Performance Study of the LHAASO-WFCTA Laser Energy Measurement System Postprint

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Date: 2023-12-04T00:00:00+00:00

Abstract

The Large High Altitude Air Shower Observatory (LHAASO) is located at Haizi Mountain, Daocheng County, Sichuan Province, at an average altitude of 4,410 m. The laser calibration system is one of the components of LHAASO's Wide Field-of-view Cherenkov Telescope Array (WFCTA), used for calibrating the absolute gain of photon numbers received by the WFCTA. The laser energy measurement system in the laser calibration system consists of three parts: energy sensor, energy meter, and temperature control system, and is mainly used for precisely measuring the energy of pulsed laser beams emitted into the field of view of the WFCTA. This work focuses on the relative calibration and performance study of the energy sensor, and the design and development of a thermal insulation system to ensure its normal operation in the harsh high-altitude environment. Through relative calibration among energy sensors, the accuracy of laser energy measurement can be improved. Performance test results of the energy sensor show that within a circular region centered at the energy sensor with a diameter of 8 mm, its non-uniformity is less than 1.5%. The incident angle of the laser beam has almost no effect on the energy sensor's measurement of laser pulse energy; however, the laser reflected by the energy sensor during normal incidence can damage the laser, thus it is necessary to avoid normal incidence of the laser beam onto the energy sensor. Additionally, the energy sensor exhibits a strong temperature effect. Therefore, an independent thermal insulation system was developed to ensure the normal operation of the energy sensor and meet the experimental requirements. These research efforts form the basis for the normal operation and functioning of the laser calibration system.

Full Text

Preamble

Vol. 20 No. 6 Nov. 2023 ASTRONOMICAL RESEARCH & TECHNOLOGY
DOI: 10.14005/j.cnki.issn1672-7673.20230912.001

Title

Performance Study of the Laser Energy Measurement System for LHAASO-WFCTA

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Abstract

The Large High Altitude Air Shower Observatory (LHAASO) is located at Haizi Mountain, Daocheng County, Sichuan Province, at an average altitude of 4,410 meters. The laser calibration system is a vital component of the Wide Field-of-view Cherenkov Telescope Array (WFCTA) in LHAASO, utilized to calibrate the absolute gain of WFCTA for received photons. The energy measurement system in the laser calibration system comprises an energy sensor, an energy meter, and a temperature control system, primarily employed to precisely measure the energy of pulsed laser beams emitted into the WFCTA field of view. This paper focuses on the relative calibration and performance characterization of the energy sensor, and proposes a temperature control system to ensure the sensor's normal operation in the harsh plateau environment. The accuracy of laser pulse energy measurement can be improved through relative calibration among sensors. Performance test results demonstrate that the non-uniformity is less than 1.5% within a circular area of 8 mm diameter centered on the energy sensor. The incident angle of the laser beam has negligible impact on pulse energy measurement, but the reflection from the sensor can damage the laser when the beam is vertically incident, making it crucial to avoid normal incidence. Furthermore, the energy sensor exhibits a strong temperature effect. Therefore, an independent temperature control system was developed to maintain stable operation, fulfilling experimental requirements. These studies provide the foundation for the regular operation of the laser calibration system.

Keywords: Laser energy measurement; LHAASO; Relative calibration; Non-uniformity; Temperature control system

1. Introduction

The Large High Altitude Air Shower Observatory (LHAASO) is a national major scientific infrastructure focused on cosmic ray observation research, consisting of three detector arrays: the Kilometer Square Array (KM2A), the Water Cherenkov Detector Array (WCDA), and the Wide Field-of-view Cherenkov Telescope Array (WFCTA)[1–3]. WFCTA comprises 18 wide-angle Cherenkov telescopes distributed around the periphery of LHAASO, primarily used to precisely measure cosmic rays in the energy range of 10^{14}–10^{18} eV[4]. The laser calibration system is an essential component of WFCTA, used to calibrate the absolute photon count received by the Cherenkov telescope array.

We have constructed two laser calibration systems. One uses a solid-state Nd:YAG laser at 355 nm, while the other uses a mobile N_2 laser at 337.1 nm (not shown in the figure). During operation, lasers in the calibration room emit beams at specific angles into the WFCTA field of view. When laser beams pass through the telescope's field of view, a portion of photons are scattered by atmospheric molecules and aerosols, then received and recorded by the telescopes[5–6]. By comparing laser events with the photon count entering the telescope field of view, we can achieve absolute calibration. The photon count entering the field of view can be calculated using Rayleigh and Mie scattering models, making accurate measurement of the laser's initial pulse energy critically important.

2. Energy Measurement System

The energy measurement system primarily consists of three components: an energy sensor, an energy meter, and a temperature control system [FIGURE:1(b)]. The energy sensor and meter are pyroelectric sensors and Ethernet adapters manufactured by Ophir (model PE25-C). During measurement, the laser pulse is absorbed by the PE25-C sensor's receiving surface and converted into heat. The pyroelectric crystal generates polarized charges at both ends when heated[7], producing a voltage signal that is detected by the energy meter and converted into a laser pulse energy value stored on the server.

[Figure 1: see original paper] shows the layout of LHAASO and a schematic diagram of the energy measurement system. In the figure, the star marks the position of the laser calibration room, while the distances from WFCTA to the calibration room are 465 m, 650 m, and 1 km respectively. The diagram illustrates how the energy sensor connects to the energy meter, with data stored in the server. In the temperature control system, the sensor housing uses aluminum alloy, with gray representing the shell, blue and black representing insulation and heating layers respectively. A temperature probe attached to the energy sensor provides real-time feedback on the environmental temperature.

3. Relative Calibration of Energy Sensors

We performed relative calibration and performance testing on the energy sensors. Performance tests included measurements of sensor non-uniformity, response to different laser incident directions, and temperature effects on both sensors and meters. Relative calibration among sensors improves laser energy measurement accuracy.

During WFCTA calibration experiments, we implemented strict measures to ensure accurate measurement of laser pulse energy. The laser is mounted on a 3D rotating platform, allowing precise adjustment of emission direction. Before calibration, we fix the platform at a specific position. On clear nights during WFCTA operation, we first preheat the laser for 30 minutes to ensure stability, then elevate the platform and emit laser pulses into the telescope field of view by rotating horizontally and vertically. After telescope operation ends, the platform returns to its original position and we repeat the laser pulse energy measurement. Due to potential pointing errors in the 3D platform[5], the incidence point and direction on the sensor may vary slightly between observations, necessitating measurement of sensor surface non-uniformity and directional response deviations.

Using a standard laser from the National Institute of Metrology (NIM), we calibrated the energy sensors. Table 1 shows the relative calibration results, where the star denotes the standard sensor. The correction factor for sensor S/N: 942580 is 0.985 with associated uncertainty. Different sensors measuring the same laser show variations, with relative calibration coefficients of 0.986 and 0.965 respectively, demonstrating that relative calibration significantly improves measurement accuracy.

4. Performance Testing

4.1 Non-uniformity of Energy Sensor Receiving Surface

To measure sensor non-uniformity, we used the NIM standard laser. The test laser had properties shown in Table 2. We selected measurement positions on the sensor with 4 mm center-to-center spacing and 3 mm spot diameter. By recording energy readings and monitor ratios at each position, we calculated non-uniformity as (R_{max} - R_{min})/R_{avg}, where R represents monitor ratios.

Results show that within a 16 mm diameter circle centered on the sensor, non-uniformity is 2.8%. Within an 8 mm diameter circle, non-uniformity improves to 1.5%. Table 3 presents non-uniformity data for different sensors at wavelengths of 532 nm and 1064 nm, showing values of 1.4%, 1.1%, 2.2%, and 2.8% for five-position measurements, and 1.2%, 1.5%, 2.3%, and 2.7% for nine-position measurements. We also tested with a 337 nm laser, yielding 0.53% non-uniformity within the 8 mm circular region.

4.2 Response to Different Incident Directions

The sensor's receiving surface is metallic with reflectivity of 0.8%. When laser beams are vertically incident, light can reflect back and forth between the laser output and sensor, causing artificially high readings and potentially damaging the laser. Therefore, we always maintain an oblique incidence angle.

To quantify directional response, we fixed the sensor on a rotation stage, centered the beam on the receiving surface, then varied the incident angle (positive for counterclockwise, negative for clockwise) [FIGURE:3(a)]. Results show that within the -5° to 5° range, different incident angles cause less than 0.37% measurement deviation, confirming negligible angular dependence. However, vertical incidence must be avoided to prevent back-reflection damage.

5. Temperature Effects and Control System

5.1 Temperature Effects

Pyroelectric materials exhibit not only the primary pyroelectric effect but also secondary effects from thermal expansion[9]. Environmental temperature changes cause charge generation through thermal expansion/contraction, making temperature effects inevitable in pyroelectric sensors.

At the LHAASO site, temperatures vary dramatically from -20°C to 15°C. Figure 4 shows temperature variations inside and outside the calibration room during the 2022-2023 observation season, with indoor temperatures ranging from -10°C to 15°C and outdoor from -20°C to 10°C.

In temperature effect experiments, we placed the sensor in a temperature-controlled chamber while keeping the laser at constant temperature outside [FIGURE:5(a)]. Results show the sensor's temperature coefficient is -5.7×10^{-3}/°C, causing a 1.5% decrease in measured pulse energy when temperature drops from 20°C to -15°C, demonstrating strong temperature dependence. In contrast, the energy meter's temperature coefficient is only 3.5×10^{-5}/°C, with a 0.015% increase over the same range, making its temperature effect negligible.

5.2 Temperature Control System Design

To ensure stable sensor operation and mitigate temperature effects, we developed a dedicated temperature control system consisting of a thermotank, temperature controller, and silicon-controlled voltage regulator [FIGURE:6(a)]. The thermotank is an 180 mm × 100 mm × 180 mm aluminum alloy chamber with internal insulation and heating layers. The insulation layer minimizes heat loss while the heating layer provides warmth[10].

During operation, a temperature probe monitors the internal temperature and feeds data to the PID controller, which outputs 4–20 mA control current to the voltage regulator. The regulator then supplies 0–220 V to the heating layer, maintaining temperature at (20 ± 0.5)°C. Even with outdoor temperatures varying from -20°C to 10°C, the thermotank maintains stable conditions [FIGURE:6(b)]. Based on the temperature coefficient, this control reduces temperature-induced measurement error to just 0.05%, effectively eliminating temperature effects on laser pulse energy measurement.

6. Conclusion

Using a standard energy sensor (S/N: 942580) as reference, we performed relative calibration of all sensors in the energy measurement system, significantly improving measurement accuracy. Performance tests demonstrated that within an 8 mm diameter circle centered on the sensor, non-uniformity is less than 1.5%, and incident angle effects are negligible. Temperature effect studies revealed strong temperature dependence in sensors but negligible effects in energy meters. We therefore designed and implemented a temperature control system that maintains sensors at (20 ± 0.5)°C, reducing temperature-induced errors to 0.05% and ensuring reliable operation in LHAASO's harsh high-altitude environment. These studies provide the essential foundation for the regular operation of the WFCTA laser calibration system.

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Note: Figure translations are in progress. See original paper for figures.