Development and Testing of the WCDA Time Calibration System (Postprint)

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Abstract

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Full Text

Preamble

Development and Testing of the WCDA Time Calibration System

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Abstract

The Water Cherenkov Detector Array (WCDA) is a crucial component of the Large High Altitude Air Shower Observatory (LHAASO) project, with the primary scientific objective of conducting an all-sky survey of gamma-ray sources in the very-high-energy (VHE) low-to-medium energy range (100 GeV–30 TeV). To ensure accurate pointing for source detection, the detector array requires precise time calibration. This paper introduces the time calibration methodology for the WCDA detector, describes the construction of the calibration system, and presents batch testing results for the critical component—the fiber optic beam splitters.

Keywords: Time calibration method, calibration system construction, fiber bundle batch testing

1. Time Calibration Scheme

The Water Cherenkov Detector Array (WCDA) is a key component of LHAASO, designed to achieve all-sky surveys of gamma-ray sources in the VHE low-to-medium energy band (100 GeV–30 TeV), including detection, monitoring, spectral measurement, and extended morphology studies of VHE gamma-ray sources. The WCDA detector consists of a large water pool structure with a total area of 78,000 m², divided into 3,120 detection units (5 m × 5 m each) using black light-proof curtains. Figure 1 [Figure 1: see original paper] shows the overall layout of the WCDA detector. In Pool 1 (lower right of the diagram), each detection unit employs one 8-inch and one 1.5-inch photomultiplier tube (PMT), while Pool 2 (lower left) and Pool 3 (upper) will each contain one 20-inch and one 3.5-inch PMT per unit.

Each detection unit of WCDA is used to detect Cherenkov light produced by secondary particles from air shower events. To meet WCDA performance specifications, the array pointing accuracy must be better than 0.1°, requiring a detector time calibration precision better than 0.2 ns. This time calibration requirement was derived from Toy Monte Carlo simulations of atmospheric shower particles incident on a shower region, which established the relationship between angular resolution and timing precision. In these simulations, represents the angular resolution of reconstructed events under various timing precision settings t, S is the trigger area, N is the number of hit PMTs, N–2 is the degrees of freedom for air shower fitting, and A is a constant coefficient obtained by averaging fitted values across different timing precision settings.

Large-scale detectors typically employ a uniform external light source to illuminate all detection units for calibration. However, for WCDA, the large detector area and the use of black light-proof curtains to prevent Cherenkov light crosstalk between units make single-source calibration impractical. Using a light source with fiber optics would require fiber lengths exceeding 220 m for a single pool, causing significant attenuation and broadening of calibration pulses that would degrade precision and complicate installation and maintenance. Therefore, WCDA adopts a distributed calibration scheme called "cross-calibration." Based on the electronics layout, every 6×6 units form a cluster, with each pool containing 900 detection units (25 clusters). The full-array calibration is achieved by first calibrating relative timing differences between clusters and then completing the entire array calibration. Each cluster is equipped with two LED+fiber bundle light source systems: one fiber bundle calibrates the 36 PMTs within the cluster, while the other exchanges fibers with adjacent clusters to enable cross-calibration across the entire array (Figure 2 [Figure 2: see original paper]).

2. Cross-Calibration Method

The central cluster is selected as the reference cluster, and other clusters determine their internal unit timing through a specific transmission path. For adjacent clusters, let ci_chi represent a unit in the cluster to be calibrated and c0_ch0 represent a reference unit in the reference cluster. The time difference ΔT between ci_chi and c0_ch0 is the target measurement.

Eight cross fibers connect the two clusters, located in units ci_chx and c0_chx (where x is the fiber number, defined as 1,2,3,4). Using one cross fiber (ci_chx), the time difference can be obtained through Equation (1). In this equation, TINci_chi represents the signal arrival time at the unit to be calibrated within the internal fiber cluster, TINci_chx is the signal arrival time at the cluster unit corresponding to fiber number x, TCRci_chx is the signal arrival time at the reference cluster unit corresponding to fiber number x, and TCRc0_ch0 is the signal arrival time at the reference unit in the reference cluster.

Four fiber groups are available between adjacent clusters, ideally providing four datasets to verify the calibration of the entire fiber channel. The time difference between the two units is obtained by averaging these four values. Fiber length and bending introduce attenuation during light transmission. To ensure uniform detector response, all fiber bundles must be calibrated before installation. Each cluster requires two fiber bundles, with 36 fibers per bundle. Per engineering requirements, the light intensity variation among fibers must not exceed $\pm$10%.

3. Calibration System Setup

The time calibration system consists of two main components:

(1) Light Source System
The light source system comprises an LED, light tube, and fiber optic beam splitter. The LED has a peak emission wavelength of 468 nm and a divergence angle of 120°, corresponding to a plastic fiber attenuation length of 26 m. The light tube is a critical component connecting the LED source to the fiber bundle. One end of the light tube secures the LED, while the other end connects to the fiber bundle input. The distance between the LED and fiber bundle input is 6.0 cm, with three black opaque perforated baffles placed at equal intervals to block stray light, achieving light spot uniformity on the fiber bundle input within $\pm$2% of the mean value.

The fiber optic beam splitter is the most critical component, responsible for light transmission. Given the large WCDA detector area and construction challenges, each fiber bundle is designed as a 1-to-41 splitter with each fiber length of 40 m to meet cross-calibration requirements.

(2) Remote Trigger System
The optical trigger system consists of a master motherboard and slave boards connected via RS485 bus. The RS485 lines enable communication between the master and slave boards, including command transmission, frequency control,

and pulse width adjustment to regulate LED operation. PMTs within the same fiber bundle receive synchronized LED signals distributed through the fiber splitter to obtain relative timing information. After correcting for fiber time differences and applying data corrections, the time differences between PMTs are determined. The overall system architecture is shown in Figure 3 [Figure 3: see original paper].

4. Fiber Bundle Batch Testing

Figure 3: Layout of the time calibration system for WCDA Pool 1

To meet detector requirements, each cluster needs two fiber bundles. During manufacturing, fiber cutting errors introduce relative time differences among fibers within each bundle that must be calibrated. Therefore, a semi-automated batch testing system was developed based on a one-dimensional electric stepping slide and VME/NIM crate modules.

4.1 Test Platform and Procedure

The fiber bundle output ends are sequentially mounted on a one-dimensional electric slide bracket. The LED trigger board provides 10 ns pulse width signals to drive the LED. The LED light pulses travel through the fiber bundle to a fast PMT. A high-voltage module powers the PMT, and its output signals pass through a signal distribution board, a 10× fast amplifier, and a leading-edge discriminator before being fed into TDC and QDC modules to collect timing and charge information, respectively. By precisely calibrating the fiber positions, only one fiber aligns with the PMT photocathode center after each stepper motor movement. Upper computer scripts control the slide driver and DAQ program to automatically scan each fiber in a bundle, measuring both output light intensity uniformity and fiber time differences. Long-term testing has demonstrated a system error of 5.40 ps, fully meeting the precision requirements.

4.2 Test Results

4.2.1 Light Intensity Uniformity Figure 4 [Figure 4: see original paper]: Fiber testing workflow diagram

Through stepper motor scanning with 10 ns pulse width signals driving the LED, light passes through the 6 cm light tube to illuminate the fiber bundle input. Figure 5 [Figure 5: see original paper] shows the light intensity results from repeated scans of 41 fibers in one bundle, demonstrating variation within 10%. The high degree of overlap in Figure 5 indicates excellent system stability.

All 53 fiber bundles were tested using this system. To accommodate engineering requirements, different LEDs and light tubes were paired with fiber bundles. The batch test results for all 53 fiber bundles are shown in Figure 6 [Figure 6: see original paper], with average light intensities ranging from 350–600 ADC counts. The statistical results of qualified fibers across the 53 bundles are presented in

Figure 7 [Figure 7: see original paper], showing that each bundle contains at least 36 fibers meeting engineering calibration requirements. Fifty fiber bundles were selected and deployed in WCDA Pool 1.

4.2.2 Time Difference By controlling the stepping slide with the upper computer, timing information for each fiber was measured. Under 10 ns LED pulses through the 6 cm light tube, Figure 8 [Figure 8: see original paper] shows the timing test results for 41 fibers in one bundle. The plot displays the difference between each fiber' s measured time and the average time of all 41 fibers, with fiber number on the horizontal axis and time difference on the vertical axis. The results show time differences within 0.4 ns.

5. Conclusion

The LHAASO-WCDA time calibration system performs full-array calibration. This paper described the system layout and methodology, conducted batch testing of the core fiber bundle components, and detailed the test platform development. All 53 fiber bundles met the requirements: light intensity consistency within ±10% of the mean value and time difference variations within ±0.4 ns of the average. The development of this time calibration system ensures data accuracy for the detector and provides valuable experience for future detector calibration efforts.

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