



Design and verification of the electric control box of the low energy x-ray telescope onboard the Insight-HXMT

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Abstract

The Low Energy X-ray telescope (LE) is one of the main instruments of the Insight-Hard X-ray Modulation Telescope (Insight-HXMT), the first Chinese X-ray astronomical satellite. The scientific objectives of LE focus on scanning and pointed observations of the X-ray sources in the soft X-ray band (0.7–13 keV). LE consists of three detector boxes (LEDs) and an electric control box (LEB). The LEB is composed of data handling unit, monitoring unit, and power distribution unit, with functions including data processing, communication, monitoring, power supply, and distribution. All the functions designed in the LEB were verified during the operation in orbit. To improve the efficiency of astronomical observations and reliability of LE, onboard data processing is designed in the LEB. The results of onboard data processing are immediately transmitted to the ground as important housekeeping data and are verified by comparing them with the processing results of the data transmitted to the ground. In the six years since launch, the LEB has performed well, operated smoothly, and met all expected requirements. The LEB has participated in numerous scientific observations, transmitted a large amount of scientific data, and obtained several observational results.

Keywords Insight-HXMT · Low energy X-ray telescope · Electric control box · Onboard data processing

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1 Introduction

The Low Energy X-ray Telescope (LE) [1] is one of the scientific instruments of the Insight-Hard X-ray Modulation Telescope (Insight-HXMT) [2, 3], which is the first X-ray astronomical satellite of China. LE performs scanning and point observation in the X-ray energy range of 0.7–13 keV [4].

LE is equipped with the Swept Charge Devices (SCDs) [5], which are non-imaging detectors. The SCD (model CCD236) is a special type of Charge Coupled Device (CCD) with a continuous readout mode for recording the time of arrival and energy of photons, achieving high energy and time resolution. For scientific observation, LE defines four types of Field Of Views (FOVs) collimators, narrow FOV ($1.6^\circ \times 6^\circ$), wide FOV ($4^\circ \times 6^\circ$), closed FOV, and all-sky monitoring FOV [1]. LE is equipped with an array of 24 SCD modules, providing a total geometrical area of 384 cm². LE also has low pile-up ratio ($< 1\% @ 18000\text{cts/s}$), which plays an important role in the soft X-ray astrophysics [6].

LE is composed of three detector boxes (LEDs) and an electric control box (LEB). The SCD detectors collect photon signals and convert them into scientific events in the LEDs. The functions of the LEB include communication, data management, and power supply [1].

This paper describes the design, development, and status of the LEB, with a focus on verifying its functions, particularly the onboard data processing.

2 The requirements of LEB

The Insight-HXMT satellite is a long-term operating satellite with a lifetime of 4 years and an expected lifetime of 8 years [3]. In order to ensure the stable operation of the satellite, high reliability is crucial for the LEB. To achieve high reliability, numerous reliability requirements were considered in the unit's design. All electronic components and materials of LEB have been carefully selected from high quality products, and all units are designed with cold redundancy to prevent any single point of failure in the circuits.

The Insight-HXMT satellite is a high-performance astronomical satellite, with the maximum data processing rate of scientific events requiring more than 35,000 counts/s to facilitate the observation of high brightness X-ray sources.

To enable rapid observations in orbit, the LEB has been designed with onboard data processing to calculate the light curve and energy spectrum of scientific data. The calculation results and raw scientific data are transmitted through different interfaces, further enhancing the reliability of LE.

Timing is very essential to the astronomical observation, and we have designed a timing system that includes a Pulse-Per-Second (PPS) signal, corresponding Universal Time Coordinated (UTC) time, and a 5 MHz clock provided by the satellite platform [7]. The PPS event and UTC event are incorporated into the data packets as absolute time references, with each scientific event also

including relative time information. The time accuracy of each event is 1µs without duplication.

DC-DC (Direct Current) converters require good heat dissipation methods because of high power consumption. However, the LEDs have poor heat dissipation due to their small installation contact area. Therefore, the power supply and distribution in LEB are designed to directly output a series of secondary power supplies to each LED.

Because of the limited power budget for LE, the power consumption of LEB is restricted to less than 35W. We have selected electronic components with low power consumption and high performance for LEB.

To solve unexpected problems that may occur in orbit, we have designed backup functions, including updating DSP software, automatic threshold adjustment, memory readout, and more. Because of space irradiation, the performance of SCD detectors will gradually decline, the driving voltage of the SCD detectors can be adjusted to improve their performance.

3 The design and development of the LEB

3.1 Overview of the LEB

The SCD detector array is connected to LEDs, and three LEDs are connected to LEB. LEB is responsible for data management, status monitoring of LE, power supply and distribution of LE, and connects all interfaces of LE [1].

Each LED contains 8 SCD detector modules, and the three LEDs are connected to the LEB via the low voltage differential signaling (LVDS) interface. The LEB consists of data handling unit, monitoring unit and power distribution unit (Fig. 1). All electrical interfaces between LE and satellite platform are located in the LEB,

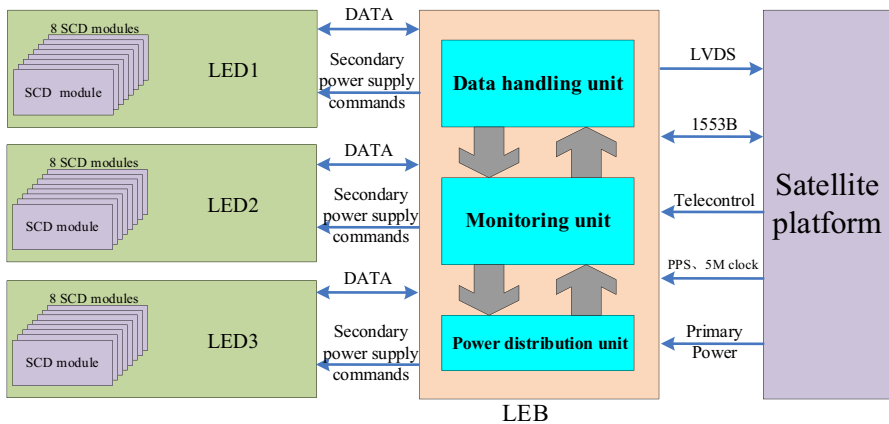


Fig. 1 The block diagram of LE electronics

including LVDS interface, 1553B interface, highly precise PPS signal, 5 MHz clock, telecontrol and power supply.

Raw scientific data is transmitted through LVDS interface, commands, upload data and housekeeping data are transmitted through 1553B interface, PPS and 5 MHz clock are used for timing system, and satellite provides the primary power of +28V.

The scientific data from the three LEDs is transmitted to the data handling unit of the LEB via the LVDS interface, where it is packed and then sent to the satellite platform. LEB collects housekeeping data from the LEDs and LEB, combines them into housekeeping data packets, and sends them to the satellite platform at regular time intervals. LEB receives commands from the satellite platform, then relays them to the LEDs or responds accordingly. LEB receives the uploaded data and stores it in the Electrically Erasable Programmable Read Only Memory (EEPROM). The power distribution unit provides four voltages required for the LEDs. The time synchronization of LE is achieved by the PPS, UTC time and highly precise 5 MHz clock. The data flow diagram of LEB is shown in Fig. 2.

The data handling unit is responsible for implementing the data management function. It comprises the Field Programmable Gate Array (FPGA), Digital Signal Processing (DSP), EEPROM, Static Random Access Memory (SRAM), Programmable Read Only Memory (PROM) and communication interfaces including LVDS and 1553B (Fig. 3). To ensure efficient operation, we have designed respective functions for the FPGA and DSP. The DSP is responsible for 1553B communication and

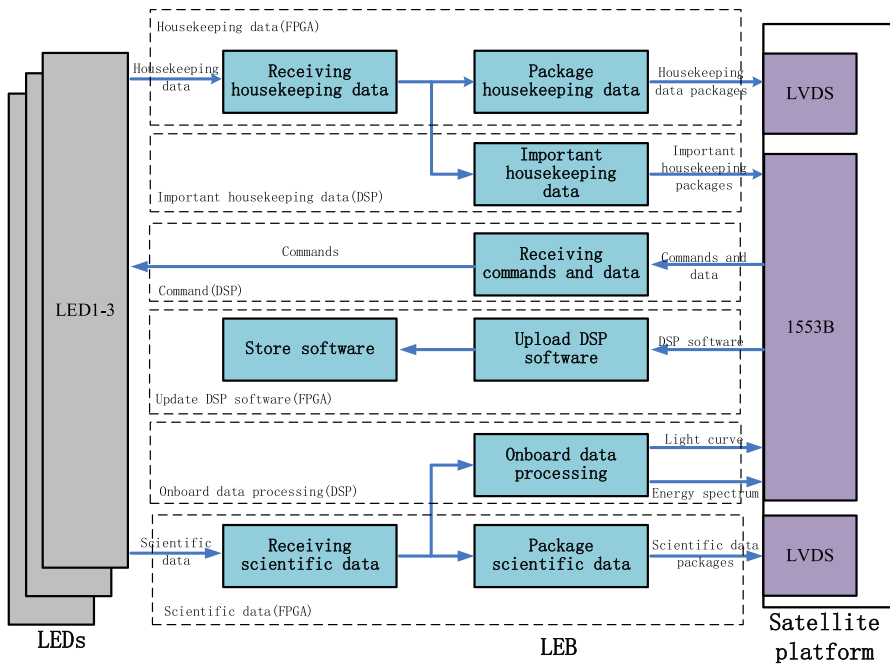


Fig. 2 The data flow diagram of the LEB

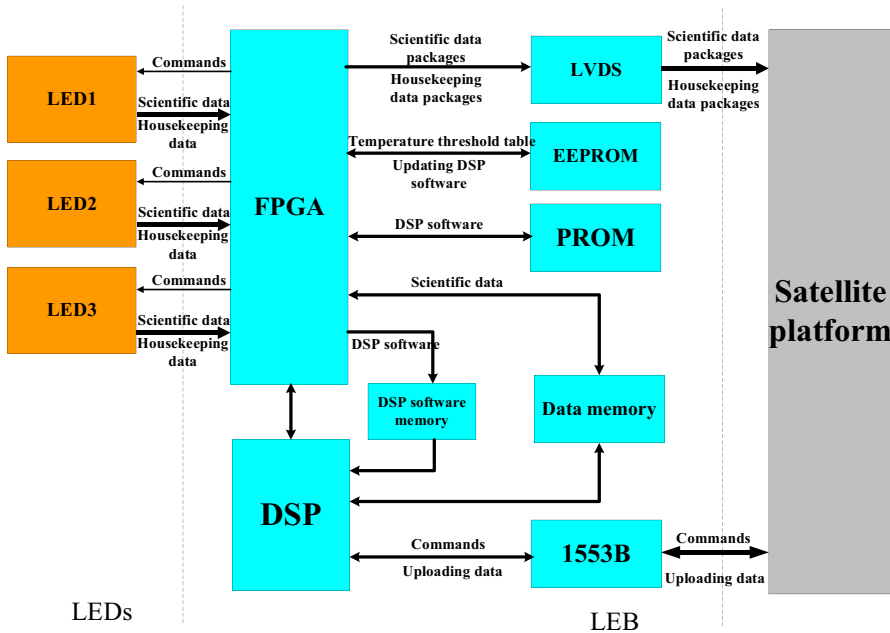


Fig. 3 The block diagram of the data handling unit

onboard data processing, the functions of FPGA are booting, data reception, packing and transmission, and LVDS interface communication, among other tasks.

3.2 Reliability

The reliability requirement of the LEB is very high, with a reference number of 0.997 for four years. According to the parts count method, the reliability result of the LEB is 0.997, meeting the specified requirements.

To achieve high reliability, numerous reliability requirements were considered in the design. All components and materials were carefully selected from high quality products used in other satellites. Additionally, all units were designed with cold redundancy, and high power consuming components were equipped with heat dissipation solutions. Different parameters were applied for electronic component derating. The LEB underwent rigorous mechanical and thermal tests, and its functions and interfaces were designed with redundancy wherever possible.

3.3 Booting

After the data handling unit is powered on, the FPGA initially runs and holds the reset signal of the DSP. It generates read and chip select signals, reads the DSP software from the onboard PROM, and writes it into the DSP software memory (SRAM array). Subsequently, the reset signal is released to enable DSP initialization. The

data handling unit commences operation, and both the FPGA and DSP perform their respective functions.

As described in Sections 3.6 and 3.8, it is possible to upload DSP software to the EEPROM. Upon successful upload, if a command to switch the DSP software is received, the FPGA will reset the DSP, read the DSP software from the onboard EEPROM, and write it to the DSP software memory. Subsequently, the reset signal is released, and the DSP will initialize. The process diagram is depicted in Fig. 4.

3.4 Scientific data

The X-ray photon signals collected by the SCD detector are recorded as scientific events in the LEDs, which are then transmitted to the LEB. Each event is comprised of 48 bits, including data type identification, SCD channel, photon energy information, photon arrival time and cyclic redundancy check (CRC). An additional SRAM array (data memory) has been implemented in the LEB to store scientific data. Memory partitions are designed within the data memory to write the data from the three LEDs into their respective partitions. LEB stores 40-bit data, excluding the data type identification.

In compliance with the requirements for satellite data transmission, the scientific data packets are all designed as CCSDS (Consultative Committee for Space Data Systems) format with a length of 441 bytes, which includes 86 scientific events (Table 1). Multiple storage zones are allocated for each LED in the data memory, with each zone capable of storing one data packet. After one zone is full, supplementary information (number of LEDs, packet count, packet length and UTC time) is added and data packets are transmitted through LVDS interface. Received data is then written to the next storage zone, and all storage zones are sequentially stored and sent.

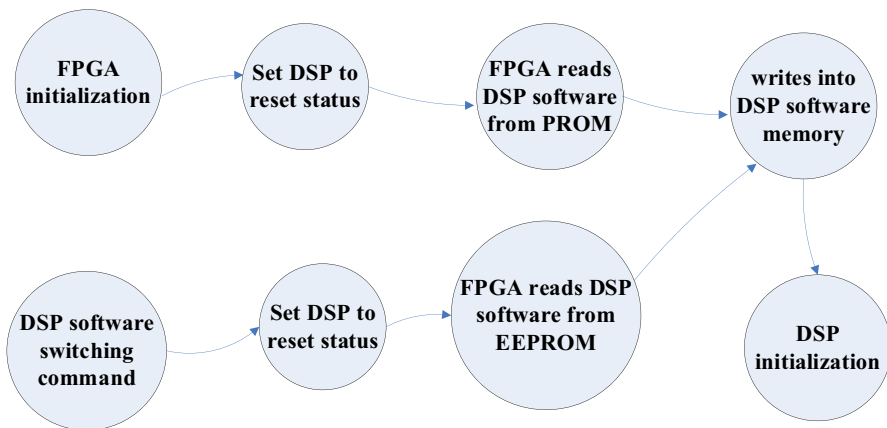


Fig. 4 The process diagram of booting

Table 1 The format of scientific packet

Length (Bytes)	Contents
2	Number of LEDs
2	Packet count
3	Packet length
4	UTC time
430	86 scientific events

Because of frequent observation of bright X-ray sources and a large amount of data, the reception, storage, and transmission of scientific data are designed as pipelines to ensure the maximum amount of data can be transmitted.

3.5 Housekeeping data

In addition to scientific data, the housekeeping data from LEDs and SCD detectors are all collected by the LEB. The housekeeping data can be categorized into two types based on different transmission methods. The amount of data sent through LVDS is large but the real-time performance is poor. On the contrary, the amount of data sent through 1553B is small but the real-time performance is good.

Unlike scientific data, housekeeping data encompasses multiple event types. The status, frequency and operation mode indicate the working status of the SCD detectors and LEDs. The voltage and temperature of each SCD module indicate the working environment. The command count of LED and LEB indicates the responsiveness to each command. Combined with the status of LEB, the total length of housekeeping data packet is 191 bytes (shown in Table 2). These packets are transmitted to the satellite platform via the LVDS interface every 5 seconds.

Table 2 The format of housekeeping data packet

Length (Bytes)	Contents
3	Packet count
3	Packet length
4	UTC time
20	Status, Frequency, Operation mode of LED1
20	Status, Frequency, Operation mode of LED2
20	Status, Frequency, Operation mode of LED3
5	Command response count of LED1
5	Command response count of LED2
5	Command response count of LED3
5	Command Receive Count of LEB
5	Command response count of LEB
48	Voltage of each SCD module
48	Temperature of each SCD module

The important housekeeping data, which is crucial for monitoring the performance of the LE, is carefully selected and packaged. It includes the status of LEDs, temperature and voltage of the SCD modules, as well as the command count of the LEDs and LEB, all of which provide insights into the operating status and performance of the LE. Along with the results of onboard data processing, they constitute the important housekeeping data.

After receiving a request for the important housekeeping data, with a time interval of approximately 2 seconds, the data is transmitted to the satellite platform through 1553B interface.

3.6 Commands

The commands for the LE are transmitted from the satellite platform through the 1553B interface and are categorized into three types: short commands, long commands, and uploaded data.

Short commands include switching the operation mode of LEDs, frequency of SCD modules and DSP software. Except the DSP software switching, which is responded by LEB, other commands are separated by LEB based on the command type and sent to the respective LEDs.

Long commands are utilized to modify the driving mode of the LEDs, adjust the detector threshold, enable the automatic threshold adjustment function, and change the driving voltage value. The first two commands receive responses from the LEDs, while the last two are responded to by LEB.

There are two types of uploaded data. The first one is the temperature threshold table, which is stored in the EEPROM of the data handling unit. After receiving the command to enable automatic threshold adjustment, the LEB can perform automatic threshold adjustment on all SCD modules, as described in Section 3.7. The second one is the DSP software, which is also stored in the EEPROM. If the LEB receives the DSP software switching command, the DSP software will be replaced, as described in Section 3.8.

3.7 Automatic threshold adjustment

To improve observation efficiency, the LEB can automatically adjust the thresholds of all SCD modules. The temperature threshold table is divided into multiple 128-byte data blocks on the ground. Utilizing the functionality outlined in Section 3.6, the temperature threshold table can be sequentially uploaded and stored in EEPROM.

When the function is enabled, the threshold can be automatically adjusted based on the comparison between the temperature feedback from all SCD modules and the temperature threshold table. This process occurs every 64 seconds and can be turned off through a command from the ground.

3.8 Update DSP software

Based on the requirements of scientific observation, we have designed onboard data processing. However, the requirements may be updated in the future with changes in observations, the existing process is no longer applicable. Therefore, we have designed a backup function that can update the DSP software in orbit to modify the data processing method.

As outlined in Section 3.6, the DSP software will be segmented into multiple 128-byte data blocks, which will be sequentially uploaded into the LEB. Each data block is equipped with a CRC, and will be checked after the data block uploaded. If an error occurs, the block will be re-uploaded until all blocks are successfully uploaded.

To directly verify the data in the EEPROM, a memory readout function has been designed. Data stored in any address can be read out and transmitted to the ground for verification. It is also possible to readout and download all the data in the EEPROM.

3.9 Power distribution

The power supply and distribution of the LE are managed by the power supply unit, which providing a series of secondary power supply to each LED. The primary power supply (+28V) is converted into four voltages (+30V, +7V and $\pm 6V$), as illustrated in Fig. 5. The power supply voltage of the SCD modules is +30V, the driving voltage of the SCD modules is +7V, and the power supply voltage of all analog and digital circuits is $\pm 6V$. The secondary power supply is required to have

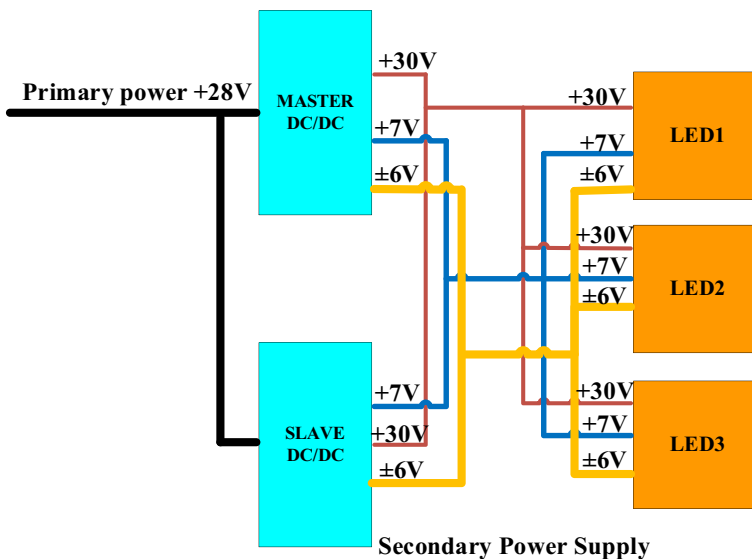


Fig. 5 The diagram of power distribution

an accuracy of less than 5% and a ripple of less than 50mV. The LEB turns on and off the LEDs by telecontrol.

The DC-DC converters have a power consumption of over 25W. For the purpose of heat dissipation and reparability of the power module, the DC-DC converters are positioned on the metal plate at the bottom of the LEB. We have carefully designed the layout and wiring of the DC-DC converters and circuit board, as depicted in Fig. 6.

In addition to the four voltages, the other voltages are generated by Low Dropout regulator (LDO) on the respective power boards because of the good noise ripple.

The performance of SCD detectors will continue to decline because of space irradiation. We have implemented a backup function to adjust the driving voltage of the SCD detectors which can improve their performance. The initial value of the driving voltage is +7V, from +6V to +9V, with a total of 7 different voltage values set at intervals of 0.5V. After receiving the driving voltage adjustment command, the LEB can modify it to any of the 7 values.

3.10 Onboard data processing

During scientific observation, a large amount of LE data is recorded and transmitted to the ground. Various data products will be generated and LE data will be analyzed by scientific users. This is not beneficial for quickly discovering astronomical phenomena because of the delay in this process. In addition, the

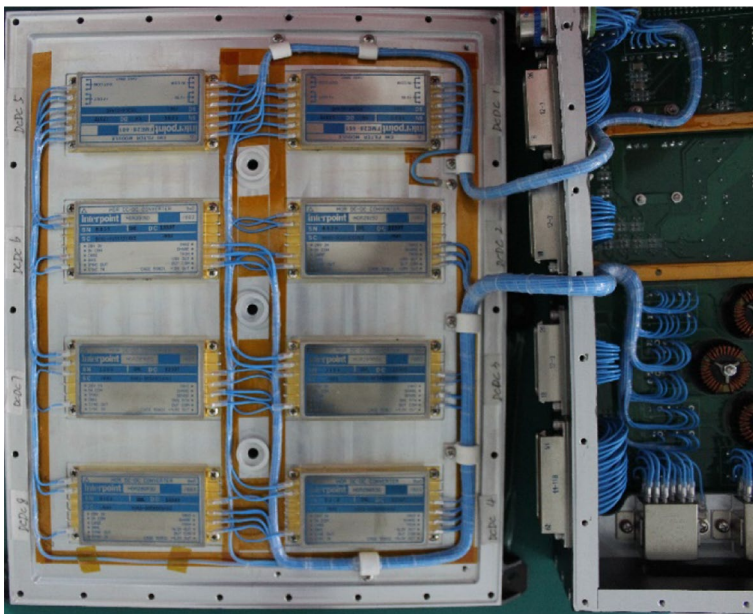


Fig. 6 The DC-DC converts of power distribution unit

Insight-HXMT is expected to be a long life astronomical satellite. LVDS interface components may not work stably because of long term operation and space irradiation, which may fail LVDS interface transmission. To improve the reliability of LE, onboard data processing has been designed in the LEB, and the processing results are transmitted through the 1553B interface as important housekeeping data while the raw scientific data is transmitted through the LVDS interface.

This function has been proven to be useful in numerous instances over the six years of scientific observation, facilitating the rapid discovery of astronomical phenomena and enabling timely updates to observation plans.

The onboard data processing is carried out by the FPGA and DSP of the data handling unit. The FPGA is responsible for receiving and writing data, while the DSP reads the data and conducts onboard processing. The DSP utilized in the data handling unit is the TSC21020F, which is a radiation-tolerant version of the Analog Devices ADSP21020, featuring a 20 M instruction rate. The DSP software is programmed in C language and developed by Visual DSP++ 5.0. There is no operating system or relevant libraries involved in the software.

The onboard data processing includes the calculation of the light curve and energy spectrum. The TSC21020F is designed to operate at 16M as part of the derating design. A single scientific event processing operation requires 6 μ s, and processing data at the maximum data rate requires 260ms, using 1/4 of the maximum computation, with sufficient margin.

Based on four different types of FOVs and three LEDs, 12 FOV numbers were defined. After receiving a new scientific event, LEB selects the number information of the event to calculate the FOV number and update the count (defined as n) for the FOV. The LEB calculates the light curve for each FOV by the equation $s = \frac{n}{t}$, t is the time interval between the request. After receiving the housekeeping packet request, the LEB sequentially sends the light curve of each FOV and recalculates the light curve from zero (Fig. 7).

In addition to the light curve, the onboard data processing also measures the energy spectrum. The FOVs are defined as previously described.

The energy spectrum of scientific data is divided into 4096 energy channels, but every 64 energy channels in the scientific data are merged into one channel because of the limitation of satellite bandwidth. Therefore, the energy spectrum by onboard data processing is 64 channels.

After receiving a new scientific event, the LEB selects the number information of the event to calculate the FOV number. Then LEB reads the energy information and measures energy spectrum for different FOVs. After receiving the housekeeping packet request sent by the satellite, the LEB sequentially sends the energy spectrum of each FOV and remeasures the energy spectrum from zero (Fig. 8).

3.11 Timing system

According to scientific requirements, LE acquires the absolute time and has a time accuracy of 1 μ s. The LEB receives 5 MHz clock, PPS and its corresponding

Fig. 7 The flow chart of calculating light curve

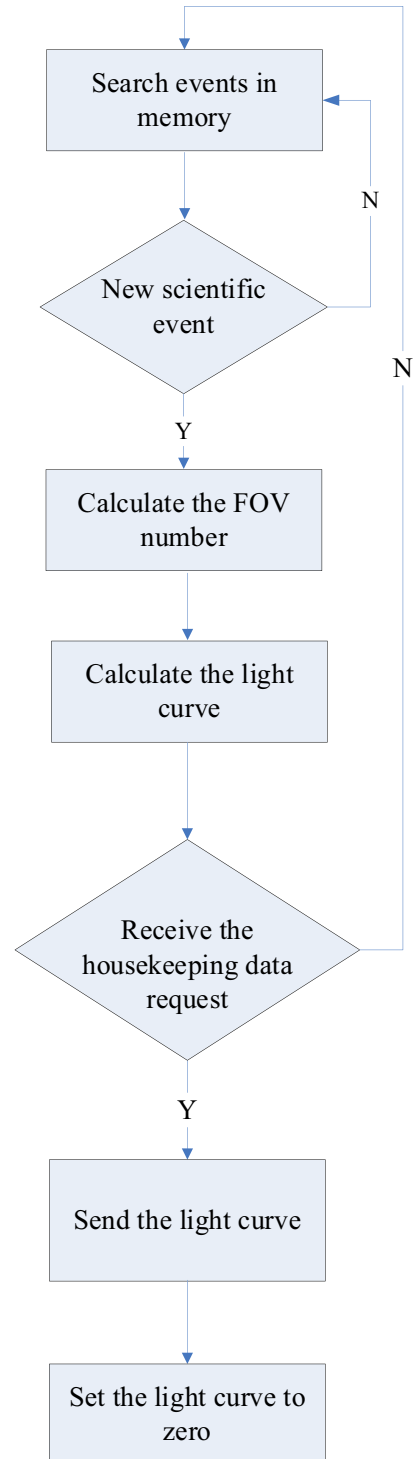
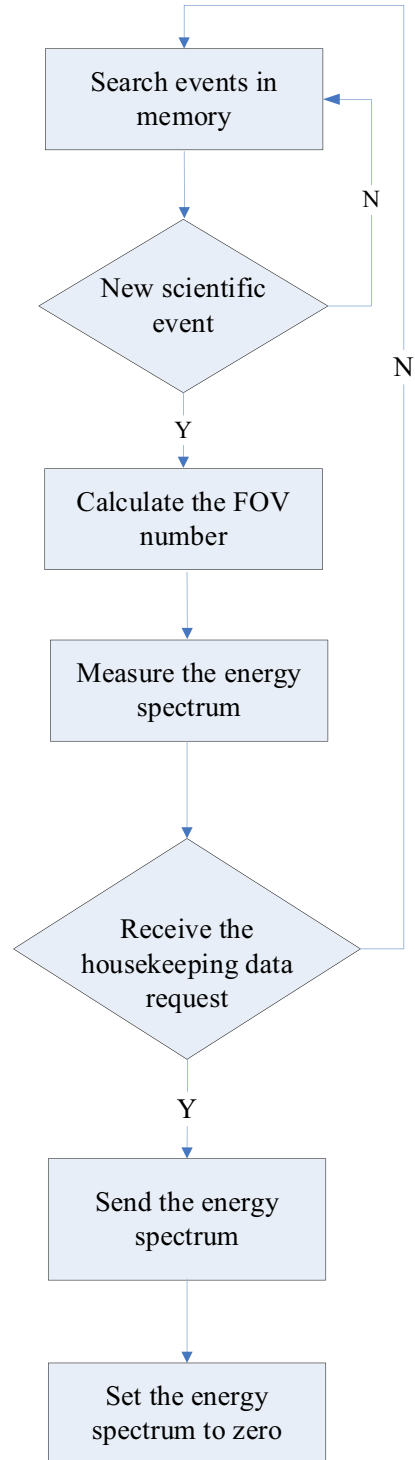


Fig. 8 The flow chart of measuring energy spectrum



UTC time from the satellite and then sends them to the LEDs. The stability of 5 MHz clock is $3 \times 10^{-8}/s$ [7].

The LEDs utilize the 5 MHz clock to generate a local clock with a period of 1 μs and count as the relative time. This relative time information is then added to each scientific event. After correction, the local clock stability is less than $\pm 0.5 \mu s$.

The PPS event and UTC event are formed by the LEDs after receiving the PPS and UTC time, and both events are sent to the LEB through the LVDS interface. Additionally, the UTC time is included in the scientific data packets. The time information of each scientific event is not duplicated.

Even in cases where PPS or UTC events are lost, or data packets are lost, time calculations can be performed on the scientific data transmitted to the ground. This ensures that scientific users can easily calculate the absolute time of any event and accurately obtain the position of the X-ray source.

3.12 Development of LEB

LE is a complex astronomical observation instrument, the development process lasted almost 7 years from Phase B to Phase D. During this period, six LEB models were developed.

In Phase B (from 2010 to 2012), the Demonstration Model (DM) and the Engineering Model (EM) were designed and manufactured, and the LVDS and 1553B interface communications were tested.

In Phase C1 (from 2012 to 2013), the Electrical and Functional Model (EFM) was designed and developed as an integrated device. All the interfaces were tested with satellite platform, also Structural Thermal Model (STM) was manufactured to verify the structure of the LEB. In Phase C2 (from 2013 to 2014), the Qualification Model (QM) was designed. All functions were tested, all experiments were completed, and long-term tests were carried out with the satellite platform.

In Phase D (from 2015 to 2016), the Flight Model (FM) was developed, and all tests and experiments were successfully completed. The FM of LEB consists of four

Fig. 9 The FM of the LEB



modules, the top two modules are data handling unit with LVDS and 1553B interfaces and its redundancy. The third module is the monitoring unit and its cold redundancy, with PPS and 5 MHz clock. The bottom module is the power supply unit and its cold redundancy, with primary power supply, secondary power supply and telecontrol (Fig. 9).

4 Verification of the LEB

The functions of the LEB were tested and verified during phase C1 and C2. On June 15, 2017, the Insight-HXMT was launched into a low earth orbit. According to the flight plan, LE would complete functional and performance verification within the first month, and then perform calibration in orbit.

Four days after the launch, the LEB was turned on and the functions were gradually tested and verified. Initially, the power supply and distribution function were verified, followed by the booting of the data handling unit. Subsequently, the LEDs were activated to verify the transmission and reception of commands, scientific data, and housekeeping data. After two days, scientific data was collected and processed, and the results were compared with the onboard data processing, confirming the accuracy of the onboard processing results. Following this, the automatic threshold adjustment was activated, and it was found that the initial threshold setting was appropriate, so this function was turned off. After a month of normal operation, the calibration in orbit commenced.

During this month, the voltage and current of the LEB remained stable. The transmission and reception of commands, scientific data, and housekeeping data were verified to be accurate. Additionally, multiple verifications were conducted on the onboard data processing. The LEB test results were consistent with the ground test results. In January 2018, the Insight-HXMT was delivered to the scientific users [8].

In the past six years, LEB has worked smoothly and performed well, all the expected requirements have been achieved. LEB participated in over 700 astronomical observations and transmitted over 5TB data. LEB plays an important role in many astronomical observations [9], such as the demonstration of X-ray pulsar navigation [10] and identifying the X-ray burst associated with a fast radio bursts in galactic Magnetar [11].

4.1 Data collection and transmission

During each phase and orbit testing, the amount of scientific data is always large. The scientific data from the three LEDs are transmitted to the LEB, where they are stored, packed separately, and then transmitted through LVDS interface. Therefore, the process of receiving and sending was analyzed in the design of the FPGA software. The software not only utilized a parallel and pipeline structure to process the data, but also optimized timing. As a result, the final scientific data processing rate was 44,000 counts/s, exceeding the required 35,000 counts/s. In ground testing, the data rate reached its maximum value without any CRC errors. The CRC error rate of

the entire transmission link in orbit is less than 10^{-9} , making it impossible to distinguish errors in LEB data transmission.

The LEB collects the housekeeping data of the three LEDs and LEB to form a housekeeping data packet, which is sent every 5 s. The LVDS interface frequency is 8MHz, and the housekeeping data rate is 305.6bps. When the satellite passes through a satellite telemetry tracking and command (TTC) station, the housekeeping data is transmitted quickly. After being processed by data software, it can be obtained in approximately 10 min. However, if the satellite does not pass through a TTC station, the data is stored on the satellite and transmitted at the appropriate time within a few hours to one day. So far, there have been no errors in the housekeeping data, and the design of the housekeeping data is also very reasonable. Using the housekeeping data can not only monitor the status of LE, but also provide assistance for analyzing scientific data.

The important housekeeping data sent to the satellite through 1553B enables scientific users to learn the LE status in real-time. The data rate of 1553B is 1Mbps, and it requires approximately 6.3kbps to transmit important housekeeping data and onboard data processing results. When the satellite passes through a TTC station, the data is transmitted in real-time and can be obtained in a matter of seconds. However, if the satellite does not pass through a TTC station, the data will be transmitted during its next pass through the TTC station. The real-time transmission of onboard data processing results provides scientific users with quickly astronomical results, which also provides assistance for scientific observation and the formulation of scientific observation plans.

In each phase and in orbit, all LE commands (more than 200) are repeatedly tested to ensure that each command is responded to as expected. Therefore, in the six years since the satellite operated in orbit, every command of LE has been responded to correctly without any errors.

4.2 Power distribution

After the LEB was powered on in orbit, the power supply unit and its redundancy were tested, and the voltage accuracy of the secondary power supply (+30V, +7V, and $\pm 6V$) was found to be less than 2%, with a ripple of less than 40mV. The main component of the power module has been operated continuously for six years, and the output voltages of the four secondary power supplies remain stable as they were six years ago. Figure 10 shows the voltage of the secondary power supply at 6 o'clock on April 30, 2022.

4.3 Verification of backup functions

The backup function designed by LEB has been tested at each phases. Because of the stable performance of LE for 6 years, the backup functions have not been utilized yet.

At the beginning of operation in orbit, the automatic threshold adjustment was tested and verified. However, this function has not been used because the thresholds of the SCDs have been calibrated before launch, and most of them

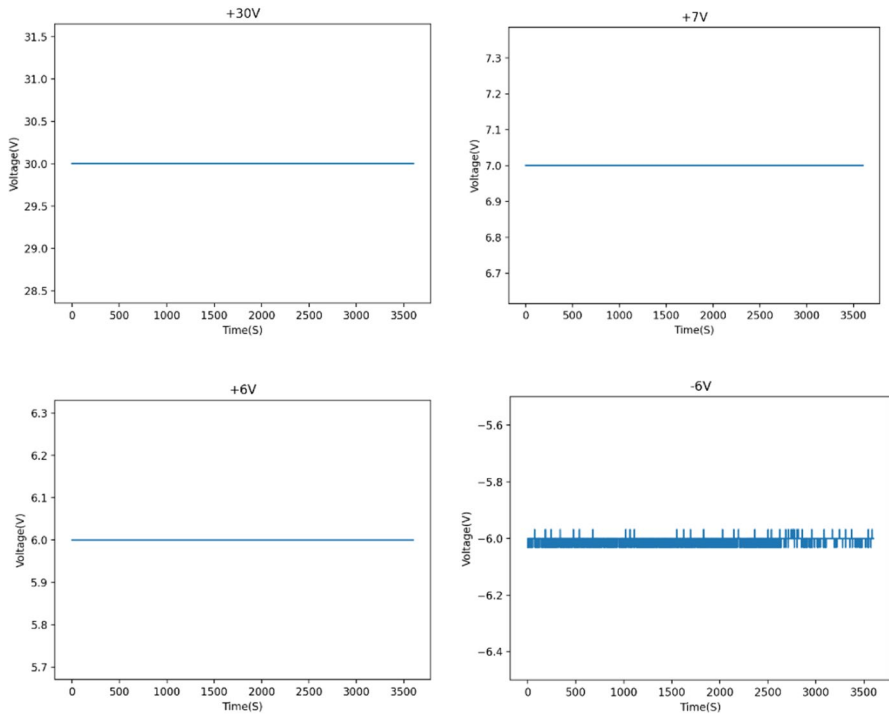


Fig. 10 The verification of the secondary power supply

have remained stable in orbit. Nevertheless, because of the decline in SCDs performance, we are preparing to enable this function recently.

Although the driving voltage adjustment has been tested and verified many times, it has also not been used. However, it is anticipated that this function will be used soon, as it has the potential to improve the performance of the SCD.

The Updating DSP software has been verified during the C2 and D phase. But the function is not enable in orbit, because the DSP software meets the requirements of astronomical observation. If scientific requirements change in the future and onboard data processing needs to be changed, this function will be enabled.

4.4 Onboard data processing

The onboard data processing has always been operated following the powering on of the LEB. To verify the function, we analysis two scientific data from LED3, comparing the light curve of the onboard data processing and that of ground data processing. The two data were randomly selected from the early and late stages of satellite orbit operation, which can prove the stability of the onboard data processing.

In the context of data processing, the four FOVs of LED3 have been defined as follows: FOV1 represents the wide FOV, FOV2 is designated as the all-sky monitoring FOV, FOV3 is the closed FOV, and FOV4 is the narrow FOV.

4.4.1 Light curve

- (1) The early data is collected on May 5, 2018 (a total of 681,000 events). Figure 11 shows the results of the light curves between the onboard and ground data processing.

The light curve of onboard data processing is very similar to the data processing in ground, and Fig. 12 shows the comparison on the light curves between the onboard and ground data processing in each FOV.

The blue lines in the light curves for the four FOVs used in onboard data processing are almost entirely covered by the yellow lines, indicating a high degree of similarity with the ground data processing.

The difference in the results is attributed to the inaccurate time intervals at which the satellite sent the request. After comparison, it can be concluded that the onboard data processing is faithful, and the results are useful and meaningful.

- (2) The late data is collected on February 12, 2022 (a total of 1,451,000 events). Figure 13 shows the results of the light curves between the onboard and ground data processing.

The light curve of onboard data processing is also very similar to the data processing in ground, and Fig. 14 shows the comparison on the light curves between the onboard and ground data processing in each FOV.

Figure 14 exhibits similar results to Fig. 12, with the blue lines almost entirely obscured by the yellow lines. From the comparison of light curve, it can be concluded that although LEB has been operated in orbit for 5 years, the light curves for

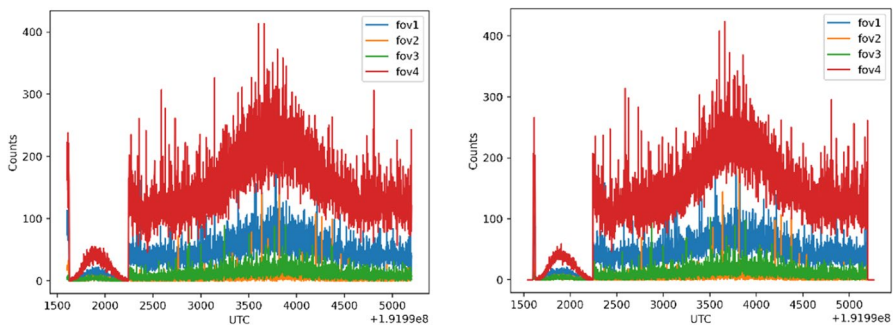


Fig. 11 Light curve of different data processing (The left panel is the light curve calculated by onboard data processing for four FOVs, the right panel is the light curve calculated by ground data processing for four FOVs)

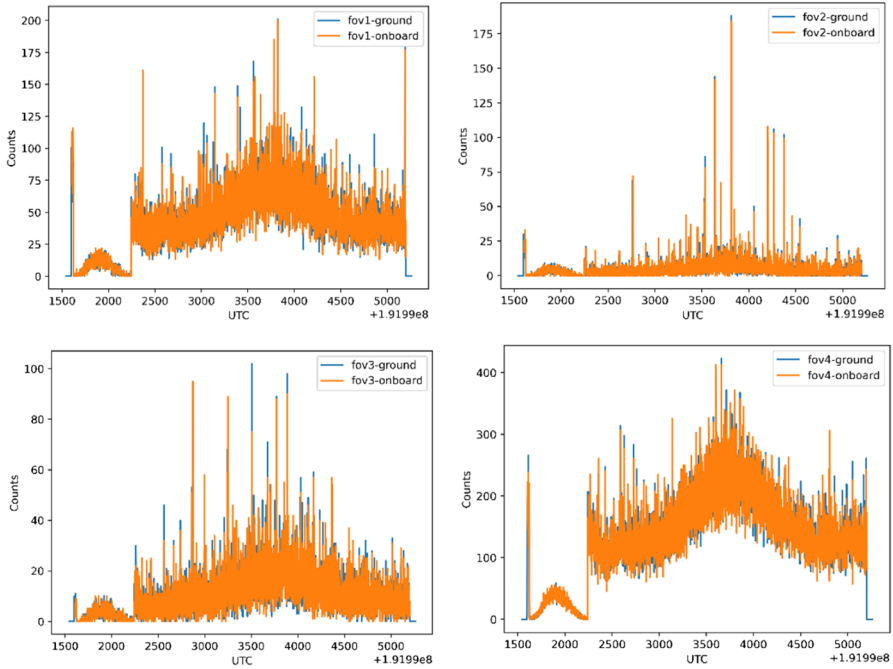


Fig. 12 Comparison of Light curve of four FOVs

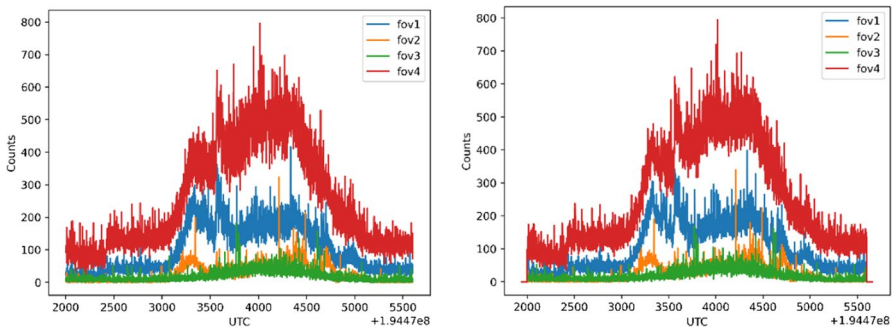


Fig. 13 Light curve of different data processing (The left panel is the light curve calculated by onboard data processing for four FOVs, the right panel is the light curve calculated by ground data processing for four FOVs)

onboard data processing remain consistent with those for ground data processing, the onboard data processing has always been operating steadily.

4.4.2 Energy spectrum

We use the same two data to compare the energy spectrum between onboard data processing and ground data processing.

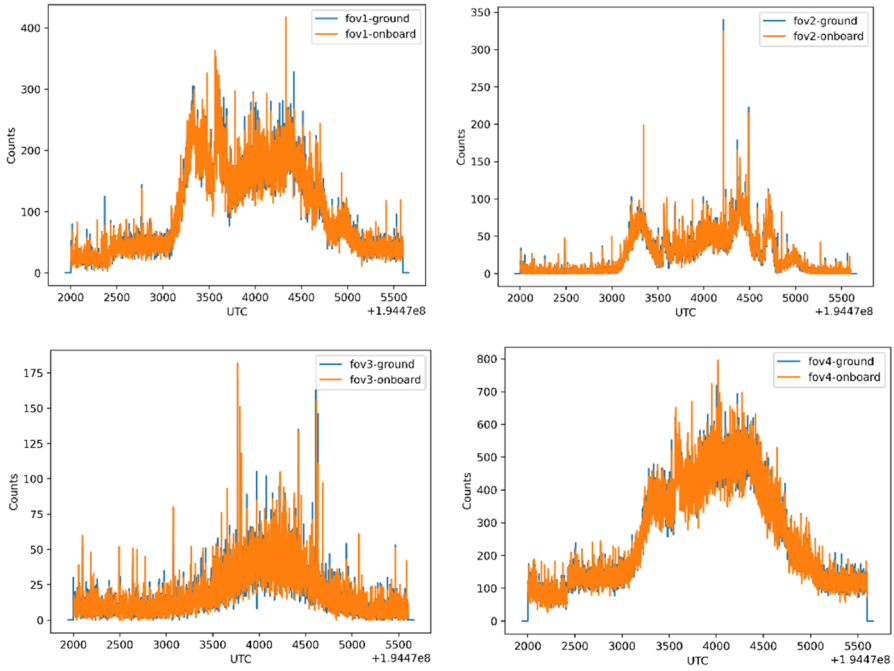


Fig. 14 Comparison of Light curve of four FOVs

- (1) Firstly, we measure the energy spectrum of the data collected on May 5, 2018. Figure 15 presents the results of the energy spectrum between the onboard and ground data processing.

The energy spectrum of onboard data processing is very similar to the data processing in ground. Because of the limited amount of energy spectrum for FOV2,

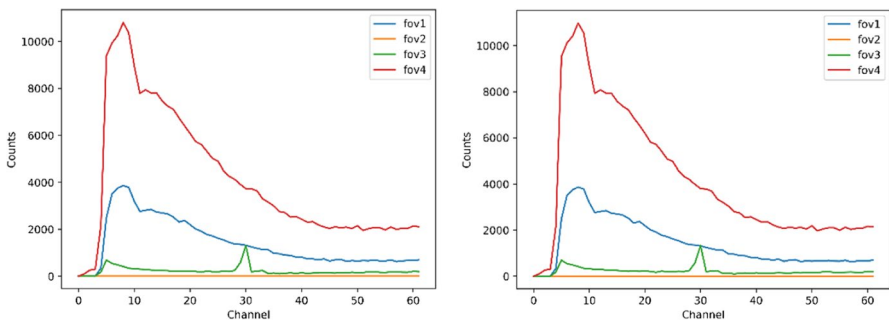


Fig. 15 Energy spectrum of different data processing (The left panel is the energy spectrum measured by onboard data processing for four FOVs, the right panel is the energy spectrum measured by ground data processing for four FOVs)

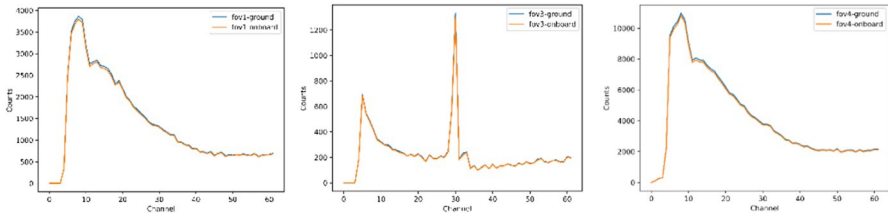


Fig. 16 Comparison of energy spectrum of FOV1, FOV3 and FOV4

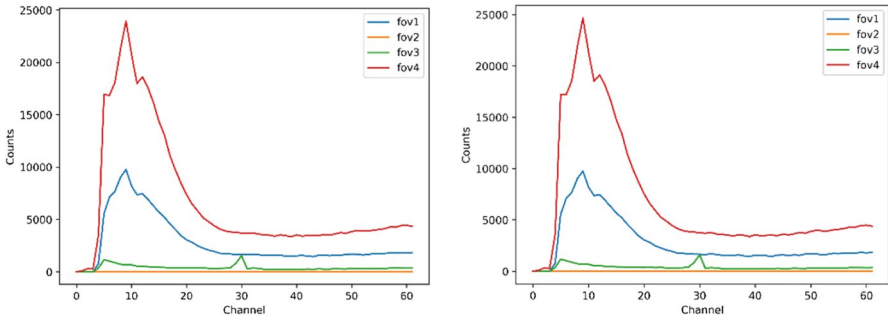


Fig. 17 Energy spectrum of different data processing (The left panel is the energy spectrum measured by onboard data processing for four FOVs, the right panel is the energy spectrum measured by ground data processing for four FOVs)

Fig. 16 shows the comparison on the energy spectrum between the onboard and ground data processing in FOV1, FOV3 and FOV4.

Because of the similarity in energy spectrum between the onboard data processing and the data processing in ground, the blue lines are almost overlapped with the yellow lines.

The difference in results is attributed to the inaccurate time intervals at which the satellite sent the request. After comparison, it can be concluded that the onboard data processing is faithful, and the results are useful and meaningful.

- (2) Secondly, we measure the energy spectrum of the data collected on February 12, 2022. Figure 17 presents the results of the energy spectrum between the onboard and ground data processing.

The energy spectrum of onboard data processing is very similar to the data processing in ground. Figure 18 presents the comparison on the energy spectrum between the onboard and ground data processing in FOV1, FOV3 and FOV4.

Figure 18 exhibits similar results to Fig. 16, with the blue lines almost overlapping with the yellow lines. From the comparison of the energy spectrum, it can be concluded that although LEB has been operated in orbit for 5 years, the energy spectrum for onboard data processing remains consistent with those for ground data processing, the onboard data processing has always been operating steadily.

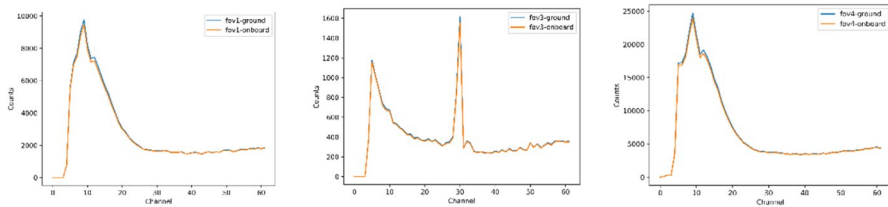


Fig. 18 Comparison of energy spectrum of FOV1, FOV3 and FOV4

Based on the experience and lessons learned from the LEB, subsequent instruments have designed more reasonable onboard data processing, such as the Einstein Probe (EP) [12] and the enhanced X-ray Timing and Polarimetry mission (eXTP) [13].

5 Summary

The LEB is an important part of LE, and it is constituted of data handling unit, monitoring unit and power distribution unit. All electrical interfaces between LEDs and satellite platform are designed in LEB, including LVDS, 1553B, PPS, 5 MHz clock, telecontrol and power supply.

The functions designed in the LEB include receiving and packeting of scientific data, collecting and packaging of housekeeping data, receiving and transmitting of commands, uploading data, automatic threshold adjustment, updating DSP software and onboard data processing. All functions are tested and verified at each phase or in orbit.

To improve the effectiveness and reliability of LE, onboard data processing is designed in the LEB, which is carried out by the FPGA and DSP in the data handling unit. The light curve and energy spectrum of onboard calculations are transmitted as important housekeeping data. By comparing the results of onboard data processing with the results of ground data processing, it can be concluded that the onboard data processing is reliable and performs stably in orbit. Onboard data processing is designed in subsequent instruments based on the experience of LEB.

LEB has been operated in orbit for six years and performed very well and participated a large number of astronomical observations and transmitted more than 5TB scientific data. All the expected requirements of LEB have been achieved.

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Author contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by [Wei Li], [Yanji Yang] and [Xiaofan Zhao]. The first draft of the manuscript was written by [Wei Li] and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability The data that support the findings of this study are not openly available due to the intellectual property belonging to the partners and are available from the corresponding author upon reasonable request. The data has been stored in the server cluster in the Institute of High Energy Physics, Chinese Academy of Sciences.

Declarations

Competing interests The authors declare no competing interests.

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