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TECHNICAL REPORT

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Data acquisition and trigger system for imaging atmospheric Cherenkov telescopes of the LHAASO

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Abstract: The Wide Field of View Cherenkov Telescope Array is an important part of the Large High Altitude Air Shower Observatory. The array adopts atmospheric Cherenkov imaging technology. The data acquisition and trigger system is central to each telescope's electronics readout system. To acquire as many Cherenkov events as possible, the system uses a two-level trigger design and partial readout technology. A telescope uses silicon photomultiplier tubes as the detector, whose status (e.g., in terms of the temperature and voltage) is monitored by the system. The instruction protocol of the system is presented.

Keywords: Front-end electronics for detector readout; Trigger concepts and systems (hardware and software)

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1 Introduction

The Large High Altitude Air Shower Observatory (LHAASO) is located at an altitude of about 4400 meters on the mountain Haizi in the Daochen county of Sichuan province [1]. The LHAASO has multiple detectors and three detection arrays: the Square Kilometer Array (KM2A), Water Cherenkov Detector Array (WCDA), and Wide Field of View Cherenkov Telescope Array (WFCTA) [2]. Each Cherenkov telescope has a spherical mirror with an area of 4.7 m^2 and a camera featuring an array of 32×32 silicon-photomultiplier (SiPM)-based pixels. Each camera has a field of view of $16° \times 16°$ and a pixel size of approximately $0.5° \times 0.5°$ and is positioned on the focal plane, 2870 mm from the center of the mirror [3].

The purpose of a WFCTA telescope is to detect Cherenkov light and a laser signal. Cherenkov light lasts from 4 to 50 ns and broadens to 160 ns when it is processed by the front-end electronics of the telescope. Cherenkov light arrives at the telescope at nearly the same time and the difference in arrival time among pixels is less than 300 ns. The image of Cherenkov light on a SiPM array has a round pattern. The difference in the arrival time of the laser signal is from tens of nanoseconds to several microseconds depending on the distance and direction from the laser to the telescope. The image of the laser signal is a line pattern.

We need to develop a data acquisition and trigger system of the telescope for the recording of Cherenkov light and the laser signal.

2 Trigger system

The main non-shower background in an image results from the night-sky background; i.e., scattered starlight, which illuminates the camera uniformly. There is thus a continuous stream of Poisson-distributed photon-electrons in each SiPM, with the rate depending on the design of the telescope (i.e., the pixel size and solid angle per pixel) and operating conditions (i.e., the observation position, amount of scattered light, and moonlight). Random coincidences of these uncorrelated photons in nearby pixels leads to random triggering. The aim of a trigger system is to detect as many Cherenkov showers as possible while rejecting events due to the night-sky background. We design a two-level trigger system to identify a Cherenkov event.

2.1 First level of trigger

The ancillary front-end electronics generate signals when the camera's pixels are struck by Cherenkov light. The first level of trigger (FLT) triggers a pixel if the signal's relative amplitude (i.e., amplitude above the baseline) exceeds a threshold. The duration of the signal is 160 ns [4], and the front-end electronics adopt 50-MHz analog-to-digital conversion (ADC) to digitize the signal [5]. The signal is therefore the combination of eight ADC sample points, and we add the ADC counts of the four consecutive points of the signal to represent the amplitude of the signal. In measuring the baseline accurately and reducing the effect of noise from the electronics, we use the average ADC counts of 256 consecutive points to calculate the baseline and we set a gap between the signal and the baseline to prevent the baseline window from containing the rising edge of the signal. The gap also comprises 256 consecutive points. The length of the coincidence window affects the FLT rate. It takes at least a window length to get the result of the FLT, and the FLT is sent within this period. A shorter window length increases the FLT rate and makes it possible for the instability of the hardware system to increase. A window length of 1.6 µs is chosen as the coincidence window of the FLT because the possibility of two Cherenkov events happening in the same 1.6-µs window is low and the FLT rate is about 10 MHz. This rate is suitable when compared with the 25-MHz clock used in our hardware system.

2.2 Second level of trigger

The FLT is the trigger for a pixel while the second level of trigger (SLT) is the trigger for the whole telescope. The second level of trigger is based on image recognition. The fired pixels (triggered at the first level) of a telescope constitute a shape, and if this shape matches a specific shape of interest, the SLT is valid. There are two strategies. One is to count the fired pixels; i.e., the SLT is valid if the count exceeds a certain number. The other is to judge the shape; i.e., the SLT is valid if the shape is an oval or line. The coincidence window of the SLT is 1.6 µs because the FLT is updated every 1.6 µs. A typical algorithm for the Cherenkov event is as follows.

- Find a fired pixel and take this pixel as a central fired pixel. The fired number N = 1.

- Find the pixels surrounding the central fired pixel. There are six surrounding pixels if the central fired pixel is located at the center of the telescope and at least two surrounding pixels if the central fired pixel is located at the corner of the telescope.

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- If the number of surrounding fired pixels is M, the fired number N = M + 1.
- There is a Cherenkov event when the fired number (N) is no less than the number threshold (N_{th}).

Figure 1 shows patterns for which the fired number meets the number threshold.

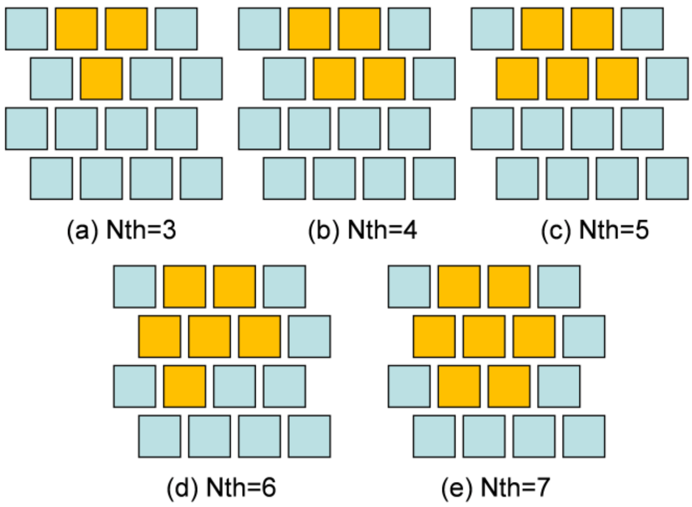

Figure 1. Typical patterns of Cherenkov events, where yellow pixels are fired pixels and blue pixels are empty pixels.

2.3 Trigger implementation

The trigger system comprises several subsystems integrated in the electronic boards of the telescope as presented in figure 2. The electronic boards include 64 sets of front-end electronics and one backplane board. One set of front-end electronics processes the signals of 16 pixels.

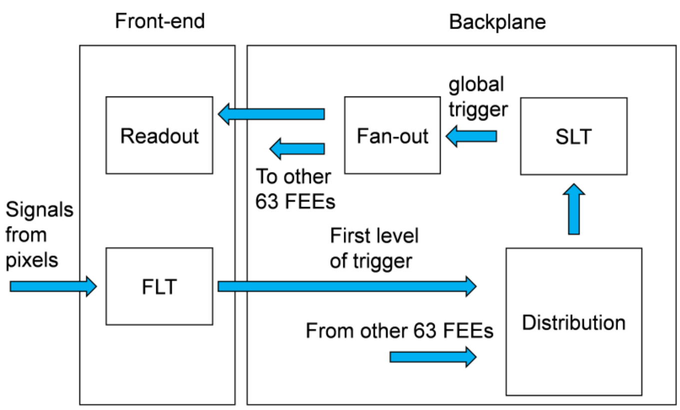

Figure 2. Architecture of the trigger system, with the physical distribution of the different subsystems between the boards.

The first subsystem is the FLT subsystem. This subsystem compares the signal of each pixel with a threshold and produces a 1-bit FLT. The subsystem encodes such triggers into a 16-bit serial signal

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and this serial signal is sent to the backplane. The distribution subsystem collects serial signals from the 64 sets of front-end electronics and, to reduce the use of differential lines with the SLT subsystem, the outputs of the distribution subsystem are divided into 32 groups of 32-bit serial signals. These outputs are fed into the SLT subsystem. The SLT subsystem judges the pattern according to pattern algorithms, such as by counting the fired pixels or through shape recognition. The pattern result (global trigger) is then replicated in the fan-out subsystem and sent back to the 64 sets of front-end electronics. There is a fixed latency from sending the FLT to receiving the global trigger for each set of front-end electronics. It takes 1.6 µs to send the FLT to the distribution subsystem, the distribution subsystem takes another 1.6 µs to send the triggers to the SLT subsystem, the SLT subsystem takes 1.6 µs to recognize the pattern, and the front-end electronics then take 1.6 µs to decode the global trigger. The latency is therefore 6.4 µs. This fixed latency is useful for data readout.

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3 Partial readout

Owing to the physics of cosmic ray showers and the optics used in a Cherenkov telescope, the long but narrow three-dimensional shower is mapped onto an elongated ellipse in the camera frame, which typically covers only a small part of the camera. In a classical readout scheme, all the camera pixels are read out for each event, regardless of the actual size of the relevant shower image. However, only a few percent of the camera pixels are struck by Cherenkov light, while the remaining pixels record only random noise. A remarkable data volume is thus to be transferred out of the camera. Partial readout is required for the telescope to operate at a higher trigger rate. Data that actually contain physical image information are read out and other empty-pixel data are discarded. A threshold is required to determine the empty pixels and then save the data of fired pixels. If the threshold is set low, the trigger rate is high and non-shower background triggers increase the whole data amount for the telescope. However, if the threshold is set high, the image of a cosmic ray event faces truncation [6]. A two-threshold readout is designed to solve this problem; one threshold (i.e., the record threshold) is used to define the readout region and a second, higher threshold (i.e., the single threshold) is used to make the FLT decision. The trigger rate is decided by the single threshold. Although this threshold is set high, the image remains complete because of the lower record threshold.

Data belonging to the same event need to be packed into one package to analyze the data conveniently and efficiently. The data length is 1024 bits for each pixel and there are 1024 pixels for one telescope. If we read out all pixel data, each event will have a fixed length of data (1 Gbit). Each event can therefore be distinguished by counting this fixed length. However, when there is partial readout, only the data of the fired pixels are read out and the data of the empty pixels are discarded. This varies the length of the event, and counting a fixed length will no longer work. To solve this problem, we count the fired pixels of each event and use this count to pack the data of all fired pixels into an event package.

Partial readout is implemented using a fully digital algorithm. Pixel data are first buffered in the line buffer of the front-end electronics and then compared with the record threshold and the single threshold to generate the FLT. The FLT is sent to the backplane for SLT recognition. Additionally, the FLT is buffered in another line buffer of the front-end electronics. When the SLT is valid, the readout subsystem takes out both the data and FLT in the line buffers and packs them together. The data package is sent to the backplane and the online filter subsystem on the backplane saves the data of the fired pixels and discards the data of empty pixels according to the FLT in the data package.

4 Status readout

Data acquisition includes not only event data of the fired pixels but also the status of the telescope; e.g., the temperature, high voltage, edition of the field-programmable gate array (FPGA) program, and threshold. In the design of the WFCTA telescope, each set of front-end electronics uses a Mini DisplayPort to communicate with the backplane. The Mini DisplayPort has five pairs of differential lines. Only one pair of differential lines is available for data transmission while the other four pairs are used for other logic. The status data and event data from front-end electronics flow to the backplane through this data transmission line. An internal finite state machine controls the process of parallel-to-serial data transmission. The start bit, parity bit, and stop bit are automatically added without user intervention. To avoid the mixing of status data and event data, we use different start bits to distinguish the status data and event data. The start bits are 0110010 if we are sending the status data and 0011100 if we are sending the event data.

There are 64 sets of front-end electronics. The status data of each set flow to the backplane. Three buffer stages are used in packing the status data of the 64 sets. The first stage has 64 First In First Out (FIFO), the second and third stage both have 8 FIFO. We use three instructions to control the data flow and read out all status data. The first instruction allows the flow of status data from the first stage to the second stage, the second instruction allows the flow of status data from the second stage to the third stage, and the third instruction allows the flow of status data from the third stage to the DDR3_SDRAM, and the data are then sent to the switch via the TCP/IP protocol. No matter whether there is data or not, when the instruction arrives, the data in the FIFO will be read out and this mechanism avoids data congestion when the system works under abnormal conditions.

5 Instruction distribution

To communicate with different sets of front-end electronics, each set of front-end electronics has a unique ID. If these IDs are integrated in the firmware of front-end electronics, there will be 64 different versions of firmware for the front-end electronics of one telescope. This will complicate the manufacturing and maintenance of each set of front-end electronics and increase the possibility of error. Therefore, all sets of front-end electronics use the same firmware, and it is necessary to give each set of front-end electronics an ID from the backplane instead of integrating a fixed ID for each set of front-end electronics. Five pairs of differential lines are used to connect each set of front-end electronics and the backplane, with one pair of differential lines being the instruction line. When the system is powered on, a bunch of instructions arrive at the front-end electronics to set IDs first. To set different IDs for different sets of front-end electronics, these instructions differ according to the route from the front-end electronics to the backplane. When the ID has been set, other logic instructions are broadcast to the front-end electronics. Each instruction comprises 560 bits, and eight bits of instruction are used for ID recognition. Each set of front-end electronics thus extracts its own instructions according to its ID. The instruction protocol can use both synchronous transfer technology and asynchronous transfer technology. If the system chooses synchronous

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transfer technology, it is necessary to send the synchronous clock and the instruction data from one FPGA to another FPGA. However, if the system chooses the asynchronous transfer technology, it only needs to send the instruction data from one FPGA to another FPGA. Considering the limited differential line resources, the system uses the asynchronous transfer technology and the front-end electronics use a 50-MHz receiving clock to decode the instruction serial data driven by a 5-MHz sending clock from the backplane.

6 Conclusion

A data acquisition and trigger system of the WFCTA was presented. The main aim is to acquire Cherenkov events. A two-level trigger architecture was developed to make full use of the system bandwidth. The FLT is a pixel trigger and only needs to send the hit signal instead of the full information of the fired pixels to the backplane. The SLT is the telescope trigger and is responsible for the data collection of all pixels. To reduce the amount of data, a partial readout method was adopted whereby only pixels containing image information are read out. Using different start bits of the transport protocol is effective in distinguishing status data and event data. Considering the architecture of the electronic system, three buffer stages are used for status readout, with each stage being read according to relevant instructions. To prevent the blocking of status data, data in the status FIFO are read out unconditionally after the instructions are received. To access each set of front-end electronics separately, it is necessary to set the ID by sending instructions. The instruction system uses an asynchronous transmission protocol, which saves routing resources and reduces the demand for timing.

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