | —     | 0.5/4.5/6.5 |

\[ PH_0 = PH_{ref}. \] Then, equation (2) can be written as

\[ c_1 + c_2 = \frac{1}{1024} \left( 1 - \frac{PH_{test}}{PH_{ref}} \right). \]  

(4)

We determined \( c_1 + c_2 \) by measuring the ratio \( PH_{test} / PH_{ref} \) for each column. From equation (3), we can obtain the relation in the CFCI experiments as

\[ c_1 + c_2 = \frac{k_1 + k_2}{PH_{ref}^\beta}. \]  

(5)

The index \( \beta \) and \( k_1 + k_2 \) were derived by fitting equation (5) to values of \( c_1 + c_2 \) obtained with the CFCI experiments with a multiple amount of charge injections (multiple \( PH_{ref}s; \) Log number 3–6 in table 1). The mean and standard deviations of the best-fit \( \beta \) of equation (5) averaged over each sensor are shown in figure 1. The mean value of \( \beta \) shows no time variation, and the time-averaged values of XIS 0, 1, and 3 are 0.31, 0.22, 0.15 for XIS 0, 1, and 3, respectively. As for XIS 2, there was only one data point, and we obtained \( \beta = 0.34 \).

If a charge packet has a volume proportional to the number of electrons, and is spherically symmetric, the probability that one electron encounters a charge trap is proportional to the cross section of the charge packet. In this case, we can expect \( k_1 = k_2 \), and \( c_1 + c_2 \) is equal to \( k_1 + k_2 \), which was estimated by the 6.4 keV line from the Sgr C region to be 0.67 and 1.5 for the FI and BI CCD, respectively (Nakajima et al. 2008). From this \( k_1 \), we can obtain the final value of \( c_1 \).

Figure 2 shows an example of the distribution of \( c_1 \) in 2006 July. We can see significant column-to-column dispersion. Figure 3 shows the change of \( c_1 \) from 2006 July to 2007 September. We can see that the CTI values of all columns increased, but the increasing rate was different from column to column. The results of figures 2 and 3 indicate that a CTI correction at the column level is strongly required. In figure 4, we show the column-averaged \( c_1 \) value as a function of time.

Since the CFCI experiments were only sparsely conducted (see table 1), we interpolated the \( c_1 \) and \( c_2 \) values for the observations of inter-CFCI epochs. As for the determination of the CTI values before the first CFCI experiment, see appendix.

4. Results of the CTI Correction and the Energy Calibration

A CTI correction, which is the conversion of \( PH'(i) \) to \( PH_0 \), is made with equation (2), where \( c_1 \) and \( c_2 \) are calculated from equation (3) by using the \( k_1, k_2, \) and \( \beta \) values determined in section 3.

4.1. Emission Lines for the Calibration

We used the emission lines from the onboard calibration sources, the Perseus cluster of galaxies, and the supernova remnant 1E 0102.2–7219. We retrieved the data from the Data Archives and Transmission System of ISAS/JAXA. All data were acquired with the normal full window mode and the 3×3 or 5×5 editing mode (Koyama et al. 2007). We used the data with ASCA grades of 0, 2, 3, 4, and 6. As mentioned in Koyama et al. (2007), a small fraction of the charge in a pixel is left behind (trailed) to the next pixel in the same column during the transfer. All data used in this paper were corrected for the trail phenomenon. The observations are summarized in table 2.

\[ \text{http://darts.isas.jaxa.jp/}. \]
Table 2. Observational log of the celestial objects.

| Object                  | Observation ID  | Date            | Exposure (ks) |
|-------------------------|-----------------|-----------------|---------------|
| The Perseus cluster of galaxies | 800010010       | 2006/2/1–2      | 50.4          |
| 1E 0102.2–7219          | 100014010       | 2005/8/31       | 24.3          |
|                         | 100044010       | 2005/12/16–19  | 59.7          |
|                         | 101005010       | 2006/4/16       | 21.3          |
|                         | 101005040       | 2006/7/17       | 20.6          |
|                         | 101005070       | 2006/10/21–22  | 18.5          |
|                         | 101005100       | 2007/1/15       | 22.6          |
|                         | 101005120       | 2007/3/18–19   | 18.2          |

Fig. 2. Number distribution of the CTI 1 parameter (c1). The parameter c1 was obtained by the checker flag charge-injection (CFCI) experiment on 2006 July 17. We show the result of XIS0 as a typical example. The typical error of c1 is \( \sim 4 \times 10^{-7} \). The mean and the peak (the most probable) values are \( 9.4 \times 10^{-6} \) and \( 6.8 \times 10^{-6} \), respectively. The equivalent X-ray energy of the reference charge packet is 4.2 keV.

Onboard Calibration Source \(^{55}\text{Fe}\)

The calibration source, \(^{55}\text{Fe}\), produces the Mn I K\(\alpha\) line. The theoretical line center energy is 5895 eV (Bearden & Burr 1967; Krause & Oliver 1979). We used the data taken from 2005 August to 2007 April.

The Perseus Cluster of Galaxies

This is one of the X-ray brightest clusters of galaxies in the sky. The X-ray spectrum is that of a thin thermal plasma with the strong K\(\alpha\) line of Fe XXV. The plasma temperature changes smoothly from \( kT \sim 4 \) keV to \( \sim 7 \) keV toward the outer region (Churazov et al. 2003), and the center energy of the Fe XXV K\(\alpha\) triplet is almost constant (\( \sim 6.56 \) keV at \( z = 0.0176 \)) within this temperature range. Its radius of \( \sim 15' \) can cover the entire field of view of the XIS (18' \( \times \) 18'). Thus, this source is suitable for measuring the positional dependence of the energy scale.

1E 0102.2–7219

This is one of the brightest supernova remnants in the Small Magellanic Cloud. With the spatial resolution of Suzaku, it can

Fig. 3. Same as figure 2, but the ratio of c1 obtained on 2006 July 17 (372 days after the launch) and on 2007 September 28 (810 days after the launch). The typical error of the ratio is \( \sim 0.1 \). The mean and the peak values are 2.89 and 2.63, respectively. The time evolution of c1 (increase with time) is clearly seen.

Fig. 4. Time history of column-averaged \( c_1 \) at 7.0 keV. We obtained \( c_1 \) at day 32 (2005 August 11) from the calibration sources and that at the other days from the CFCI experiments. We used the relation \( c_1 \propto (PH_0)^{-\beta} \) when obtaining \( c_1 \) at 7.0 keV. Here, we used \( \beta \) shown in section 3.
be regarded as a point source. There are many bright emission lines originated from thermal plasma in the X-ray spectrum below 2 keV. These lines are resolved with the XMM-Newton RGS, and the accurate energies of the line centroids are known (Rasmussen et al. 2001). This object has been used by many instruments for calibration in the low-energy band, and an empirical model to describe the spectrum has been established.\(^3\) We used this source as an energy-scale calibrator in the low-energy band.

4.2. Positional Dependence of the Energy Scale

For the data of the Perseus cluster of galaxies, we divided the imaging area into four regions along the \(\text{ActY}\) axis, and extracted a spectrum from each region. We then fitted the spectra in the 5–7.3 keV band with a power-law model and a Gaussian function, and obtained the center pulse height of the Fe XXV K\(\alpha\) line. Figure 5 shows the center pulse height as a function of \(i\). Triangles and circles indicate the data before and after the CTI correction, respectively. We can see no significant \(i\) dependence after the CTI correction, and this supports the validity of our correction.

4.3. Energy Scale

We decided a relation of \(PH_o\) and the X-ray energy, \(E\). From ground experiments, we found that the \(PH_o–E\) relation can be expressed as a broken-linear function linked at the Si-K edge energy of 1839 eV (Koyama et al. 2007). We then determined the \(PH_o–E\) relation of each segment by using the lines of the calibration sources (Mn I K\(\alpha\) line at 5895 eV) and 1E 0102.2–7219 (K\(\alpha\) lines of O VIII, Ne IX, and Ne X around 650–1020 eV).

We show the results after the CTI correction and the \(PH_o–E\) conversion. Figure 6 shows the measured center energies of the Mn I K\(\alpha\) line as a function of time. Each mark (except for the last one of XIS 2) was obtained from forty data points of figure 6. The mean values of the center energy are 5896.2, 5895.4, 5895.0, and 5895.4 eV for XIS 0, 1, 2, and 3, respectively. The deviation around the theoretical center energy (5895 eV) is 7.8, 4.4, 6.6, and 7.8 eV for XIS 0, 1, 2, and 3, respectively. Therefore, the time-averaged uncertainty of the absolute energy is \(\sim \pm 0.1\%\) for the Mn I K\(\alpha\) line of the calibration sources.

We also studied the time evolution of the deviation around the theoretical center energy; the results are shown in figure 7. We can see that the deviation gradually increases with time.

Figure 8 shows the center energy of the O VIII K\(\alpha\) line obtained from the 1E 0102.2–7219 data. The mean values of the center energy are 652.6, 653.8, 652.7, and 652.8 eV for XIS 0, 1, 2, and 3, respectively. The deviations around the center energy of the empirical model (653 eV) are 1.4, 1.4, 2.3, and 1.1 eV for XIS 0, 1, 2, and 3. Therefore, the uncertainty of the absolute energy is \(\sim \pm 0.2\%\) for the O VIII K\(\alpha\) line of 1E 0102.2–7219.
4.4. Energy Resolution

We examined the energy resolution in $\Delta E$ (FWHM) (Koyama et al. 2007) for each sensor; $\Delta E$ is common to all segments. We expressed $\Delta E$ as

$$\Delta E (eV) = \sqrt{[a \times \left(\frac{E}{5895\text{ eV}}\right)^b]^2 + (\Delta E_0)^2},$$

where $a$ and $b$ are time-dependent parameters and $\Delta E_0$ is the energy resolution determined by ground experiments and obtained using equation (1) in Koyama et al. (2007). We determined $a$ and $b$ by using the time history of the calibration sources and 1E 0102.2–7219. The $\Delta E$ values obtained in this way were incorporated into the redistribution matrix file (RMF).

Figure 9 shows the energy resolution of the Mn I K line after the column-to-column CTI correction. We also plotted the results of the CTI correction, where we used the CTI values averaged over a segment (the column-averaged CTI correction). We can see that the energy resolution is greatly improved by the column-to-column CTI correction. For example, the energy resolution in 2006 December is $\sim 230$ eV without any CTI correction. With the column-averaged correction, the resolution is $\sim 230$ eV, which is not significantly improved. On the other hand, with the column-to-column correction, it is greatly improved to $\sim 190$ eV.

In figure 10, we compare the energy resolution of the Mn I K line after the column-to-column CTI correction with our RMF model. The deviation of the data points around our model are 5.6, 4.9, 3.4, and 6.3 eV for XIS 0, 1, 2, and 3, respectively.

5. Summary

We have conducted the CFCI experiments six times in orbit. The CTI correction has been made with the CFCI results.

We calibrated the energy scale of the XIS precisely using the onboard calibration sources and 1E 0102.2–7219. Our calibration results have been applied to all of the data obtained with the normal full window mode without any spaced-row charge injection. The results of the CFCI experiments and the current calibration status are summarized as follows:

1. We determined the CTI 1 and CTI 2 values of each column precisely based on the data of the CFCI experiments. We also found that the pulse-height dependence of the CTI does not change with time.
2. After the column-to-column CTI correction, we determined the $PH_{\text{e}}–E$ relation. We also modeled the time-dependent energy resolution.
3. The uncertainty of the energy scale is $\pm 0.2\%$ for the O VIII K line ($\sim 0.65$ keV) of 1E 0102.2–7219, and $\pm 0.1\%$ for the Mn I K line ($\sim 5.9$ keV) of the calibration sources.
4. With the column-to-column CTI correction, the energy resolution at $5.9$ keV in 2006 December was greatly improved from $\sim 230$ eV to $\sim 190$ eV.
Appendix. Determination of the CTI Values before the First CFCI Experiment

First, we determined the CTI values of segments A and D in 2005 August. We combined the data of the calibration sources from 2005 August 11 to 31, and obtained $PH_0$ of the Mn I Kα line. We also estimated $PH_0$ at 5895 eV from the $PH_0$–$E$ relation determined by ground experiments, and obtained the ratio $PH_0/PH_0$. From equation (2), the ratio can be expressed approximately as $PH_0/PH_0 = 1/i_{cal} - 1024/c_2$, where $i_{cal}$ is the mean transfer number of the calibration events (typically ~900). We determined $c_1$ and $c_2$ at 5895 eV from $PH_0/PH_0$ with the $c_1/c_2$ ratio being fixed to the values shown in section 3. The $c_1$ and $c_2$ for other pulse-height values were calculated from equation (3), where we used the column-averaged and time-averaged $\beta$ values determined in section 3. Then for segments B and C, we took the average CTI values of the segments A and D. We regard the CTI values obtained in this procedure as those on 2005 August 11 (the day of the XIS first light). Note that these values are determined for each segment, not for each column.

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