Use of a Charge-Injection Technique to Improve Performance of the Soft X-ray Imager aboard ASTRO-H

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Abstract

We are developing the Soft X-ray Imager (SXI), a charge-coupled device (CCD) camera system to be deployed onboard the ASTRO-H satellite. Using an engineering model system, we measured charge transfer inefficiency (CTI) and the effects of charge trailing. The CCD was irradiated with monochromatic X-rays produced by a radio isotope (\(^{55}\)Fe) and X-ray generator using alpha particles from \(^{241}\)Am. Since CTI degrades energy resolution, we have adopted the charge injection technique to the SXI. However, the charge-injection technique can cause positional variations in gain on the CCD chip. Thus, we constructed a method for correcting CTI. We also evaluated the charge trailing effect and tested a method for correcting its effects. After applying these corrections to charge injection, variations in gain improved from 0.5% to 0.1% over the CCD chip, and the energy resolution (FWHM) improved from ~220 eV to ~180 eV at 5.9 keV.

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

1. Introduction

We are developing the Soft X-ray Imager (SXI) (Tsunemi et al. 2010), a CCD camera system to be deployed onboard the ASTRO-H satellite. Using an engineering model system, we measured charge transfer inefficiency (CTI) and the effects of charge trailing. The CCD was irradiated with monochromatic X-rays produced by a radio isotope (\(^{55}\)Fe) and X-ray generator using alpha particles from \(^{241}\)Am. Since CTI degrades energy resolution, we adopted the charge-injection technique to the SXI. However, the charge-injection technique can cause positional variations in gain on the CCD chip. Thus, we constructed a method for correcting CTI. We also evaluated the charge trailing effect and tested a method for correcting its effects. After applying these corrections to charge injection, variations in gain improved from 0.5% to 0.1% over the CCD chip, and the energy resolution (FWHM) improved from ~220 eV to ~180 eV at 5.9 keV.

2. Charge Trailing

We extracted averaged pulse heights for pixels following and preceding the event center from the grade-0 event for Mn Kα. We found that the pulse height of pixels following the event center increase in proportion to $RawY$, while the pulse height of pixels preceding the event center is almost constant. We define position in the imaging area by detector-fixed coordinates ($RawX$, $RawY$), where the origin (0, 0) is taken to be the first pixel read.
out. This difference may be caused by charge trailing from the center pixel. Some charges spilled into the following pixel during charge transfer (charge trailing).

Following Yamaguchi et al. (2006), who define the probability of charge trailing per transfer as the charge trail ratio (CTR), we estimated CTR to be \(3 \times 10^{-6}\) [binned transfer\(^{-1}\)] for Mn K\(_\alpha\) events. We define binned transfer as 2 pixel transfer in the physical coordinate. We estimate CTR for other energies and found that the final equation of charge trailing is \(\text{CTR} = 2.9 \times 10^{-6} \times (\text{PH'}/\text{PH}_0)^{-0.74}\) [binned transfer\(^{-1}\)]. Here, PH' and PH\(_0\) are defined to be the pulse height of the grade-0 event for Mn K\(_\alpha\) after correcting for the charge trailing and after correcting for the charge trailing and CTI, respectively (see next section). After the charge-trailing correction, the pulse height of pixels following the event center becomes constant at any RawY.

3. Charge Transfer Inefficiency with CI Technique

We constructed spectra along a vertical line and fit the Mn K\(_\alpha\) line to a Gaussian. The top and bottom panels in Figure 1 show the center value and width of the Gaussian as functions of RawY, respectively. The gray and black points represent data taken without and with the CI, respectively. The degradation of energy resolution is properly restored with the CI. However, the profile for the pulse height (PH') shows a "sawtooth shape" with edges at the charge-injected rows; this results in the positional variations in gain of \(\sim 0.5\%\). This is because CTI depends on the distance between the pixel and charge-injected row. We need further calibration for the positional variations in gain of the pulse height.

Following the discussion given by Uchiyama et al. (2009), we assume two different CTIs: CTI1 (\(c_1\)) for slow transfers and CTI2 (\(c_2\)) for fast transfers. PH' at RawY = \(i\) is expressed as the original pulse height generated by an X-ray (PH") with the two CTI components, PH'\((i) = \text{PH'\((1 - c_1)\) (1 - c_2)\) }^{640}\). The CTI1 is described by a periodic sawtooth, \(c_1 = c_{10} \cdot \{1 - p_1 \cdot \exp(-\delta t_1 \cdot j/\tau_1)\}\), where \(c_{10}, p_1, \delta t_1, j\) and \(\tau_1\) are the normalization of \(c_1\), the probability of filling a charge trap, the time between one vertical transfer and the next, the RawY value between a pixel and its preceding charge-injected row, and the re-emitting time scale, respectively. CTI2 is similarly expressed by, \(c_2 = c_{20} \cdot \{1 - p_1 \cdot \exp(-\delta t_2 \cdot j/\tau_2)\}\). The dashed line in Figure 1 shows our model, which is the best-fit result. Since PH" and \(c_{20}\) are easily coupled and cannot be constrained from the experiment, we define PH" = 940. We also fix \(c_{10}\) to the value measured from the data without CI. We obtained \(c_{10} = 3.6 \times 10^{-5}\) [binned transfer\(^{-1}\)].

The other parameters are found to be \(c_{20} = 8.0 \times 10^{-6}\) [binned transfer\(^{-1}\)], \(p_1 = 0.9, \delta t_1 / \tau_1 = 1.1 \times 10^{-3}\), \(\delta t_2 / \tau_2 = 1.5 \times 10^{-2}\). Uchiyama et al. (2009) present a CTI correction method for Suzaku. They adopt a linear function as an approximation to the exponential function, which satisfies the calibration since they had limited in-orbit data. However, their model does not fit our data with high statistics.

Using the CTI model with the obtained parameters, we conduct the CTI correction. The red symbols in the top panel of Figure 1 show the Gaussian center of the corrected pulse height (PH'). We reduce positional variations in gain to within \(\sim 0.1\%\). This satisfies requirement of 0.1% for flight operations.

We adopt the CTI model to events at other X-ray energies. We fit each profile with PH" and the one parameter that normalizes \(c_1\) [\(c_{10}\) free]. Other parameters and the ratio of two normalizations (\(c_{10}, c_{20}\)) are fixed to those of the Mn K\(_\alpha\) line. Thus, we can calculate the CTI at any pulse height with \(c_{10}\) [binned transfer\(^{-1}\)] = \(3.7 \times 10^{-5} \times (\text{PH'}/\text{PH}_0)^{-0.37}\). Here, PH\(_0\) is defined as the PH" of Mn K\(_\alpha\). We performed the CTI correction and successfully reduced the RawY variations within \(\sim 0.1\%\).

After corrections for CTI and charge trailing, the energy resolution improves from 220 eV to 184 eV at 5.9 keV.

References

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