In-Orbit Performance of Digital Electronics of X-ray micro-calorimeter onboard Hitomi

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1. INTRODUCTION

The Soft X-ray Spectrometer (SXS)[1] onboard the Hitomi X-ray satellite[2] is the high-resolution X-ray spectrometer based on X-ray micro-calorimetry. The mission was deployed successfully after the launch in February 2016, proving its unprecedented performance and making an epoch for being the first X-ray micro-calorimeter in the orbit to observe astronomical sources. The mission was discontinued during the commissioning phase due to the loss of the spacecraft control, but it left a precious dataset in its short lifetime for future missions.

The Pulse Shape Processor (PSP) is the onboard digital electronics[3] of the SXS, which is responsible for the event reconstruction of individual X-ray photons. The design exploits the heritage of the digital electronics[4] for the X-Ray Spectrometer (XRS)[5] onboard the Suzaku satellite. The design, as well as the pre-flight and some early in-flight performances, were reported previously[6,7,3]. The PSP was started two days after the launch and was operated continuously with no issues until the end of the mission for 36 days[8]. The purpose of this poster is to show the in-flight results, focusing on the performance as an onboard digital signal processing unit of an X-ray micro-calorimeter.

2. OVERVIEW

Figure 1 Env. test model

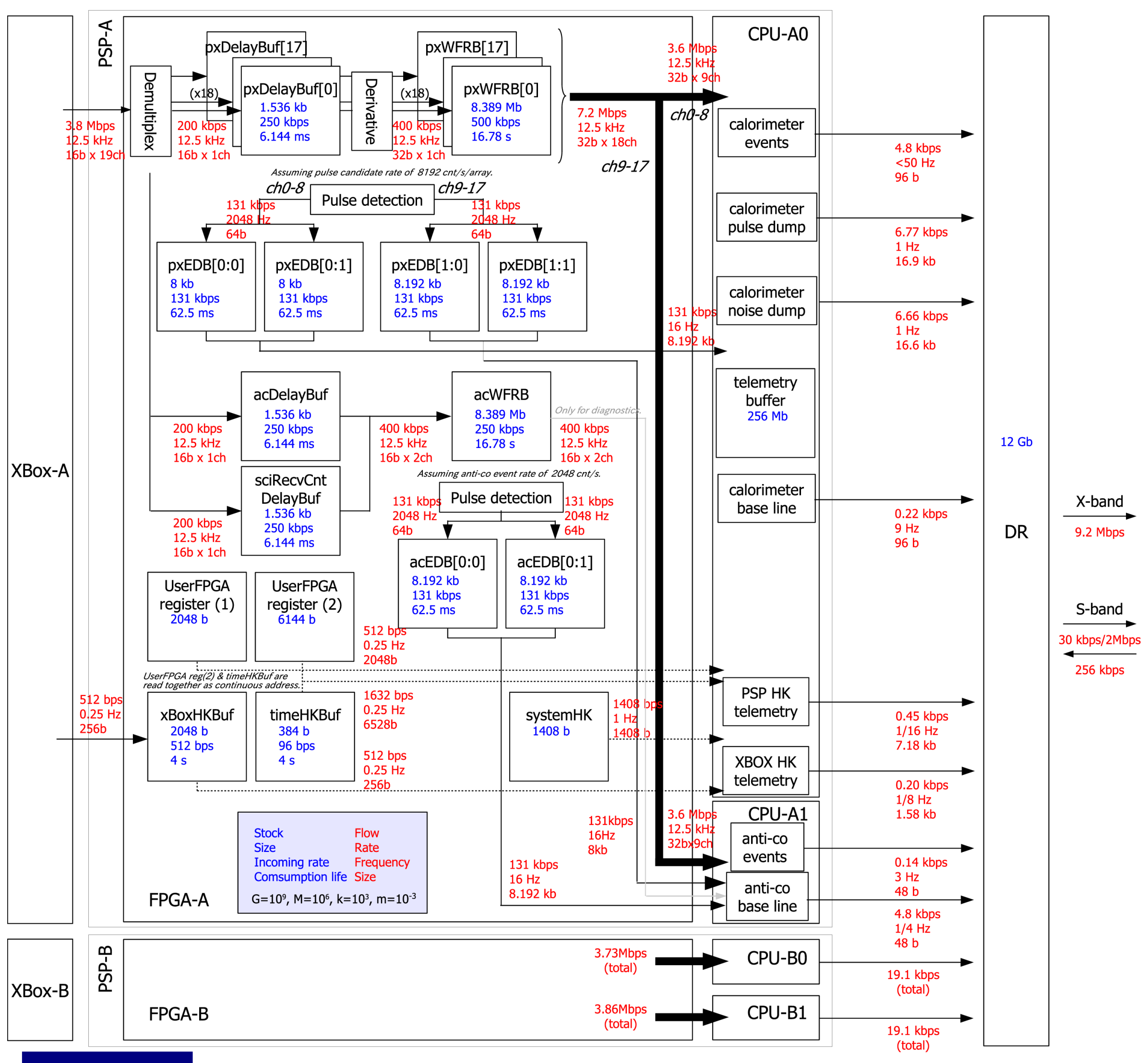

Figure 2 Data stock size (blue) and maximum flow rate (red).

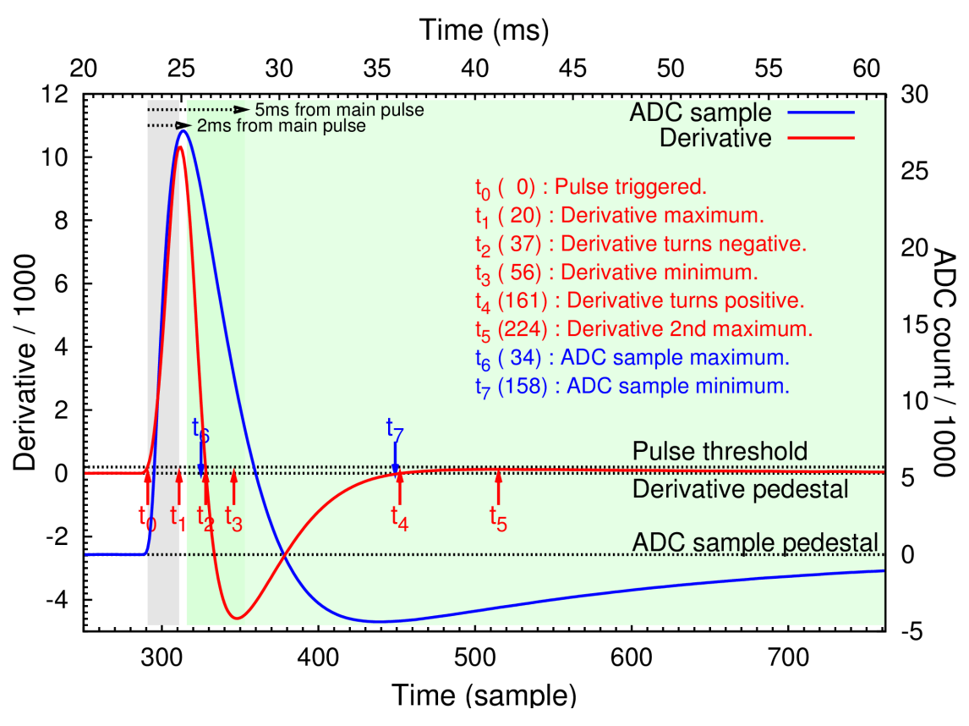

Figure 3 Typical pulse shape

The PSP is composed of two identical units (A & B). Each has a dimension of 250×350×91 mm³, a mass of 3.9 kg, and a nominal power consumption of 16.6 W. One unit has a stack of one power supply, one FPGA, and two CPU (0 & 1) boards. The FPGA and CPU are driven at 20 and 60 MHz, respectively. The two units are placed inside of a side panel of the spacecraft. They were fabricated by MHI (Fig .1).

The PSP has one operation mode and continues the same processing while it is running. It receives the data from the onboard analog electronics (XBOX) with LVDS. The XBOX samples the 36-pixel calorimeter and 2 anti-co detector channels at 12.5 kHz, and amplifies, shapes, digitizes with a 14 bit ADC, and multiplexes the signal. All 38 channels are independent, which are handled by the two units of the PSP in half. The FPGA board receives data from the XBOX, which are first demuxed into 19 channels (Fig. 2). For the 18 calorimeter channels, a time derivative is calculated, based on which event candidates are triggered above a threshold of ~104 eV. The event candidate table and the waveform are transferred to the 2 CPU boards in half.

The CPU deblends overlapping pulses upon FPGA-triggered candidates and cross-correlates them with a template. The templates were calculated using the optimum filtering method on the ground. The characteristic quantities of individual pulses (arrival time, energy, flags, etc) are transmitted to the data recorder (DR) of the spacecraft bus via the SpaceWire. For the one anti-co channel, events are triggered and their arrival times, pulse heights, and duration are downlinked. No processing involving multiple channels are performed in the orbit.

Upon these signal processing, the PSP is responsible for generating clocks for the XBOX, and receiving, interpreting, and relaying the commands and HK telemetry of the PSP and XBOX. Also, it generates a table matching the GPS-synchronized time and the FPGA clock, so that event arrival times are mapped into UTC. When resources are available, it dumps the raw data for diagnostic purposes. The anti-co and XBOX telemetries are edited respectively by the 1 and 0 board of the CPU.

3. INPUT DATA

A typical pulse rise and decay times are a few ms with a large undershoot (Fig.3). We use a sufficiently long pulse length of 1024 samples = 82 ms for a pulse to settle. All events are graded depending on the proximity to the adjacent pulse in time in the same pixel. If they are apart by more than 1 or 1/4 pulse length, the pulse is graded high or mid resolution (HR or MR). Others are graded as low resolution (LR). High energy resolution is achieved only for HR and MR events. LR events are usually discarded for science analysis.

Fig. 4 shows the distribution of calorimet events during the entire 9.7 ks observati of the Crab nebula. Downlinked ("unfiltered") events are screened using various flags in the ground processing fo X-ray ("cleaned") events. The screening flags include: (1) coincidence with anti-c events, (2) recoil electrons from the ^{55}Fe calibration X-ray source, (3) electrical cross-talks, (4) events by cosmic-rays hitting the detector frame, (5) events wit a pulse decay time slower than the average shape, (6) pseudo events by a wrong subtraction of the average shape during deblending (slope), (7) time shift out of range in cross-correlating with the template, and (8) non-monotonic decline of the decay (quick). Also, (9) some even out of the pixel good-time-intervals are processed for nothing due to a software bug, which are removed. Finally, (10) events with LR grade are discarded.

The screenings (5–8) are based on the pulse shape, while (10) is on the time coincidence with events in the same pixel. They are flagged onboard by the PSP. On the other hand, the screenings (1–4) are based on the time coincidence (and partially coarse energy) with events in other pixels. They are flagged on the ground. The false positive is non-negligible or bright sources for (3) and (4), thus are omitted by default. Events were further screened using the rise time versus energy elation ("rise time cut" in Fig. 4).

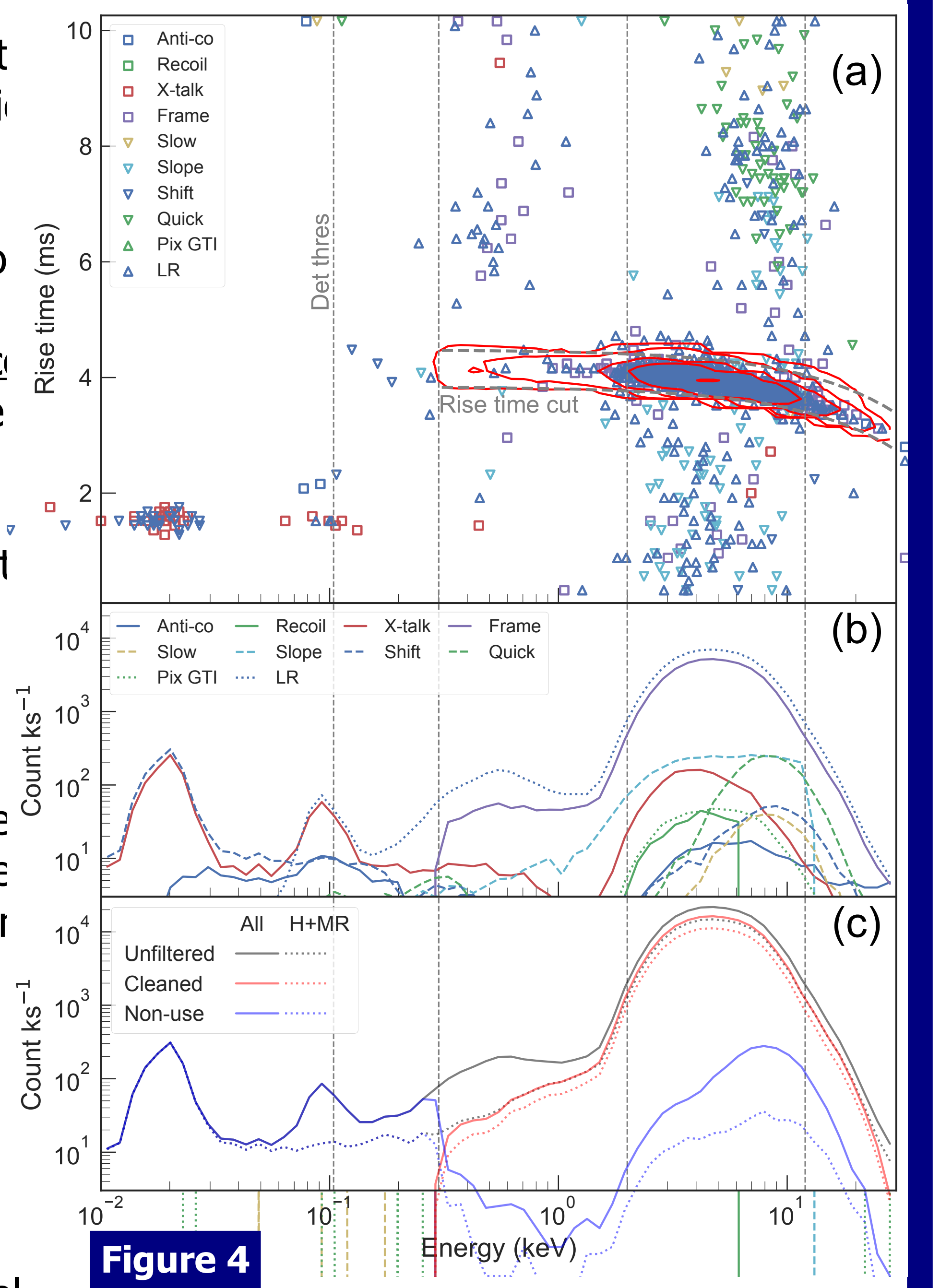

Figure 4

Calorimeter event distribution during the Crab observation. The energy bandpass are shown for that required (0.3–12 keV) and achieved (2.0–30.0 keV) with the closed gate valve. (a) Energy versus pulse rise time of randomly sampled 3% of all events. Different symbols are used for different flags used for screening. The contours show the distribution of cleaned events. (b) Histogram of events screened by various flags. (c) Histogram of unfiltered, cleaned, and non-use events, and their fraction of HR+MR events.

4. PERFORMANCE

Table 1 Count rate during 100% load

	Sum	HR	MR	LR
Unfiltered	202.1	60.7	75.9	65.0
Cleaned	187.4	56.7	72.6	58.1
2–12 keV[a]	182.2	55.3	70.5	56.4

[a] ^{55}Fe calibration events ($\sim 3.9\ \mathrm{s}^{-1}$) excluded.

4-1. PSP limit and event processing speed

The most time-consuming process is the cross-correlation between the pulse and the template in the time domain by the CPU. The correlation is iterated over shifted times until it reaches the maximum to derive the energy and arrival time. HR and MR events use 1 and ¼ length of the full template, respectively, while LR events are skipped for the calculation. A HR or MR event uses $\sim 2\times10^{-2}$ % CPU time, while a LR event uses $\sim 6\times10^{-4}$ %. Including the baseline load of ~7%, the CPU consumption cannot exceed 100% in each of the four CPUs. The entire throughput of the SXS is limited by this when observing bright sources.

The limit was actually hit routinely during the SAA passages and the Crab observation. Table 1 shows a statistics of a 1 ks observation of the Crab nebula when the PSP limit was hit in most of the times with an average CPU consumption of 99.4%. The PSP processed 202 s^{-1} events, among which 187 s^{-1} remained after event screening. In the 2–12 keV for science analysis, 182 s^{-1} remained, which satisfies the requirement of >150 s^{-1} but is less than the actual incoming rate of 251 s^{-1}.

4-2. Arrival and dead times

We performed a simultaneous observation of the Crab pulsar with the Hitomi satellite and ground-based radio observatories. Using the 34 ms pulse shape, the arrival time was calibrated to less than ~20 μs[9]. The pulse shape is easily resolved without making any corrections besides the barycentric correction. During this observation, the PSP limit was hit and 12 pixels suffered dead times of up to 73%. The duration of the dead times was longer than 5 s. Therefore, the 34 ms pulse profile is little distorted.

4-3. Telemetry

The telemetry from the PSP is categorized into four (Fig. 2): (a) calorimeter and anti-co events, (b) their baseline events, (c) the pulse and noise data dumps, and (d) HK. The data dumps are the waveforms of randomly sampled triggered (pulse) or untriggered (noise) data. The rate of the calorimeter event telemetry increases with the incoming rate, but saturates at the PSP limit. Other telemetry types have a fixed rate. As a result, the PSP telemetry is smaller than ~100 kbps regardless of the source brightness, which is below the allocated 200 kpbs. We suffered no telemetry loss in the orbit, except for the first few days when the data dump rate was not yet tuned.

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