X-ray Imaging Spectrometers for Astro-E: Ground Calibration in Soft X-ray Range

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ABSTRACT

Soft X-ray response of X-ray Imaging Spectrometers (XIS) for the Astro-E satellite is measured with a grating spectrometer system at Osaka. First, relation between incident X-ray energy and output pulse height peak (E-PH relation) is examined with an SX grating. It is found that jump in the E-PH relation around Si-K edge is at most 2.7 eV. Second, quantum efficiency (QE) of the XIS in 0.4-2.2 keV range is measured relatively to the reference CCD of which absolute QE was calibrated with a gas proportional counter. The QE is fitted with a model in which CCD gate structures are considered. Systematic error on the QE results is estimated by referring an independent measurement. Third, tuning and improvement of the response function is performed. We employ six components to reproduce the response profile of the XIS. In this paper, improvement of one component which is originated in the events absorbed in the channel-stop is presented.

Nevertheless, Astro-E was lost due to the launch failure. We overview the XIS project in its flight model phase, modified points of the design, problems and solutions etc., in order to be utilized in a possible recovery of the satellite.

Keywords: Astro-E, X-ray CCD, Calibration

1. INTRODUCTION

X-ray Imaging Spectrometers (XIS) are X-ray CCD camera systems on board X-ray astronomy satellite Astro-E. The XIS consists of four cameras, each is installed at the focal plane of X-ray Telescope (XRT). The XIS cover energy range of 0.4 to 10 keV with spectral resolution of about 130eV@5.9keV and with imaging capability with FOV of 17 arcmin squared. Net effective area of the XIS plus XRT system amounts to about 1300 cm$^2$ at 1.5 keV and 800 cm$^2$ at 7 keV. At the same time, imaging capability of XIS works as a complement to the limited FOV of XRS (X-Ray Spectrometer), and the sensitivity of XIS upto 10 keV assures smooth connection to the low energy end of the Hard X-ray Detectors.

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In section 2, we present the summary of ground calibration of the XIS flight model in its soft X-ray part. We focus on recent developments on the calibration, namely, energy pulse-height relation around Si-K edge, quantum efficiency with its uncertainty, and response profile. Some description on the XIS system itself is found in Hayashida et al. (1998). However, since the description in it is mainly on its Engineering Model (EM), we list up modified points of the design for the Flight Model (FM) in section 3.

2. SOFT X-RAY RESPONSE OF XIS

2.1. Ground Calibration of the XIS

We planned ground calibration at three sites for the XIS FM. Chip level calibration was performed at MIT using characteristic X-ray lines. After the chip level calibration, the CCD was installed in the XIS base and was brought to Japan. In Japan, the XIS camera base and bonnet were assembled, and camera level calibration was done, soft X-ray part (0.4-2.2 keV) at Osaka and hard X-ray part (above 1.5 keV) at Kyoto. Flight combination of analog electronics and camera was kept as much as possible in the calibration in Japan, except that most of the calibration in Japan was performed without the optical blocking filter (OBF) in the bonnet. Furthermore, soft X-ray calibration for continuous energy was only done at Osaka. Therefore, in this paper, we principally use the calibration results taken in Japan. However, the calibration at MIT is important to see the consistency of the results.

Unfortunately, delay of the schedule due to some problems (see section 3) did not allow us to complete full sets of the FM calibration planned at the beginning. In particular, calibration of high energy side planned at Kyoto was performed only for XIS0 among the final set of four flight sensors. Some of the calibration data taken at MIT are also used in order to compensate this point.

2.2. Osaka Calibration System

In the following sub sections, we summarize the soft X-ray response of the XIS derived mainly from the experiment at Osaka. Earlier reports on the topic are found in Hayashida et al. (1998), Katayama et al. (1999), Kohmura et al. (1999), Shouho et al. (1999), Katayama et al. (1999), Kohmura et al. (2000), and Katayama et al. (2000). Calibration at high energy part performed at Kyoto is appeared in Nishiuchi et al. (1998) and (1999). The soft X-ray calibration system at Osaka is described in Hashimotodani et al. (1998). The system consists of an X-ray generator, a grating spectrometer, and a chamber with moving stages and a LN2 cooling system. Continuum X-rays from the generator, though several characteristic X-rays are contaminated, are dispersed by the grating in the spectrometer. The CCD installed in the XIS camera is irradiated by the dispersed X-rays. The key idea of this calibration system is that we can get CCD responses to single energy X-rays for continuous energy range at the same time. We construct CCD pulse height spectra of each CCD column, when we set the X-ray dispersion direction is perpendicular to the CCD column.

In reality, however, there are significant contaminations from higher order X-rays and non-dispersed X-rays. The former can be separated from the first order X-rays by looking at the CCD pulse height itself, though it cause a problem when we investigate detailed tail profile of the CCD response. The latter, non-dispersed X-rays, become most significant background, though we have established a way to estimate their level and the spectrum.

In the following sections, we describe the soft X-ray response of XIS measured at Osaka. Unless noted, CCD clocking mode is normal 8 seconds exposure. We take grade02346 spectrum with split threshold of 20 ADU (about 70-80 eV).

2.3. Energy Pulse-Height Relation

Using the Osaka calibration system, it is easy to construct a CCD pulse height (PH) spectrum for a given incident X-ray energy within the available energy range. The relation between the PH peak vs the incident X-ray energy, i.e., Energy-Pulse Height (E-PH) relation, is one of the most important item to be calibrated. In particular, we have payed a special attention to a possible jump around Si-K edge. In the previous reports, though we surely found deviations of 3-4 ADU (10-14 eV) from linear relation around Si-K edge energy, we could not concluded it really represents the CCD response or not. That was because we know the PH peak is affected by the profile model we employed, and because finite resolution of the spectrometer and the sharp drop in the dispersed spectrum above 1.8 keV.
2.3.1. Experiment with SX grating

To clarify the E-PH relation around Si-K edge, we performed an extra experiment by replacing SA grating which is optimized for O-K with SX grating optimized for Si-K edge. As compared in Fig. 1, the dispersion spectrum of SX is smoother than that of SA around 1.8-2.0keV range. We used one of the spare XIS cameras and electronics, since all the flight models were already installed on the satellite. In Fig. 2, we show that the E-PH relation and its residual to a straight line fit. To make this E-PH relation, we employed a simple Gaussian plus constant model to fit the PH
spectra. Nevertheless, the residual is less than ±2 ADU, much smaller than that obtained with the SA grating.\textsuperscript{1,4}

Figure 3. Energy-PH relation, residual to a straight line crossing the origin and the Mn-K line point. For the left panel (a), XIS response profile model is used to determine the PH peak. For the right panel (b), contribution of Si-line is taken into account.

We next examine the influence of response profile models on the results. We use a profile model consisting of two Gaussian peak, triangle function, plus constant, which are the current XIS response function model mentioned below. We show the residual for this XIS response function model, in Fig. 3(a). Note that to derive the residual in this figure, we adopt the straight line of \( \text{PH(ADU)} = 258.138 \times \text{E(keV)} \), which is the line crossing the origin and the Mn-\( K\alpha \) point. We found the peak PH is shifted upward by about 1 ADU by using the XIS response function, which is reasonable because the function takes into account the tail in the spectrum. At the same time, the jump is reduced. We further investigate the contamination of Si-\( K\) line which should be present for incident X-ray energy above Si-\( K\) edge. The residual is plotted in Fig. 3(b). Data points above Si-\( K\) edge go downward and the jump is further reduced. When we fit the points in Fig. 3(b) with a step function, we get the jump at Si-\( K\) edge energy to be \( 0.63 \pm 0.06 \) ADU (2.44 ± 0.23 eV).

As shown in Fig. 1, however, the dispersion spectrum from SX grating measured with XIS CCD has a jump at Si-\( K\) edge. Since the spectrometer has a finite energy resolution of about a few eV, each data point in E-PH relation has a contamination from the adjacent X-ray energy. It affects the peak PH at the energy where the spectrum intensity jumps, i.e., Si-\( K\) edge. We model this effect and compare the observed residual. It is found that significant part of the minus residual around Si-\( K\) edge can be explained by this effect. So, we may had better to regard the residual this region is due to the spectrometer. If we neglect the energy range 1.75-1.9 keV, we get the jump to be \( 0.47 \pm 0.06 \) ADU (1.82 ± 0.23 eV).

Fraser et al.\textsuperscript{(1994)}\textsuperscript{11} investigated theoretically how the mean ionization energy (W) shifts around the Si-\( K\) edge. They expect +0.2% jump in W. Though its absolute value is comparable to the value we obtained, the direction is inverse. On the other hand, Torii \textit{et al.} (1995)\textsuperscript{12} measured the jump using Si-SSD and gave 1.5 ± 2.6eV, which is consistent with ours. Physical interpretation of our result needs further study. Nevertheless, the jump of this level can be neglected in most of the practical usage of the XIS.

2.4. Quantum Efficiency

2.4.1. Soft X-ray QE

The soft X-ray Quantum Efficiency (QE) was measured with the grating spectrometer in Osaka. We referred a gas proportional counter (PC) to determine the absolute QE. We took the following steps to get the results. Note that we don’t include the absorption due to the XIS optical blocking filter (OBF) or the XRT thermal shield in the QE
values described here. The X-ray transmission of the OBF is described in Kohmura et al. (1999)\textsuperscript{3} and Kohmura et al. (2000)\textsuperscript{6}. It is about 70% at 0.5keV.

1. **Absolute QE of PC**... The X-ray absorption of the PC window was measured as a function of X-ray energy through on/off experiment with the spectrometer. We used one of the XIS cameras as a detector. The thickness of the polypropylene window and the covering fraction of the supporting mesh were measured to be 1.49 $\mu$m and 0.28, respectively. We also found that additional contribution of oxygen (may be in the form of water) of 0.17 $\mu$m thickness must be included to reproduce the measured absorption of the window. The absolute QE of the PC is modeled from the window thickness, the gas content (Ar 90% + CH\textsubscript{4} 10%, 1atm) and the geometrical depth of the counter (40.9mm).

2. **QE of Reference CCD : Measurement**... X-rays from the spectrometer were shone to the PC and to the reference CCD camera alternately to measure the relative QE of the reference CCD to that of the PC. The reference CCD we used here is one of the engineering models (EM) of XIS. We monitored the beam current of the X-ray generator and used it for the compensation of the intensity change of the incident X-rays. We used a slit to limit the irradiation area of the incident X-ray and its energy. Though the slit was placed at 9 different positions, we obtained 14 points from 0.460 to 2.242 keV X-ray energy by using 2nd order light in some positions. The pulse height (PH) spectra of either PC and reference CCD are fitted with a Gaussian model to derive the counts, which give the relative QE. The absolute QE of the reference CCD at 14 energy points is obtained by multiplying those values by the QE of the PC.

3. **QE of Reference CCD : Model**... We further make the QE model of the reference CCD, which is based on a CCD structure model in which gate structure is taken into account. We employ the CCD structure model described in Pivovaroff et al. (1998).\textsuperscript{13} We make the gate Si thickness and the SiO\textsubscript{2} thickness as free parameters in the fitting of our QE data. Many other parameters, such as gate overlap fraction, Si\textsubscript{3}N\textsubscript{4} thickness, channel stop width and thickness are fixed to their model values.\textsuperscript{13} We also fix the depletion layer thickness to be 70 $\mu$m. The best fit model parameters of our reference CCD are Gate Si thickness of 0.314 $\pm$ 0.088 $\mu$m and Gate SiO\textsubscript{2} thickness of 0.373 $\pm$ 0.063 $\mu$m.

4. **QE of FM CCD**... We irradiated the dispersed X-rays of the spectrometer to the reference CCD camera and to the XIS flight model (FM) cameras. We normalized the incident X-ray intensity by monitoring the beam current. Nevertheless, since monitor data was not available for the experiment of XIS0, we show the results for other three FMs. In these measurements, the slit was not used so that X-rays of continuous energies were

![Figure 4](image-url)  
**Figure 4.** Relative QE of three XIS FM to the reference CCD (EMJ2).
Figure 5. QE of the XIS1 CCD. Circles are measurement points at Osaka system, squares are those obtained at MIT system. QE model for the Osaka data points, in which CCD gate structure is taken into account, is also shown. Note that absorption due to the XIS OBF and the XRT thermal shield are not taken into account.

Table 1. QE Model parameters for four XIS FM CCDs. CCD gate structure is taken into account. The thicknesses of gate Si and gate SiO₂ are those for the region where the gate has no overlap. At the area where the gate is overlapped, the total gate Si thickness and the total SiO₂ thickness are assumed to be 2 and 1.7 times of those thicknesses. Only for XIS0, we use the chip level calibration data taken at MIT.

<table>
<thead>
<tr>
<th>SENSOR</th>
<th>Gate Si</th>
<th>Gate SiO₂</th>
<th>Depletion Layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>XIS0</td>
<td>0.2811 ± 0.0005</td>
<td>0.2252 ± 0.0004</td>
<td>74.66 ± 1.83</td>
</tr>
<tr>
<td>XIS1</td>
<td>0.2778 ± 0.0001</td>
<td>0.3488 ± 0.0010</td>
<td>70.22 ± 1.72</td>
</tr>
<tr>
<td>XIS2</td>
<td>0.2808 ± 0.0005</td>
<td>0.3525 ± 0.0034</td>
<td>73.15 ± 1.37</td>
</tr>
<tr>
<td>XIS3</td>
<td>0.2572 ± 0.0100</td>
<td>0.3253 ± 0.0026</td>
<td>73.09 ± 2.70</td>
</tr>
</tbody>
</table>

irradiated to the CCD. We construct the PH spectrum for each dispersed position, i.e., X-ray energy. Counting rates derived from those PH spectra give the relative QE of the XIS FM to the reference CCD as a function of X-ray energy, as shown in Fig. 4. Using the modeled QE of the reference CCD derived above, we get the absolute QE of the XIS FM. One of the examples is shown in Fig. 5. As shown in the figure, we fit the data points with the QE model based on the CCD gate structure. The best fit parameters of thicknesses of Gate Si and Gate SiO₂ are listed in Table 1.
Figure 6. Ratio of the QE model derived from the measurement at MIT and that from the measurement at Osaka. Relative discrepancy is at most 30% above O-K edge where QE is small.

2.4.2. Effective thickness of the depletion layer
The QE at high energy side is mainly determined by the effective thickness of the depletion layer. We determined it from the measurement with Mn-K X-rays from $^{55}$Fe isotope $^\ast$. We principally employ the method using a grade bracing ratio, as described in the ACIS calibration report.$^{14}$ The results are listed in table 1. The results here are for normal clocking mode and grade02346. We also measured the QE of P-sum mode, which is 94-95% of the normal mode QE at 5.89 keV. Higher QE in the normal mode is due to higher voltage applied to the imaging area clock in the exposure period.

2.4.3. Systematic Errors on the QE
Each CCD has an independent chip level QE measurement performed at MIT. In the measurement, seven kinds of characteristic X-rays ranging from O-K(0.525keV) to Cu-K(8.04keV) are used. In the measurement, a reference CCD, which is not the same one we used in Osaka, was also employed, to which relative QE of each FM CCD is measured. The absolute QE of the reference CCD was calibrated in a synchrotron facility through the method described in Bautz $et$ $al.$.$^{15}$ Therefore, the QE derived in Osaka measurement and that in MIT measurement are fully independent.

In Fig. 5, we also plot the QE values derived from the measurement at MIT. Deviation of these points from those of the Osaka experiment is at most 0.06 for three FM CCDs, XIS1, XIS2, and XIS3. We model the QE data from the MIT experiment with the same model we used above and take the ratio of (QE model from the MIT experiment)/ (QE model from the Osaka experiment). As shown in Fig. 6, the relative difference of at most 30% is found just above O-K edge (0.54keV) for XIS3. Difference in the best fit parameters for SiO$_2$ thickness ($0.325 \pm 0.003\mu m$ for the Osaka data, $0.253 \pm 0.002\mu m$ for the MIT data) reflects this discrepancy. This is one of the points we have to consider further. On the other hand, the relative discrepancy in the QE at high energy side, $e.g.$, 5.89 keV is less than 5%.

We also investigate the XAFS structure around O-K edge and Si-K edge. See Mori $et$ $al.$$^{16}$ about it.

$^\ast$We had intended to determine it in characteristic X-ray experiment at Kyoto. However, the schedule allowed us to do it only for one XIS FM among the four.
<table>
<thead>
<tr>
<th>Component</th>
<th>Origin</th>
<th>Function Form</th>
</tr>
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<tbody>
<tr>
<td>Main Gaussian</td>
<td>Depletion Layer</td>
<td>Gaussian</td>
</tr>
<tr>
<td>Sub Gaussian</td>
<td>Depletion Layer (Split Event)</td>
<td>Gaussian</td>
</tr>
<tr>
<td>Channel Stop</td>
<td>Channel Stop</td>
<td>Triangle</td>
</tr>
<tr>
<td>Constant Tail</td>
<td>Insulator/Depletion Layer</td>
<td>Constant</td>
</tr>
<tr>
<td>Si Line</td>
<td>Depletion Layer</td>
<td>Gaussian</td>
</tr>
<tr>
<td>Si Escape</td>
<td>Depletion Layer</td>
<td>Gaussian</td>
</tr>
</tbody>
</table>

Table 2. Components of XIS Response Profile.

2.5. Response Profile

We modeled the response profile of XIS CCD for a single energy X-ray incidence with six components summarized in table 2 and Fig. 7.

Among these components, the sub Gaussian component is due to the events absorbed near pixel boundaries and some of the charge is not accounted to the PH because the pixel level is below the split threshold. The peak position of this component is about (split threshold)/2 below the main Gaussian peak. Relative contribution of this component to the main Gaussian component is about 4% at 1keV and 10% at 5keV. Detailed description is given in Nishiuchi et al. (1999).9

The constant tail component is originated in the events absorbed around the boundary region between the Si depletion layer and the SiO\textsubscript{2} insulator. Although the constant component had been taken into account in the ASCA SIS response, the interpretation was made by Prigozhin et al. (1998).17 This component, and Si line, Si escape component are studied in detail by Imanishi et al. (2000).18

![Figure 7](image)

**Figure 7.** Components of response profile (model). Four components, main Gaussian, sub Gaussian, channel-stop, constant are employed to reproduce the profile when the incident X-ray energy is below the Si-K edge (left panel). Above the Si-K edge, Si-K line and Si-escape have to be taken into account (right panel).

2.6. Channel Stop Component: Revision from the Triangle Component

The channel stop component was introduced by Prigozhin et al. (1998)17 and Katayama et al. (1999).2 We consider this component is originated in the channel stop, because it is remarkable in grade 3, 4 (horizontally split events)
spectra for low energy X-ray incidence. This component was not taken into account in the ASCA SIS response, though it might be confused with the sub Gaussian component.

In Katayama et al. (1999), this component is approximated with a triangle function as

\[ f_{\text{triangle}}(PH) \propto \begin{cases} (PH - F \times PH_C) & (F \times PH_C < PH < PH_C) \\ 0 & \text{Otherwise} \end{cases} \]

where \( PH_C \) is the center PH channel of the main Gaussian component, and \( F \) represents cutoff of the spectrum. Though this form is introduced to reproduce the PH spectrum of O-K line, it implicitly assumes the absorption depth dependence of the charge loss in the channel stop as

\[ g(x) = (1 - F)(1 - (x/d_{cs})^\alpha), \]

where \( x \) is the absorption depth from the surface of the channel stop, \( d_{cs} \) is the thickness of the channel stop, \( \alpha \) is a parameter, for which 0.5 was adopted. The cutoff \( F \) was also fixed to be 0.5 so as to fit the PH spectrum of O-K line. In this approximation, however, we neglected that the absorption depth has a distribution of \( \mu_{Si} \exp(-\mu_{Si}x)dx \), where \( \mu_{Si} \) is the absorption coefficient of Si. If we take this into account, the PH distribution should have a form

\[ f_{\text{new-\text{chstop}}}(PH) \propto \begin{cases} \exp[-\mu_{Si}d_{cs}(PH/PH_C-F)^{(1/\alpha)}] \times (PH/PH_C - F)^{(1/\alpha-1)} & (F \times PH_C < PH < PH_C) \\ 0 & \text{Otherwise} \end{cases} \]

We fit this model to the PH spectra for O-K, Mg-K, and Al-K lines and find \( d_{cs} \sim 1 - 1.2 \mu m \) and \( \alpha \sim 0.4 - 0.6 \) gives the best fit. The PH spectrum and model for O-K is shown in Fig. 8. Adopting \( d_{cs} = 1 \mu m \) and \( \alpha = 0.5 \), and we determine \( F \) as a function of \( E \). \( F \) is about 0.6 at 0.6keV and 0.9 at 5.9keV. The relative contribution of this channel stop component to the main Gaussian component is 4% at 0.6keV and 0.7% at 5.9keV.

![Figure 8. Response to O-K Line (0.525keV). Measured PH spectrum and model fit to the profile including the new model for the channel stop component are shown. The left panel shows the grade 3+4 (horizontally split events) spectrum, while the right panel shows the grade02346 spectrum.](image)

2.7. Response Matrix and XIS Simulator

We construct the response matrix (function) of XIS using the QE model, E-PH relation, and the response profile model we described above. The current version of the response matrix is for grade 02346 spectrum for normal clocking mode, and the triangle function is used to reproduce the channel stop component. We have been tuning the parameter of the response function. As far as possible, analytical expression is employed for each parameter.
of response function, such as the width of the main Gaussian component as a function of energy (i.e. energy resolution), relative contribution of each component. Reproducibility of the response matrix is discussed in Imanishi et al. (2000).18

As described in Katayama et al. (1999),2 we also constructed a Monte-Carlo simulator which tracks the process of X-ray absorption, the following charge generation and collection inside the XIS CCD. The output of the simulator is frame data as for the real measurement. We also have been tuning the parameters used in the simulator. One example of its reproducibility is shown in Fig. 9. This simulator has been used to confirmation and extrapolation of the XIS response function. It will also be useful to see how the response is modified from the standard one by increasing flux or else.

![Figure 9](image)

**Figure 9.** PH spectrum for Al-K line (1.49keV) and for Cl-K (2.62keV). Measured data are plotted with crosses and simulation data are with stars.

### 2.8. Summary of Ground Calibration

We have determined the E-PH relation, QE, and the response profile for the XIS FM. We could determine the E-PH relation with an error of 3 eV at least in the range of 0.4-2.2keV. Because we have an on-board calibration source in each XIS camera, we expect that the energy scale of the XIS spectrum can be determined within a few eV accuracy, which we think enough for most of the cases.

We established the way to measure the soft X-ray QE of the XIS. The absolute systematic error of 6% seems good, but it reflects up to 30% relative QE error for the points just above O-K edge. We may need further study for this systematic error or inconsistency. We don’t have a good standard object on the sky which can be used for the in-orbit calibration of the QE in the soft X-ray band. It contrasts to the fact that high energy efficiency can be calibrated with the Crab nebulae or bright AGNs. Therefore, the inconsistency in the QE at soft X-ray range should be minimized on the ground.

Comparing these two, the E-PH relation and the QE, the response profile is a higher order item in the calibration. For it, we have improved our knowledge enough for the practical use.

### 3. FROM ENGINEERING MODEL TO FLIGHT MODEL

We described design and configuration of the XIS in Hayashida et al.(1998).1 However, the description is mainly on its engineering model (EM), which is not necessarily identical to the flight model (FM). In this section, we would look back on what points we modified the design of the XIS from the EM to the FM. We also list up problems we encountered in the FM phase of the XIS project with their solutions. Though these kinds of information seldom appear in a proceeding article, they will be useful for future projects.
3.1. Camera Base

The most significant change from the EM XIS to the final FM XIS is a CCD supporting system inside the XIS camera base. The design was severe at the first point to satisfy both strength against the impulse shock at the launch and a good thermal performance. The latter is established both by a good thermal contact between the Thermo Electric Cooler (TEC) and the CCD and by a small heat input through a CCD/TEC supporting structure.

![Diagram of supporting structure of CCD and TEC.](image)

Figure 10. Schematic view of supporting structure of CCD and TEC. In the final FM design, the flexure in the figure was replaced with the 2 stage flexure with 2 directional flexibility.

In the FM design, three TECs (each has three stages) are sandwiched between the CCD chip and the heat sink plate (see Fig. 10). A small flexure is put on the top stage of the TEC. The flexure is compressed by the pillars connecting the heat sink and the CCD. After assembling the FM camera with this design, we experienced that cooling performance of some cameras was degraded in some occasion. Some of the TECs were turned out to be broken, due to thermal and/or mechanical stress. After detailed examination of the problem, we introduced counter measures; TECs with stiffer bonding materials, more flexible (two directions) flexure on the TEC top stage, and further tuning of the assemble. After applying these counter measures, the flight models survived in all the shock/thermal tests. Required thermal performance (to keep CCD at $-90^\circ \text{C}$ for the heat sink temperature less than $-40^\circ \text{C}$) was also satisfied.

3.2. CCD Chips

CCD chips used in the flight cameras were screened from CCID17 manufactured by Lincoln Laboratory MIT. The points of screening were readout noise, FWHM for Mn-K X-rays, and the number of dead pixels and so on. Although we needed 5 chips (4 flights and 1 spare), several other spares were prepared. However, we lost some of the flight chips after installation in the camera base. One chip got a crack at its edge during repeated thermal test phase before rebuilding the camera base mentioned above. Other two chips installed in the flight cameras that had nice performance and small deficiencies turned out to show instability in output signal gain. The time scale of the instability is hours, and the gain variation is typically 1%. These two chips belonged to the same lot, in which PSG cover over on-chip readout circuit was not put by some reason. The instability is likely to be induced with this missing structure. We finally abandon to use these two as flight chips.

At last, we are forced to choose the forth flight CCD from two chips; one has an electrode shortage in the imaging area, which makes a big hot spot depending on the way of clocking, another has a broken read out port out of four. We chose the latter as the fourth flight model, and the former as a spare model. Although one outer segment of this fourth flight chip does not generate signals in normal clocking mode, we could have special clocking modes with which the corresponding area is read out from the other read out port.

3.3. Camera Bonnet

The design was basically unchanged from the EM to the FM. Although the initial FM bonnet had a problem of vacuum leakage owing to an inappropriate surface finish at the interface, re-treatment satisfy the specification.
Calibration sources ($^{55}Fe$) were installed in the FM bonnet first time. The source emit collimated X-rays at one corner of each CCD chip. The area of the irradiated region is about 3 or 5 mm radius at the corner. The X-ray intensity (Mn-K) measured on September 3, 1999 is 0.15-0.56 c/sec, depending on the sensors.

### 3.4. Optical Blocking Filter

Initial EM design of the Optical Blocking Filter (OBF) was Al coated Lexan with thickness of Al/Lexan/Al = 400 Å/1000 Å/ 400 Å. Since polyimide, which is stronger than Lexan, became available, we replaced the Lexan with polyimide for the FM OBF. We measured the optical and the X-ray transmission of the FM OBFs of which design were Al/Polyimide/Al = 400 Å/1000 Å/ 400 Å. It was found that the optical transmission of these OBFs was greater than $10^{-3}$, which was much higher than our expectation of $10^{-5}$. Considering the data on X-ray transmission, we supposed that oxidization of Al occurred for these OBFs, as reported by authors of other missions. So, finally the design of FM OBF was fixed to be Al/Polyimide/Al = 200 Å/1000 Å/ 1000 Å. The detailed description is given in Kohmura et al. (1999) and in Kohmura et al. (2000).

### 3.5. Analog Electronics

Minor modifications, such as tuning the stability of TEC control circuit, rearranging the HK items to take were made.

### 3.6. Digital Electronics

Hardware design was almost unchanged, though software modifications and debugs were made on several points. One important change was done to the X-ray event editing mode. We replaced Top3 mode (output pixel levels of 1st, 2nd, 3rd highest in $3 \times 3$ pixels around event center) with $2 \times 2$ mode (output pixel levels of the $2 \times 2$ pixels including the event center and the 2nd high pixel). This is meant for unified data reduction on the ground; grade 6 events are extracted in the same way in all the telemetry editing mode, $5 \times 5$, $3 \times 3$, and $2 \times 2$. Another modification of the DE software was needed to avoid incorrect HK output from the AE which occurs at a some special timing.

### 3.7. Ground Data Processing

For normal clocking mode, the on-board data processing yields $5 \times 5$, $3 \times 3$ or $2 \times 2$ mode, none of them has a ASCA type grade. Nevertheless, we intended to use grade to make a pulse height of each X-ray event as a baseline. One important change from the original ASCA grade method is to use surrounding 16 pixels in $5 \times 5$ pixels. If we find a pixel of which pixel level exceed a given threshold among the surrounding pixels adjacent to event pixels, we discard the event. This is intended to reject piled up events or particle events. In addition, small modification were made on the definition of grade 6. For example, we sum up the corner pixels adjacent to 2nd high, 3rd high pixels regardless of its pixel levels; this is found to reduce the offset of synthesized pulse height from that of other grades.

Although we consider the grading method is the baseline of ground data processing, a new fitting method to extract PH was developed. This method is effective to improve the high energy QE.

Software for the ground data processing are constructed on the framework of ASTROE-ANL, which was jointly developed among Japanese Astro-E team. Software used in the ground calibration and test, such as, QL system, DL system, software to simulate the DE functions, and XIS CCD simulator were all constructed on the same framework. Some of the functions and modules are commonly used among these softwares. The softwares for general guest observers of Astro-E XIS, which have the form of FTOOLS, are created based on these modules and functions.

### 3.8. Radiation Damage

From ASCA experience, we know that radiation damage is the most significant problem in the in-orbit performance of X-ray CCD. We take several countermeasures against it.

However, we had to reconsider the issue in the final test stage of the XIS, September-October of 1999, since unexpected level of radiation damage was observed in the ACIS CCDs on Chandra, the same CCID17 are used in it. The radiation damage is likely to be due to low energy (0.1-0.2MeV) protons. Energy distribution of the proton in the Astro-E orbit is, however, largely different from that for Chandra’s eccentric orbit. For low earth orbit, the number of low energy (0.1-0.2MeV) protons is evaluated to be several orders of magnitude lower. Furthermore, the thermal shield of the XRT is effective to scatter the protons so as not to be collected to the XRT focal point. Finally,
we had an experience of ASCA which have similar orbit and system to the Astro-E XIS. From these points, we
determined not to do any modifications to the XIS design.

The amelioration of the CCD radiation damage, in particular, restoration of the CTE is possible to some extent
with introducing sacrificial charge (or charge injection) method. The method is to fill the charge traps with sacrificial
charge (charge other than the signal) before transferring the signal charge. The source of the charge is either cosmic
ray events, dark current, or artificially injected charge. Application of the method on the ground to some damaged
CCID17 is described in Prigozhin et al. (2000) and in http://space.mit.edu/ACIS/Rad\_damage\_amelioration.html.
Note that the report is mainly on the experiment with the ACIS CCD and electronics, similar results are expected
for the Astro-E XIS CCD and electronics for it. One of the disadvantages of this method when we apply to the
Astro-E XIS is that the effective exposure time is halved. Even so, the method may be useful in the latter stage of
the mission.

3.9. Thermal Vacuum Test at ISAS and Function Test at KSC

Various kinds of tests on XIS FM were performed at ISAS in 1998 and 1999. Among them, thermal vacuum (TV)
test of the whole Astro-E satellite August to September 1999 was one of the most important. During the TV test,
full set of the XIS system, sensor, analog electronics, and digital electronics was operated in the same fashion as
in the orbit. The cold plates under the XIS sensor were cooled as a simulation of the orbit, and the XIS TECs
were operated so as to cool the CCD chips. The CCD chips were cooled down to $-90^\circ C$ as expected. The energy
resolution was about 130-148eV@5.89keV in the normal clocking mode, and 126-132eV@5.89keV in P-sum clocking
mode. Readout noise was as small as $2 \sim 3 e^{-}$. Only one minor problem, which had been known before the TV test,
was that the read out noise increased up to $7e^{-}$ when we drive some sensor in normal mode and others in P-sum
mode at the same time.

After the movement of the satellite from ISAS to Kagoshima Space Center (KSC), several function tests were
done until the launch. No significant problems were found in the XIS system. The inner pressure of the XIS camera
was 30-40 Torr at the launch, satisfying our specification of less than 50 Torr determined from the vibration test.
The XIS system had no problem in the final function test on the launch day.

4. FINAL COMMENT

M-V-4 rocket which carried the Astro-E satellite was launched on 10:30 AM of Feburuayr 10th, 2000 from KSC. Never-
theless, the launch failed owing to some problem in the first stage motor of the M-V-4 rocket; the velocity of the Astro-
E was too low to be a satellite. Quick report on the launch is appeared in http://www.astro.isas.ac.jp/docs/sat/astro-
e/prompt\_report.html.

Although we lost the Astro-E satellite and the XIS on it, discussion has started how to recover it. We hope that
we have a chance to utilize our experience on development and calibration of the XIS in the near future.

REFERENCES

1. K. Hayashida, S. Kitamoto, E. Miyata, H. Tsumeni, K. Katayama, T. Kohmura, R. Asakura, K. Yoshita,
M. W. Bautz, S. E. Kissel, and R. F. Foster, “Soft X-ray Response of the Proto-type CCD Camera(XIS) for

2. H. Katayama, M. Shouho, T. Kohmura, K. Katayama, M. Ohta, T. Tsumeni, S. Kitamoto, K. Hayashida,
E. Miyata, K. Yoshita, K. Koyama, G. Ricker, M. W. Bautz, R. Foster, S. Kissel, and J. Doty, “Calibration of the
x-ray ccd camera (xis) for the astro-e in the soft x-ray band,” in EUV, X-ray, and Gamma-Ray Instrumentation

3. T. Kohmura, K. Katayama, H. Katayama, M. Shouho, T. Tsumeni, S. Kitamoto, K. Hayashida, E. Miyata,
efficieny measurement of the x-ray ccd camera (xis) for the astro-e mission in the soft x-ray band,” in EUV,
X-ray, and Gamma-Ray Instrumentation for Astronomy X, R. B. Hoover and A. B. C. W. II, eds., *Proceeding,


