In-orbit performance of the soft X-ray imaging system aboard Hitomi (ASTRO-H) *

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Abstract

We describe the in-orbit performance of the soft X-ray imaging system consisting of the Soft X-ray Telescope and the Soft X-ray Imager aboard Hitomi. Verification and calibration of imaging and spectroscopic performance are carried out making the best use of the limited data of less than three weeks. Basic performance including a large field of view of $38' \times 38'$ is verified with the first light image of the Perseus cluster of galaxies. Amongst the small number of observed targets, the on-minus-off pulse image for the out-of-time events of the Crab pulsar enables us to measure a half power diameter of the telescope as $\sim 1.3'$. The average energy resolution measured with the onboard calibration source events at 5.89 keV is $179 \pm 3$ eV in full width at half maximum. Light leak and cross talk issues affected the effective exposure time and the effective area, respectively, because all the observations were performed before optimizing an observation schedule and parameters for the dark level calculation. Screening the data affected by these two issues, we measure the background level to be $5.6 \times 10^{-6}$ counts s$^{-1}$ arcmin$^{-2}$ cm$^{-2}$ in the energy band of 5–12 keV, which is seven times lower than that of the Suzaku XIS-BI.

Key words: Instrumentation: detectors — Techniques: imaging spectroscopy — Telescopes

1 Introduction

Extra-solar X-ray astronomy has advanced with advent and utilization of the state-of-the-art instruments. Key features of the instruments are imaging and spectroscopic capabilities and wide-band coverage. The X-ray imaging capability jumped up when the first Wolter-I type telescope was launched by the sounding rocket (Rappaport et al. 1979). Further improvement was achieved with Einstein (Giacconi et al. 1979) and ROSAT (Truemper 1982). Energy resolution increased with the adoption of an X-ray CCD, which was first realized by ASCA (Tanaka et al. 1994) simultaneously extending the energy band up to 10 keV. This achievement was followed by Chandra (Weisskopf et al. 2002), XMM-Newton (Jansen and XMM Science Operations Team 2000), Swift (Burrows et al. 2005) and Suzaku (Mitsuda et al. 2007). Wide band coverage was at first realized combining soft X-ray telescopes and hard X-ray detectors like those aboard BeppoSAX (Boella et al. 1997), Suzaku and ASTROSAT (Singh et al. 2014). NuSTAR (Harrison et al. 2013) broadened the energy range of X-ray telescope up to $\sim 80$ keV, which was achieved using mirrors with depth-graded multilayer coating and CdZnTe detectors. In this context, ASTRO-H (Takahashi et al. 2016) increased the energy resolution drastically with the wide band coverage.

ASTRO-H, the Japan-led X-ray observatory was launched on February 17th, 2016 from Tanegashima Space Center. It was successfully put into a planned low earth orbit (LEO) and named Hitomi that is a Japanese word for the pupil of the eye. It is characterized by the wide-band imaging spectroscopy from soft X-rays (0.3 keV) to soft gamma-rays (600 keV) and high-resolution non-dispersive spectroscopy in soft X-rays. Soft X-ray imaging system, one of the four mission instruments, consists of the Soft X-ray Telescope (SXT-I) (Serlemitsos et al. in preparation) and the Soft X-ray Imager (SXI) (Tanaka et al. 2017).

The detailed specification and the ground calibration of the SXT-I and the SXI are described in other papers (Iizuka et al. 2017; Tanaka et al. 2017; Hayashi et al. 2016; Inoue et al. 2016; Inoue et al. 2016; Kikuchi et al. 2016; Kurashima et al. 2016; Maeda et al. 2016; Sato et al. 2016b; Sato et al. 2016c; Iizuka et al. 2014; Sato et al. 2014; Mori et al. 2013). This paper focuses on the in-orbit performance of the soft X-ray imaging system achieved by fully utilizing the data obtained in the unexpectedly short mission life. After describing the soft X-ray imaging system and initial operations in section 2 and 3, respectively, we summarize our observations in section 4 and note two issues that affect the imaging and spectroscopic performances in...
section 5. The primary calibration items are highlighted in section 6, followed by summary in section 7. Errors quoted in this paper are in 90% confidence level.

2 The Soft X-ray Imaging System

The basic design of the SXT-I (Serlemitsos et al. in preparation) is the same as that of Suzaku XRT (Serlemitsos et al. 2007). Thin Al foils with Au coated surfaces are nested in a confocal way to form a conically-approximated Wolter-I type optics. This type of telescope provides relatively high effective area per unit mass compared with the accurate Wolter-I type telescope aboard Chandra (Weisskopf 2012). Improvement of the uniformity of the housing quality and alignment structure, and the consistent quality of the flight reflectors lead to remarkably better image quality than that of Suzaku XRT. The on-axis angular resolution of the SXT-I in the 1.5–17.5 keV band was measured to be 1.3–1.5 in a half power diameter (HPD) by the on-ground calibration (Iizuka et al. 2017).

The SXI adopts P-channel back-illumination type CCDs manufactured by Hamamatsu Photonics K. K. (Tanaka et al. 2017). The thin surface dead layer allows high quantum efficiency in soft X-rays and high tolerance against impacts of micrometeoroids. The depletion layer of 200 µm (Tsunemi et al. 2008) is substantially thicker than that of Suzaku XIS-BI of 42 µm (Koyama et al. 2007), which enhances quantum efficiency for X-rays above 6 keV. Four CCDs (hereafter CCD1, CCD2, CCD3 and CCD4, respectively) are placed in a 2 × 2 array at the focal plane of the SXT-I and form an imaging area with a size of ≈60 mm × 60 mm.

The SXI consists of four components: the sensor (SXI-S), the pixel processing electronics (SXI-PE), the digital electronics (SXI-DE), and the cooler driver (SXI-CD). The SXI-S includes the CCDs and the single-stage Stirling coolers (SXI-S-1ST) as well as analog electronics for driving the CCDs (SXI-S-FE) and for processing the output signals from the CCDs (Video board). The UserFPGA on the mission I/O board in the SXI-PE generates CCD clock patterns and processes digitized frame data from the Video board. The SXI-DE performs further data processing and controls the heaters to keep the CCD temperature constant. It also receives commands from the satellite management unit (SMU) and sends telemetry including the frame and housekeeping data to the SMU and the data recorder of the spacecraft. The detailed design and specification of the SXI components are summarized in another paper (Tanaka et al. 2017).

Combining the SXT-I and the SXI, we realize an imaging system with a focal length of 5.6 m and a field of view (FoV) of 38′ × 38′. This is the largest FoV among focal plane X-ray detectors that cover up to 10 keV. A large effective area and FoV yield a large collecting power, $\text{grasp} = A \cdot \Omega_{\text{eff}}$, where $A$ is the effective area and $\Omega_{\text{eff}}$ is the effective FoV. The soft X-ray imaging system provides a grasp of 54 cm$^2$ deg$^{-2}$ at 7 keV, the largest among the focal plane X-ray CCD detectors (Nakajima and collaboration 2017). These characteristics not only work complementary to the narrow-field, high resolution spectroscopy of the Soft X-ray Spectrometer (SXS) (Kelley et al. 2017) but also enable us to observe extended objects such as clusters of galaxies and Galactic supernova remnants with a single pointing.

3 Initial Operations

Following the critical operations such as the deployment of the solar paddles and the extension of the extensible optical bench, mission instruments were sequentially started up. Startup procedures of the SXI began 13 days after the launch with the steps summarized in table 1. Function and performance checks were carried out during the procedures as described in the following subsections. The SXI switched to the regular event mode on 7th March after the initialization of the dark level.

3.1 Readout Noise

Frame images were obtained just after the startup of the front-end electronics. Because the CCDs were not yet cooled, significant charges due to dark current were generated in the sensors. Therefore we transfer the charges in the serial register toward the opposite direction from the readout node to measure the readout noise. The standard deviations of the pulse height (PH) distributions in the frame images are measured for all the segments. The noise levels were distributed over a range of 4.3–5.3 ch (analog-to-digital unit) for all the segments over 70 continuous frames. While the scale between the PH and the incident X-ray energy depends on the gain of each analog-to-digital converter (ADC), 1 ch approximately corresponds to 6 eV. Parameters for the event detection and the dark level calculation should be determined according to the readout noise level. The values obtained in orbit agree with those measured in the ground tests. Therefore we determined that initial values of all the parameters such as split thresholds and dark thresholds should be the same as those adopted in the ground tests.

3.2 CCD Temperature

The CCDs and a cold plate are cooled using one of the two SXI-S-1ST. Two heaters are attached to the cold plate and an application software in the SXI-DE controls the sensor temperature by applying an electrical current to the heaters using a proportional-integral-derivative controller (Tanaka et al. 2017). Considering possible accumulation of contaminants including water onto the CCDs and consequent degradation of quantum efficiency in the soft energy band, we set the operating temper-
Table 1. Startup procedures of the SXI.

| Date in 2016 (UTC) | Operation                                                                 |
|--------------------|---------------------------------------------------------------------------|
| 2nd March          | SXI-DE and SXI-PE power on and initialization                            |
| 3rd March          | SXI-S-FE power on and initialization                                      |
|                    | Load microcodes for inverse transfer mode                                 |
|                    | Activate autonomous commands for South Atlantic Anomaly (SAA)            |
| 4th March          | Readout noise check with frame images                                     |
|                    | Load microcodes for observation modes                                     |
|                    | SXI-CD power on                                                           |
| 5th March          | SXI-S-1ST power on                                                        |
| 6th March          | SXI-S-1ST increase voltage                                                |
| 7th March          | Initialize dark level and switch to the event mode                       |

ature to $-110 ^\circ C$ in the initial phase of the mission. Because a charge transfer efficiency significantly changes as a function of the CCD temperature (Mori et al. 2013), it is crucial to keep the temperature constant during observations for better spectroscopic performance. The temperatures of all the CCDs were stable within three digits corresponding to 0.24 $^\circ C$ in peak to peak throughout the mission.

3.3 Charge Injection

We found that the charge transfer inefficiency (CTI) of the SXI CCDs is not negligibly small in the ground calibration (Tanaka et al. 2017). Although we conjecture that the initial CTI is due to lattice defects in the wafer or defects at the interface between the silicon substrate and the oxide layer, the cause has not been identified. Therefore the charge injection (CI) capability was utilized since the beginning of the mission. Although the structures of the injecting gate and drain are different from those of the XIS (Nakajima et al. 2008), we adopt the spaced-row CI method as was applied to the XIS (Ozawa et al. 2009; Uchiyama et al. 2009). The interval and the offset of injected rows are 80 logical pixels and 1 in ACTY coordinate, respectively, as those adopted in the ground tests (for ACT coordinate, see figure 7 in Tanaka et al. 2017). The amount of injected charge is set so that the PHs of the injected pixels are saturated but that leakages to the preceding and trailing rows do not affect the spectroscopic performance.

The PH distribution as a function of ACTY is investigated by measuring the amount of the injected and leaked charges. Figure 1 shows an example of the dark frame image of CCD4 Segment CD obtained during the observation of the Perseus cluster of galaxies. Color scale indicates PH of each pixel. (Right) PH averaged for each row (ACTY) of the left image. Note that the PHs at the injected rows (ACTY = 321 and 401) are out of the range in abscissa.

4 Observations

Comprehensive function checks were followed by the scientific observations and calibrations. Table 2 summarizes observation logs of all the celestial objects. Other pointings for the purposes of checking the attitude and orbit control subsystem (AOCS) are omitted. All the observations were performed with the clocking mode of “Full Window + No Burst” except for the Crab nebula for which the “Full Window + 0.1-s Burst” mode was chosen for CCD1 and CCD2 to suppress pile-up. Some parameters
such as the event threshold and the area discrimination were changed especially for the interval when the minus Z axis of the spacecraft, the direction from the mirror to the detector along the optical axis, points to the day earth (MZDYE) as described in section 5. The effective exposure times in table 2 are those excluding the MZDYE intervals. Note that the pointing direction of the SXT-I gradually shifted during the observation of N132D (Danziger and Dennefeld 1976; Miller et al. 2017), a supernova remnant in the Large Magellanic Cloud, due to unstable behavior of the AOCS. The observation of IGR J16318–4848 (Courvoisier et al. 2003; Hitomi Collaboration 2017), a highly obscured high mass X-ray binary, was performed before optimizing the alignment matrices of the star trackers (STT), which resulted in off-axis angles of 8′ and 5′ during the tracking with STT1 and STT2, respectively. Its effective exposure time is the sum of the two intervals. Although the SXS missed both targets during most of the exposure times, we successfully obtained CCD spectra thanks to the large FoV of the SXI.

All the event data are once processed using a script version 03.01.005.005 and subsequently reprocessed using the SXI calibration database that reflects the ground calibration. Results shown hereafter are obtained with the cleaned event files unless otherwise noted. The detailed criteria for the cleaning are summarized in the calibration database (Angelini et al. 2017). In the spectral fit with XSPEC (Arnaud 1996), we adopt the model phabs for the photoelectric absorption with a solar metal composition of Wilms et al. (2000) and a photoionization cross-sections provided by Balucinska-Church and McCammon (1992).

Figure 2 shows the first light SXI image of the Perseus cluster of galaxies. We confirm that the FoV of the soft X-ray imaging system covers the central region of the Perseus cluster of galaxies with a diameter of approximately 650 kpc. Events originating from two 55Fe onboard calibration sources are seen at the edges of the FoV. The offset of the center of the four CCDs with regard to the center of SXS FoV is found to be slightly smaller than the design value, making the center of the SXS FoV nearer to the gaps of CCDs by 65″. We also compare the images obtained with the SXI and the SXS. The size of a CCD logical pixel is 48 μm that corresponds to 1″/768. Thanks to the smaller plate scale compared with that of the SXS (29″/968/pixel), the position and the flux of the point source can be precisely measured.

The source and background spectra of the Perseus cluster are shown in figure 3. The source spectrum is extracted from the core region with a radius of 3′ as shown in figure 2, while the background spectrum comes from the entire FoV excluding the core region with a radius of 12′ and the calibration source regions. The strong emission line of Fe Heα (6.7 keV, rest frame), the weak lines of Fe Lyα (7.0 keV), and the mixture of Fe Heβ and Ni Heα (7.8–7.9 keV) can be seen, which demonstrates the spectroscopic performance of the soft X-ray imaging system.

5 Issues Found in Orbit

A part of the data are affected in terms of the effective exposure time and the effective area by two issues: a light leak and a cross talk. Following subsections elaborate on the problems and the measures.

5.1 Light Leak

5.1.1 Light Leak during MZDYE

The ground tests using a visible light LED revealed the light leak through pinholes in the optical blocking layer (OBL) on the CCDs (Tanaka et al. 2017). The regions near the physical edges of the CCDs were also found to be sensitive to visible light. Then we thickened Al layers in the contamination blocking filter (CBF), which was originally implemented to block contaminants onto the CCDs, to accommodate the requirement regarding the transmittance of the visible light and ultraviolet. The CBF was confirmed to have survived the launch environment with data when the plus Z axis of the spacecraft points to the day earth. However, it was found that visible light and/or infrared unexpectedly entered the sensor during MZDYE through holes in the base panel of the spacecraft. These incoming lights induced considerable number of false events at the positions of pinholes and the physical edges identified in the ground tests.

We define the light leak pixels as those whose median PHs during MZDYE exceed those during non-MZDYE by more than 40 ch. Then approximately 7% of the pixels in the region that corresponds to the SXS FoV are classified as the light leak ones. Figure 4 shows an example of the PH history averaged among the light leak pixels in CCD4 Segment AB that is a half region of the imaging area of CCD4 (for the segment designation, see figure 4 in Tanaka et al. 2017) during the observation of the isolated neutron star RX J1856.5–3754 (Walter et al. 1996). The PH began to increase at the start of MZDYE and became highly time-variable during MZDYE. Because the event threshold was set to 40 ch in this period, a large number of events are produced due to this light leak.

To eliminate these false events, we defined a new screening criterion to produce scientifically useful good time intervals. When the minus Z axis of the spacecraft points to the earth and an elevation angle of the minus Z axis above the day earth limb is larger than that above the night earth limb, there is little effect due to the light leak because the boundary of the day earth and the night earth is clear. On the other hand, the boundary between the day earth and the sky is indistinct in terms of the light flux due to the earth atmosphere. In fact, the average PH changes even after MZDYE as seen in figure 4. Considering

1 https://heasarc.gsfc.nasa.gov/docs/hitomi/calib/
these circumstances, we define the screening criterion using the extended housekeeping data as
\[(\text{MZDYE-ELV} > \text{MNZTE-ELV}) \parallel (\text{MZDYE-ELV} > 20),\]
where MZDYE-ELV and MNZTE-ELV mean the elevation angles of the minus Z axis of the spacecraft from the day and night earth limbs, respectively, in the unit of degree.

### 5.1.2 Light Leak during the Sun Illumination of the Spacecraft

Even though we can eliminate the light leak effect during MZDYE with the above screening criterion, there is another small effect seen during the sun illumination of the spacecraft. Figure 5 shows the spectra of the Mn K lines from the onboard $^{55}$Fe calibration source detected by CCD4 Segment CD. Note that only the gain difference between two ADCs in the Video board (Nakajima et al. 2013) is corrected while the charge trail and CTI corrections are not performed. We utilize SUN-ALT, the solar altitude from the earth limb, in the extended housekeeping data to discriminate the intervals of the sun illumination of the spacecraft (SUN-ALT > 0) and the eclipse of the spacecraft (SUN-ALT < 0). For further investigation of a possible shift of the line centroid depending on the time after the passage of the SAA ($T_{\text{SAA-SXI}}$) in the unit of second, we divide the data during the eclipse of the spacecraft into two with the boundary of $T_{\text{SAA-SXI}} = 1800$. The difference of the line centroids between the eclipse and sun illumination with $T_{\text{SAA-SXI}} > 1800$ is $5.8 \pm 0.1$ ch that corresponds to approximately 35 eV. We see this effect because the region irradiated with the calibration sources is close to the physical edge of the CCDs that is most sensitive to the visible light. N132D and IGR J16318–4848 were unexpectedly caught at the edge of CCD1 and hence an additional screening with regard to SUN-ALT may be needed after the standard screening.

There is also a small difference of the line centroid between the spectra summed during $T_{\text{SAA-SXI}} \leq 1800$ and $T_{\text{SAA-SXI}} > 1800$. There may be some charges left at least near the physical edges of the CCDs after the passage of the SAA. We stop the sequence of driving and reading out the CCDs during the SAA. Because this operation leads to a considerable amount of charges accumulated in the imaging area, we sweep up the charges just after the passage of the SAA by starting the sequence with the reversed electric field in the substrate. One of the possible reasons of the line shift depending on the time after the passage of the SAA is that the parameters used to sweep up the charges such as the applied voltages and the duration of the sweeping are not optimized.

### 5.2 Cross Talk

An extraordinary large signal from a pixel may cause a cross talk with negative polarity to induce an anomalously low PH in the pixel at the same coordinate of the adjacent segment (e.g., Yagi 2012). Such cross talk produced false events which occupied the telemetry during the initial phase. Figure 6 shows...
raw frame images from the same part of the adjacent segments obtained at the same time. Charged particles produce a large amount of signal charges along their tracks in the CCDs and also produce negative signals in the adjacent segment. The PHs of the pixels return to their normal levels in the next frame. Nevertheless, if the negative PHs fall below the lower threshold for the dark level update, the anomalously low dark levels are set and kept for the pixels because the original PHs are recognized to be high due to signals by X-rays or charged particles. In this way, the cross talk produces false events continuously from these pixels. Because the particle events occur randomly in time and position, the cross talk results in the gradual increase of the event rate. The PHs of the false events are mostly below 100 ch in this case. Also, when the affected pixels are in the $3 \times 3$ pixels of the normal events, the PHs of the events become higher than the true values by similar amounts of the PHs of the false events.

Curiously, the polarity of the cross talk signal is opposite only in the on-axis segment, possibly due to the difference in capacitive and/or inductive coupling along the signal path from the CCDs to the ASICs. Thus the on-axis segment does not suffer from the false events. According to an exposure map summed over the intervals when the spacecraft point to the night earth, the exposure time of the off-axis segments decrease by approximately 17% of that of the on-axis segment.
6 Calibration

6.1 Energy Scale and Energy Response

The energy scale of the SXI is monitored with Mn Kα and Kβ from the calibration sources for all the CCDs. To minimize the effects described in section 5.1, we extract the data during the eclipse of the spacecraft and the ground calibration test by $\sim 10$ eV (Tanaka et al. 2017). Although the reason of the degradation is not clear, there might be remaining effect by the issues described in section 5. All the spectral analyses shown hereafter are performed using the updated response function.

The line profile in the response function is calibrated using the Mn K spectrum integrated over long duration. Figure 8 shows a spectrum from one of the $^{55}$Fe calibration sources obtained during the observation of the pulsar wind nebula G21.5–0.9 (Matheson and Safi-Harb 2010; Hitomi Collaboration in preparation). The exposure time is 76 ks after the screening with $SUN_{ALT} > 0$ and T_{SAA,SXI} > 1800. The energy resolution averaged among all the segments is $179 \pm 3$ eV at 5.89 keV, which is larger than the value determined from the ground calibration test by $\sim 10$ eV (Tanaka et al. 2017). The Mn Kα and Kβ lines are fitted with Gaussian functions using the updated response function. We add a power-law model to represent the non-X-ray background (NXB). The intensities of the Si escape lines and the constant components are well reproduced with the line profile parameters determined from the ground calibration (Inoue et al. 2016) in which we utilized fluorescence lines and monochromatic X-rays.

6.2 Effective Area and Quantum Efficiency

In-flight calibration of the quantum efficiency and the effective area was carried out with the data of the Crab nebula. At the center of the nebula, the Crab pulsar lies with a spin period of $\sim 34$ ms and is viewed as a point-like source. In the X-ray band, the Crab nebula including its central pulsar emits synchrotron radiation which is reproduced by an absorbed power-law model.
Fig. 6. Zoom-up view of raw frame images obtained with 4 s exposure for the two segments of CCD4 obtained at the same time in orbit. The large number of charges distribute along the tracks of the charged particles in the Segment CD. The pixels in the Segment AB read out at the same time as those in the Segment CD with high PHs exhibit lower PHs compared with those of surrounding pixels.

Fig. 7. Mn K spectra during the first half of the observation of IGR J16318–4848. Filtering of the affected pixels by cross talk issue is applied to the data in black but not for the data in red. Parameters in the filtering are $N_{min}$ of 6, $PHA_{sp}$ of 15, and $R$ of 0.7.

Fig. 8. Mn K spectrum of CCD4 Segment CD accumulated during the observation of G21.5–0.9. The events are extracted in the period of the eclipse of the spacecraft and of 1800 s or later after the passage of the SAA. The spectral model shown with a dashed line is a power-law model to reproduce NXB component.

Toor and Seward (1974) suggested that the 2–10 keV flux shows 15% variation. Wilson-Hodge et al. (2011) also reported that the flux in the 2–15 keV band varies by approximately 10% over long timescales. While the variability limits the reliability of the flux estimation to the level of approximately 10%, the Crab nebula has been used as a standard candle for effective area calibration (Toor and Seward 1974; Kirsch et al. 2005; Weisskopf et al. 2010; Madsen et al. 2015).

Since the Crab nebula is as bright as $\sim 3 \times 10^3$ counts s$^{-1}$ SXI$^{-1}$ at the nominal position, it is important to minimize pile-up. The “Full Window + 0.1-s Burst” mode was then adopted for CCD1 and CCD2. This mode provides the shortest exposure per frame and hence reduces the pile-up probability as much as possible (Tanaka et al. 2017). Its integration time per 1 frame cycle is as short as 0.0606 s. CCD3 and CCD4 were operated with the nominal exposure of 4 s. The data are screened with the standard criteria and further screened for intervals in which the pointing is expected to be stable.

The image of the Crab nebula taken with this combined mode is shown in figure 9. The Crab nebula is imaged at around the optical axis on CCD2. The brightness at the off-axis area in CCD1 and CCD2 is much lower than that in CCD3 and CCD4 due to the short effective exposure of the burst mode. The diffuse structure seen in CCD3 and CCD4 is due to the tail of the point spread function (PSF) together with the dust scattering in the interstellar matter. The fine structure is clearly seen owing to the efficient exposure of “Full Window + No Burst” mode.

With the “Full Window + 0.1-s Burst” mode, it is found that the core of the Crab nebula image is still piled up by 20%. Photons are not only registered during the actual integration
Fig. 9. SXI image of the Crab nebula observation in the DET coordinate with no energy cut. The source and background events are extracted from green and cyan regions, respectively. The size of the extracted region is $320 \times 200$ pixels for both of the source and background. The quadrant-like spots at the top (in CCD3) and the bottom (in CCD4) are identified with the Mn K events for energy calibration.

interval but also during the vertical transfer. These so called Out-of-Time (OoT) events are seen like a bar along the vertical transfer direction in figure 9. The OoT events are well known to experience much less pile-up. The magnitude of this effect scales with the ratio of readout time and integration time. The pile-up fraction of the OoT events is negligibly small as it is reduced by two orders of magnitude compared with that of the integrated events. All the below spectral and timing analyses of the Crab data are performed using these OoT events.

The spectrum of the Crab nebula including the pulsar contribution is plotted in figure 10. The event threshold was set to 100 ch that corresponds to 0.6 keV during the Crab observation to minimize the effect of the cross-talk issue. Then we utilize the events above 0.7 keV for the spectral analysis avoiding those just above the threshold. We extract the Crab nebula spectra from the green rectangular region (figure 9) that covers a half of the OoT events. The count rate of the spectra is 2,569 counts s$^{-1}$. It takes 18.432 ms to transfer charges throughout the extracted region in each frame. The total exposure time summed over all frames is 21.3 s. The binning factor is 2–95 ch per bin depending on the energy. Each bin contains 36–649 counts below 11.8 keV. Five or more photons are contained above 11.8 keV. The background spectrum is extracted from the adjoining rectangular region in cyan (figure 9). The count rate of the background spectrum is 57 counts s$^{-1}$ that is about 2.2% of that of the source spectrum and is found to be dominated by the X-rays from the outskirts of the PSF of the Crab nebula.

We fit the spectrum with a model composed of a power-law with photoelectric absorption ($\text{phabs}$ with the absorber abundance fixed to solar). The result is summarized in table 3, and is shown in figure 10. In the fit, we adopt two kinds of the effective area (so-called ancillary response file : arf). Both are calculated using the standard ftools $\text{aharfgen}$ (Angelini et al. 2016) assuming a point source, but with and without the correction (or fudge) factor (figure 11). We do not collapse the two-dimensional PSF to one dimension because the PSF shape exhibits little energy dependence (see figure 2 in Sato et al. 2016b). It is found that the effective area calculated by $\text{aharfgen}$ has some discrepancy with that measured on ground$^2$. The correction factor is modelled as a ratio of effective areas between the output of $\text{aharfgen}$ and that measured on ground. The ground measurements were made at 1.5, 4.5, 8.0, 9.4, 11.0 and 17.5 keV. A spline interpolation was applied inbetween the energies.

The best-fit parameters of $\Gamma$ and flux in table 3 are in agreement with those of $\Gamma = 2.10 \pm 0.03$ and flux $= (2.2 \pm 0.2) \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$ by Toor and Seward (1974). This agreement supports the suggestion by Madsen et al. (2017) that the X-ray variability on yearly timescales of the Crab nebula is not part of a long term trend, but instead results from fluctuations around a steady mean.

The effective area of the SXI is calibrated by combining the ground-based measurements. The measurements of the effective area of the mirror assembly, the transmissivity of the assembly filter (i.e., thermal shield), the transmissivity of the detector filters and the quantum efficiency of the detector are already reported separately (Iizuka et al. 2017; Tawara et al. 2011; Kohmura et al. 2014; Kawai et al. 2012; Tsunemi et al. 2008). The good agreement of the spectral parameters to the

Fig. 10. (a) Crab nebula spectrum with the best-fit model (red solid line). The correction factor is applied to the effective area. (b) Residuals of the data from the best-fit model in (a). (c) Same as (b) but the correction factor is not applied to the effective area.

\[\text{https://heasarc.gsfc.nasa.gov/docs/hitomi/calib/caldb/doc/asth_sxt_caldb_fudge_v20161223.pdf}\]
Table 3. Best-fit parameters of the absorbed power-law model for the Crab spectra.

| Correction factor | $N_H^*$ | Photon index $\Gamma$ | Flux$^\dagger$ | Red. $\chi^2$ (d.o.f.) |
|------------------|---------|----------------------|---------------|------------------------|
| Applied          | 3.9 ± 0.1 | 2.14 ± 0.02 | 2.06 ± 0.02 | 1.024 (245) |
| Not Applied      | 3.8 ± 0.1  | 2.11 ± 0.02 | 2.06 ± 0.02 | 1.072 (245) |

* Equivalent hydrogen column density in units of $10^{21}$ cm$^{-2}$.
† Unabsorbed energy flux in units of $10^{-8}$ erg cm$^{-2}$ s$^{-1}$ in the 2–10 keV band.

Fig. 11. SXI effective area at on-axis. Black and Red lines correspond to the areas that are calculated without and with the correction factor, respectively. The bottom panel show their ratio.

numbers in Toor and Seward (1974) suggests that the effective area of the soft X-ray imaging system in orbit is consistent with those measured on ground.

6.3 Contamination

Recently, contaminants on the light path of X-ray optics are recognized to be issues in terms of the quantum efficiency in the low energy band. Volatile materials desorbed from the various components in the spacecraft may be adsorbed by the cold surface such as the CCDs. According to the extensive investigation through the ground test of Suzaku, most problematic contaminants is a macromolecular compound often used in plastics (Anabuki 2005). Furthermore, the in-orbit calibration of the XIS showed that the contaminant composition evolved throughout the mission. Thus, continuous monitoring of the contamination thickness is essential to properly calibrate quantum efficiency. Monitoring the contamination on the SXI also gives criterion to open the gate valve of the SXS in the initial operation.

Hitomi observed RX J1856.5–3754 twice, a week apart, to monitor any possible accumulation of such a contaminant. Although Hitomi aimed at the target direction precisely for both pointings, the signal events were detected only for the SXI because the quantum efficiency of the SXS below 2 keV is too low to detect the emission from the target with the gate valve closed. The emission from the target is too soft for the hard X-ray imaging system (Awaki et al. 2014; Sato et al. 2016a).

The X-ray spectrum of RX J1856.5–3754 is well reproduced with the two-temperature blackbody emission model (Beuermann et al. 2006). Because the spectrum has been stable over years (Sartore et al. 2012) with small fraction of the pulsation (1.2%) in the 0.15–1.2 keV band (Tiengo and Mereghetti 2007), RX J1856.5–3754 has often been used to calibrate other soft X-ray instruments. Although the excess of the emission over the conventional two-temperature blackbody model around 1 keV is recently reported (Yoneyama et al. 2017), we do not introduce the excess because of the limited photon statistics.

Figure 12 shows the background-subtracted spectra from the two observations. We extract the source spectra from a circular region with a radius of 90″ and the background spectra is chosen from the entire region of the on-axis segment excluding a circular source region with a radius of 5″. The difference of the effective area between the source and background regions is corrected as well as the difference of the area between the regions.

We fit the spectra with the model of $\text{phabs}\ast\{\text{bbodyrad}+\text{bbodyrad}\}\ast\text{constant}$, where the constant factor is introduced to absorb the calibration uncertainty of the effective area in the soft energy band. To estimate systematic errors, we perform the spectral fit by fixing the constant factor to 0.9 and to 1.1 that are conventionally used as an uncertainty range of the absolute effective area and are exemplified in section 6.2. The model equivalent hydrogen column density, blackbody temperatures, and radii for each temperature component are adopted from Beuermann et al. (2006). Additional multiplicative model of the column densities due to the contaminants is applied. Possible compositions of the contaminants are neutral H, C, and O. However, we allow only the column density of C ($N_C$) to vary from the statistical point of view.

Table 4 summarizes the best-fit parameters from the two observations. Although $N_C$ is consistent with zero or negative in the case of the constant factor of 0.9, it is significantly detected when we set the factor to 1.1. Considering
Fig. 12. (Top) RX J1856.5–3754 spectrum at the first observation with background subtracted. Red and blue lines correspond to the best-fit model with a constant factor of 1.1 and 0.9, respectively. (Bottom) Same as the top panel, but for the second observation.

these facts, we conclude that $N_C$ is less than $9.4\times10^{17}$ cm$^{-2}$ and $5.5\times10^{17}$ cm$^{-2}$ for the first and second observations, respectively, which corresponds to the mass column density of C ($\rho_C = 12 \times N_C/N_A$) of $18.8 \mu g$ cm$^{-2}$ and $10.8 \mu g$ cm$^{-2}$. The pre-launch requirement of the SXI for the limit of any contaminant is $\rho_C < 10 \mu g$ cm$^{-2}$. Follow-up calibrations would have made the results more precise. Another important fact is that $N_C$ did not show significant increase during the interval between the two observations, which assures the opening safety of the SXS gate valve.

6.4 Point Spread Function

PSF of a focusing telescope system is usually calibrated using a bright and point-like source. The brightness reduces the uncertainty of the background subtraction at its tail whereas the point-like emission works to resolve its sharp core. Due to the limited numbers of the observed targets of Hitomi, any bright and point-like source was not observed. Instead, we use an on-pulse image (the pulsar image) of the Crab.

6.4.1 Extraction of the On-pulse Component

OoT events give a huge merit in terms of the timing resolution. The row position (DETX) can be used as a time tag of events with the time unit of 57.6 $\mu$s that corresponds to the readout clock per row. However, the focus of the SXT-I is blurred with its PSF. The tagged time is then smoothed by the PSF (0.7 or 1.14 mm in half power widths (HPWs), see below). The effective time-resolution becomes $\sim 1.3$ ms.

Figure 13 shows a folded light curve of the Crab in the total band. We adopt a period of 33.7204626 ms at the epoch of 17472 d (TJD) that is obtained with the SXS (Maeda et al. 2017). The timing analysis of all the Hitomi instruments is comprehensively summarized in other papers (Leutenegger et al. 2016; Koyama et al. in preparation). The pulse is clearly detected in the folded light curve.

The pulses have widths of 0.1–0.2 phase that corresponds to 3–6 ms. The emission region of the pulsed component must be smaller than $3–6\times10^{-7}$ times the speed of light $(\approx 1–2\times10^7$ cm). If we assume that the distance to the Crab nebula is 2 kpc, the source of the pulsed component (i.e., the Crab pulsar) is securely regarded as a point-like source.

Dust scattering is known to make a halo structure around the source (Draine 2003). Once the emission from the pulsar is scattered, it experiences a time lag due to a detour of the arrival pass and makes the emission unpulsed. Therefore, the pulsed component is an ideal point-like source that is free from the dust scattering halo. Owing to its large brightness of the Crab pulsar, the pulsed component is used as an in-flight calibration of the PSF.

6.4.2 One Dimensional Point Spread Function

Figure 14 shows the 0.6–15 keV band images of the on-pulse, the off-pulse and the on-minus-off pulse. The images are extracted from the green region shown in figure 9. In figure 13,

Table 4. Best-fit parameters for RX J1856.5–3754 spectra.

| Parameters          | First Observation | Second Observation |
|---------------------|-------------------|--------------------|
| Constant factor$^*$ (fixed) | 0.9 1.1           | 0.9 1.1            |
| $N_C$ (10$^{17}$ cm$^{-2}$) | $2.6^{+1.0}_{-0.9}$ | $4.5^{+1.0}_{-0.9}$ |
| Reduced $\chi^2$(d.o.f.) | 1.305 (47)        | 1.340 (59)         |
| Reduced $\chi^2$(d.o.f.) | 1.032 (47)        | 0.939 (59)         |

$^*$ Constant factor is introduced to take charge of the calibration uncertainty of the effective area in the soft energy band.
we define the phase intervals 0.1–0.3 and 0.5–0.7 as the on-pulse phase. The phase interval 0.8–1.0 is adopted as an off-pulse phase. The effective exposure times of the on- and off-pulse images are 8.6 s and 4.3 s, respectively. The on-minus-off pulse image is made by subtracting the off-pulse image from the on-pulse. The on-minus-off pulse image appears narrower in the DETY direction. It is because the on-minus-off pulse image originates from the pulsar radiation, i.e., the point-like emission.

Since the OoT trail along the direction of DETX remained, we make a histogram of the events as a function of DETY. This histogram corresponds to a one-dimensional PSF and is shown in figure 15. To compare the ground measurements with the in-flight PSF, we simply collapse the image taken on ground down to one dimension along the direction of DETX and make a one-dimensional PSF for the ground measurements. The cumulative distribution function from the peak of the one-dimensional PSF is plotted in figure 15 as well as the output of ray-tracing. HPWs are calculated using the cumulative distribution function and are listed in table 5. Within the limited statistics of the data, the HPW of the Crab pulsar is consistent with that of the ground measurement at 4.51 keV and that of the ray-tracing used in the calculation of the response function of the SXT-I. It can be concluded that the in-flight PSF of the SXT-I is consistent with the on-ground measurements. This indicates that the HPD of the SXT-I is \( \sim 1.3 \) in orbit that is the number we measured on ground.

![Fig. 13. Folded light curve of the OoT events of the Crab nebula. The phase zero is taken arbitrarily.](image)

![Fig. 14. (Top) Out-of-Time images of the Crab nebula observation in the DET coordinate for the on-pulse (left), the off-pulse (middle) and the on-minus-off pulse (right). (Bottom) Projection along the DETX direction. The black, red and green data correspond to the projections using the pulse phase of on, off and on-minus-off, respectively.](image)

**Table 5.** Half power widths calculated from the one dimensional PSFs.

| Data                        | HPW (arcmin) | References‡ |
|-----------------------------|--------------|-------------|
| The Crab pulsar*            | 0.74 ± 0.12  | This work.  |
| Ground measurements†        | 0.67 ± 0.01  | (1), (2)    |
| Ray-tracing                 | 0.68 ± 0.02  | (3)         |

* The value is derived from the on-minus-off pulse image (see the text for details).
† Monochromatic energy of 4.51 keV.
‡ (1)Sato et al. (2016b); (2)Iizuka et al. (2017); (3)Yaqoob et al. (2017).

6.5 Non X-ray Background

Low and stable background is essential for precise observations especially of extended targets. Hitomi adopts almost the same LEO as Suzaku that realized low and reproducible NXB (Tawa et al. 2008). Design of the camera body is another key to suppress the NXB. Considering a result of a Monte-Carlo simulation (Anada et al. 2008), we designed the sensor body so that
The thickness of the housing is $\geq 10 \text{ g cm}^{-2}$.

During the three weeks of the observations, we accumulated the events in the period when the spacecraft pointed to the night earth and regard those events as NXB. To securely extract only the NXB events, we define a screening criterion from extended house keeping data as

$$\left( \text{SAA\_SXI} = 0 \right) \& \left( \text{SAA\_SXI} > 277 \right) \& \left( \text{ELV} < -5 \right) \& \left( \text{DYE\_ELV} > 100 \right).$$

As a result, the total exposure is 118.3 ks for the on-axis segment including multiple pointings for the check of the AOCS and excluding the Crab observation that is not performed with the normal clocking mode of “Full Window + No Burst”. The exposure times for the other segments are different among pixels depending on whether the pixel was affected by the cross talk issue. Figure 16 shows the integrated NXB spectrum normalized with respect to the area of a physical pixel. All the good grade events are summed over the whole FoV with the exception of the regions irradiated with the calibration source events and their OoT events. Data of Suzaku XIS-BI that have the same physical pixel area is also shown for comparison. The data of the XIS-BI is adopted from Tawa et al. (2008).

Emission lines from Au L$\alpha$, Au L$\beta$, Au M$\alpha$, and weak lines from Al K, Si K, Ni K$\alpha$, and Au L$\gamma$ are seen. Primarily the emission lines from Au originates from the inner surface of the housing. The surface of the CCD package and the cold plate are also vapor deposited by Au. Ni is under the Au layer of the housing. The OBL on the surface of the CCD and the CBF consist of Al and hence they are responsible for the Al emission line. The Si line is emitted from the inside of the CCD wafer. The NXB spectrum of XIS-BI has a hump above 6 keV, which limits the sensitivity in the energy band. In contrast, the NXB spectrum of the SXI shows no hump in the energy band up to 15 keV. The Ni K$\alpha$ line at 7.5 keV is weaker than that of the XIS because of a thicker Au layer vapor deposited onto the inner surface of the housing. This allows us to obtain a better estimation of the spectral parameter from celestial objects such as supernova remnants because the centroid of the Ni K$\alpha$ overlaps with those of Fe He$\beta$ and Ni He$\alpha$.

The NXB intensity in general depends on the cut-off rigidity (COR) as investigated for the XIS (Tawa et al. 2008). Figure 17(a) shows a count rate of the NXB in the energy band of 5–12 keV as a function of COR that is based on the international geomagnetic reference field model version 12 (Thébault et al. 2015). The NXB also depends on the position in the CCD as shown in figure 17(b). If the spatial distributions of the charged particles or hard X-rays are uniform throughout the sensor including the frame store region, the intensity of the NXB depends on the exposed duration at each position. Taking
and by the solid angle of the FoV. Hence it illustrates a surface brightness of the sky background and provides a measure of sensitivity for extended targets. The CXB intensity is set to be $9.3 \times 10^{-7} \ (E/1 \text{ keV})^{-1.4} \ \text{counts} \ s^{-1} \ \text{keV}^{-1} \ \text{arcmin}^{-2} \ \text{cm}^{-2}$ as a reference. Thanks to the high quantum efficiency of the SXI, the soft X-ray imaging system aboard Hitomi achieve better sensitivity than Suzaku XIS-BI above 6 keV. The sky background intensity is $5.6 \times 10^{-6} \ \text{counts} \ s^{-1} \ \text{arcmin}^{-2} \ \text{cm}^{-2}$ in the energy band of 5–12 keV, which is seven times lower than that of the XIS-BI.

7 Summary

In spite of the short lifetime of the mission, the soft X-ray imaging system confirmed its function and performance. The observation of the Perseus cluster of galaxies demonstrated the imaging capability over the large FoV of 38$' \times$ 38$'$. We measured the HPW using the on-minus-off pulse image for the OoT events of the Crab pulsar. It is found that the HPW is consistent with that of the ground measurement and that of the ray-tracing. We thus conclude that the angular resolution is as good as $\sim 1.3$ in orbit. The best-fit parameters of the absorbed power-law model for the Crab spectra is consistent with those in the literature, suggesting the correctness of the effective area calibration. The effective exposure time is affected by the light leak issue primarily when the minus Z axis of the spacecraft points to the day earth. The cross talk issue affects a part of effective area. We would not see the issue any longer if we had optimized the threshold for the dark level update before the loss of the spacecraft. After the screening of the data affected by these two issues, the spectra of the onboard calibration source events prove that the energy resolution at 5.89 keV is $179 \pm 3 \ \text{eV}$ in FWHM. The sky background level is seven times lower than that of Suzaku XIS-BI in the energy band of 5–12 keV.

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Fig. 18. SXI sky background spectrum normalized by effective area and solid angle of the FoV. CXB level and data of other instruments using X-ray CCDs are also shown for comparison. Datasets of ASCA, Chandra, and XMM-Newton are adopted from Katayama et al. (2004). Suzaku XIS data are adopted from Tawa et al. (2008).

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