PROCEEDINGS OF SCIENCE

Precise Laser Energy Measurement for the Calibration of LHAASO-WFCTA

Huimin Yang,[a] **Qinning Sun,**[b] **Yang Wang,**[a] **Long Chen,**[a] **Yong Zhang,**[b,c] **Fengrong Zhu**[a,†] **and Min Jin**[a,*]

[a] *Southwest Jiaotong University, School of Physical Science and Technology, No.999, Xi'an Road, Chengdu, 611756, China*
[b] *Key Laboratory of Particle Astrophysics Experimental Physics Division Computing Center, Institute of High Energy Physics, Chinese Academy of Sciences, 19B Yuquan Road, Beijing, 100049, China*
[c] *TIANFU Cosmic Ray Research Center, Institute of HighEnergy Physics, Chinese Academy of Sciences, 1500 Kezhi Road, Chengdu, 610000, China*

E-mail: zhufr@home.swjtu.edu.cn

The Large High Altitude Air Shower Observatory (LHAASO) is a major scientific research facility focused on cosmic ray observation. The entire array consists of four types of detector arrays, one of which is the Wide Field-of-view Cherenkov Telescope Array (WFCTA). The WFCTA is designed to achieve precise measurements of the cosmic ray energy spectrum across the range of 1013 eV to 1018 eV. A pivotal component of the Cherenkov telescope is its laser calibration system, which currently comprises five fixed laser units employing an end-to-end calibration method to ascertain the calibration coefficients for individual telescopes in response to photon detection. This paper elucidates the results of the relative calibration and performance testing of the energy sensor, which underpin the routine operation of the laser calibration system.

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*Speaker

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1. Introduction

The Large High Altitude Air Shower Observatory (LHAASO), located on Haizi Mountain in Daocheng County, Sichuan Province, at an average elevation of 4,410 meters, represents a significant advancement in cosmic ray research. The core scientific goal of the Large High Altitude Air Shower Observatory (LHAASO) is to explore the origin of high-energy cosmic rays, as well as the associated studies on cosmic evolution, high-energy astrophysical phenomena, and dark matter. It is primarily composed of three types of 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]. Among these, the WFCTA measures Cherenkov light or fluorescence generated in the atmosphere when high-energy cosmic rays or gamma rays pass through and induce air showers. By combining data from other arrays, it can accurately measure the cosmic ray components in the energy range from 10^{13} to 10^{18} eV [4]. Central to the operation of the WFCTA are the laser calibration systems (LCS), which are strategically distributed around the edges of the LHAASO site. The laser calibration system consists of seven key components: a laser source, a temperature control system for the laser, an energy measurement system, a three-dimensional lift and rotation platform, a timing system, a standard zero-point monitoring system, and a control unit. As of November 2022, five LCS units have been established at the site, as shown in Figure 1. Among these units, three nitrogen laser devices, each operating at a wavelength of 337.1 nm, are positioned in locations L2, L4, and L5. In addition, a single Nd:YAG laser device with a wavelength of 355 nm is located in L3, while L1 situated outside the main LHAASO facility[5,6].

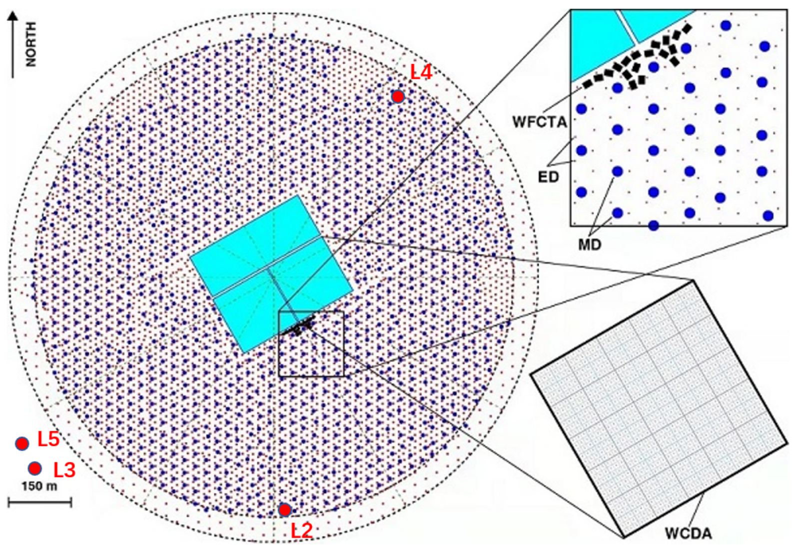

Figure 1: Schematic representation of the LHAASO layout, highlighting the positions of the laser calibration systems (LCS) denoted by circle. Specifically, the locations L2, L3, L4, and L5 are positioned at distances of 465 m, 1000 m, 650 m, and 1000 m from the WFCTA, respectively.

The entire laser calibration system utilizes a laser source in the laser calibration chamber to emit laser pulses at specific angles toward the field of view of the Wide Field-of-view Cherenkov

Telescope Array. As the laser pulse passes through the telescope's field of view, some photons are scattered by air molecules and aerosols in the atmosphere, and these data can be detected and recorded by the telescope [7, 8]. By comparing the recorded laser events with the number of photons entering the telescope's field of view, we can achieve absolute calibration of the telescope. The number of photons entering this field can be calculated using Rayleigh and Mie scattering models, highlighting the importance of accurately measuring the initial pulse energy of the laser. The energy measurement system is crucial for precisely determining this initial pulse energy. In this paper, we present a relative calibration and energy testing of the energy sensor. The energy testing focuses on the sensor's response to laser beams incident at various angles. Additionally, the experiment involved enhancements to the previous relative calibration method and the identification of other factors affecting energy measurements. Our findings indicate that relative calibration among energy sensors can significantly minimize measurement errors, particularly when utilizing sensors from different production batches. It is also crucial to acknowledge that during calibration, the non-uniform response of the energy sensor to laser beams at varying angles should not be overlooked.

2. The relative calibration of energy sensor

In this experiment, we used standard energy probes sourced from the Chinese Academy of Metrology, comprising a total of five standard energy probes. Detailed performance specifications are outlined in Table 1. During the initial phase of the experiment, we selected the L5 laser for energy measurements, with the standard probe designated as 942580, originally numbered 3055763. The testing procedure involved several steps: preheating, replacing the standard energy probe, resetting the system, conducting tests, reverting to the original probe, resetting again, and repeating the process. This cycle was performed three times, after which the system was returned to its original state. Following the experimental trials, we analyzed the data and generated Figure 2. By examining phases 1 and 3 in conjunction with the testing procedure, we concluded that the reset operation halted the laser's function and initiated a new preheating cycle. This insight prompted improvements for subsequent experiments. Moreover, further analysis of phase 2, as illustrated in Figure 3, revealed that changing the laser energy probe also altered the probe's position and the angle of light incidence. Consequently, the average values derived from the same probe varied. This finding underscored the necessity of accurately determining the probe's orientation during the experiment. To resolve this issue, we developed a probe positioning method as part of our design enhancements.

Table 1: Relative calibration and non-uniformity of energy sensors

Number	Relative calibration	Non-uniformity
942580	0.94	±1.04%
3134373	0.962	±2.06%
3134377	0.96	±2.06%
3138254	0.988	±1.52%
3138256	0.97	±1.02%

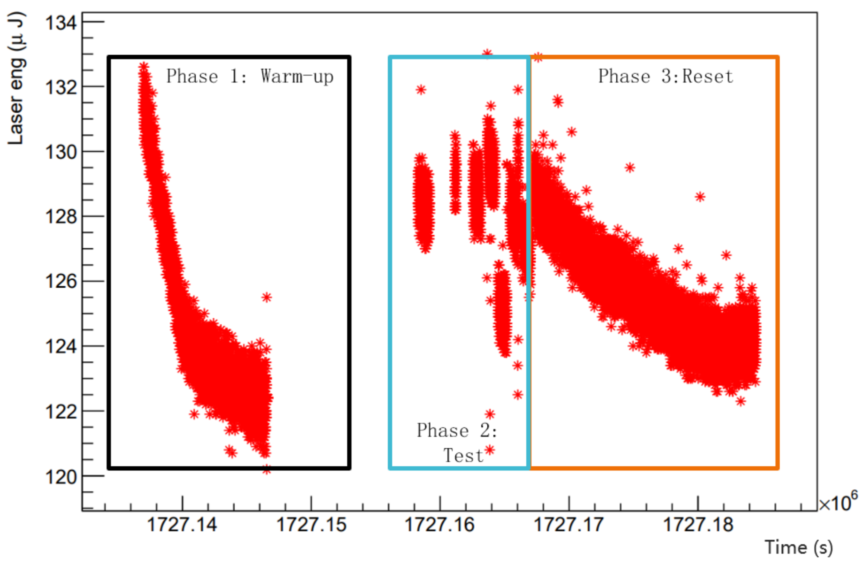

Figure 2: Energy measurement for the L5 laser, categorized into three phases: warm-up, testing, and reset.

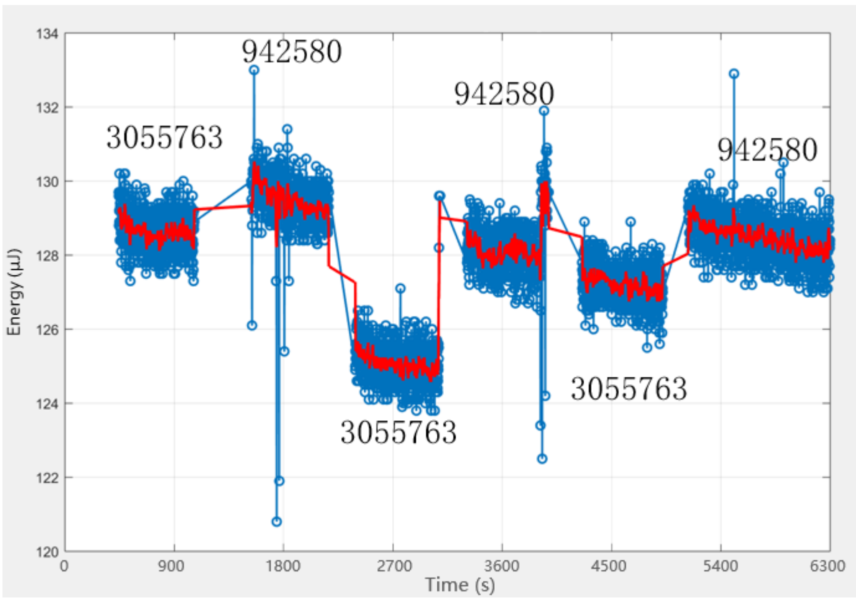

Figure 3: Three sets of tests conducted in Phase 2. The numbers in the figure correspond to the respective probe numbers. The red line in the center represents the average energy measured per minute.

The specific methodology involves initially securing a laser light source and directing the laser beam toward the energy probe. The laser beam is reflected off the probe's mirrored surface, creating a reflected light spot on the wall. This spot serves as the reference point for establishing the height and position of the probe. When replacing the probe, the angle is adjusted so that the reflected light spot aligns with the reference point once again. This ensures that both the angle of incidence and the position of the light remain consistent with those of the prior measurement. This method was subsequently employed to conduct a series of replacement experiments. The results indicated that the average interpolation value of energy from the two tests was less than 0.5 μJ, significantly improving upon the previous experimental error. Subsequently, it was observed that the 942580 probe displayed several data points markedly lower than the anticipated values during measurements, suggesting inadequate energy resolution. Consequently, prior to the formal experiment, a preliminary assessment was conducted on the remaining standard probes to eliminate those with subpar energy resolution. Figure 4 presents the experimental outcomes of this evaluation. The findings revealed that, with the exception of probe 3138256, all other probes demonstrated satisfactory energy resolution. Thus, three standard probes were ultimately selected for the formal experimentation.

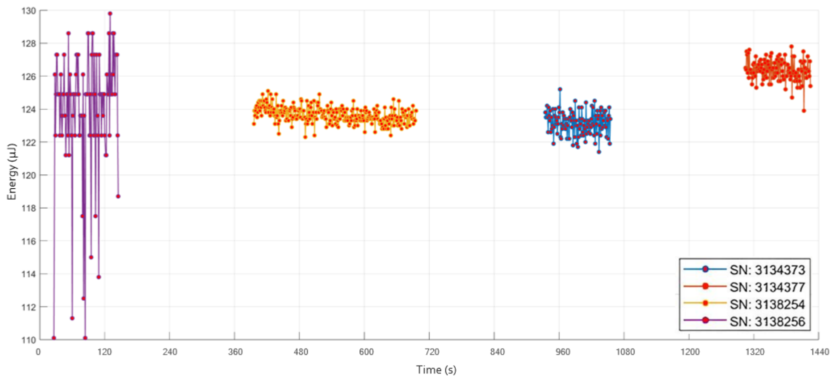

Figure 4: Experimental results of the remaining four standardized probes, each identified by its corresponding number.

In the formal experiment, standardized probes obtained from the Metrology Institute were uniformly employed for calibration purposes. Utilizing the established reference point, the laser was consistently directed to the same orientation and position each time the energy probe was replaced, thereby ensuring uniform energy input to the probe. Each test was conducted over a duration of 2 minutes per set, with each probe undergoing two sets of measurements. This paper primarily focuses on the energy calibration results for three nitrogen molecular lasers, designated as L2, L4, and L5, while the YAG laser located at the L3 station is not addressed. The subsequent table provides a summary of the data collected during this experiment.

Table 2: L2 site calibration results

Number	Measured pulse (µJ) energy	Relative calibration	Calibration pulse (µJ) energy
3134373	126.05	0.962	121.26
3134377	129.6	0.96	124.41
3138254	126.35	0.988	124.83
940574	137.6	——	——(Original probe)

Table 3: L4 site calibration results

Number	Measured pulse (µJ) energy	Relative calibration	Calibration pulse (µJ) energy
3134373	121.75	0.962	117.12
3134377	125.9	0.96	120.864
3138254	122.7	0.988	121.2276
946780	130.1	——	—— (Original probe)

Table 4: Calibration Results for the L5 Site

Number	Measured pulse (µJ) energy	Relative calibration	Calibration pulse (µJ) energy
3134373	123.9	0.962	119.19
3134377	126.95	0.96	121.872
3138254	123.9	0.988	122.413
3055763	127.35	——	—— (Original probe)

The data obtained from probes 3134377 and 3138254, after being adjusted by their respective relative calibration coefficients, were found to be relatively close in value. In contrast, when probe 3134373 was multiplied by its calibration coefficient, it continued to exhibit discrepancies compared to the other two probes. However, the correlation among the measurements from the three probes across the three stations remained consistent. Taking all factors into account, probe 3134377 was ultimately selected for the final energy calibration of the lasers at the station sites. The relative calibration coefficients for the original probes at the L2, L4, and L5 stations were established as 0.90, 0.92, and 0.96, respectively.

3. The non-uniformity response of the energy sensors to laser beams at varying angles

Building upon previous experiments that demonstrated the influence of incidence angle on energy measurements obtained from the energy probe, a follow-up investigation was undertaken to further explore the effects of angular variation on these measurements. Utilizing the same nitrogen molecular laser, this experiment incorporated a preheating duration of two hours. The energy probe was affixed to a rotating base equipped with angular scales, allowing for sequential adjustments of the angle. For each specified angle, energy was recorded over a duration of three minutes. The resulting energy-angle relationship is depicted in Figure 5(b), while the experimental configuration is illustrated in Figure 5(a). The findings indicated that maximum energy measurement was achieved when the energy was incident perpendicularly to the probe. As the angle of incidence was varied slightly, a pronounced decrease in measured energy was observed, followed by a gradual change at a reduced rate. This behavior corroborates the results from prior experiments. Consequently, it is imperative that future investigations prioritize precise angular alignment of the probe to enhance measurement accuracy.

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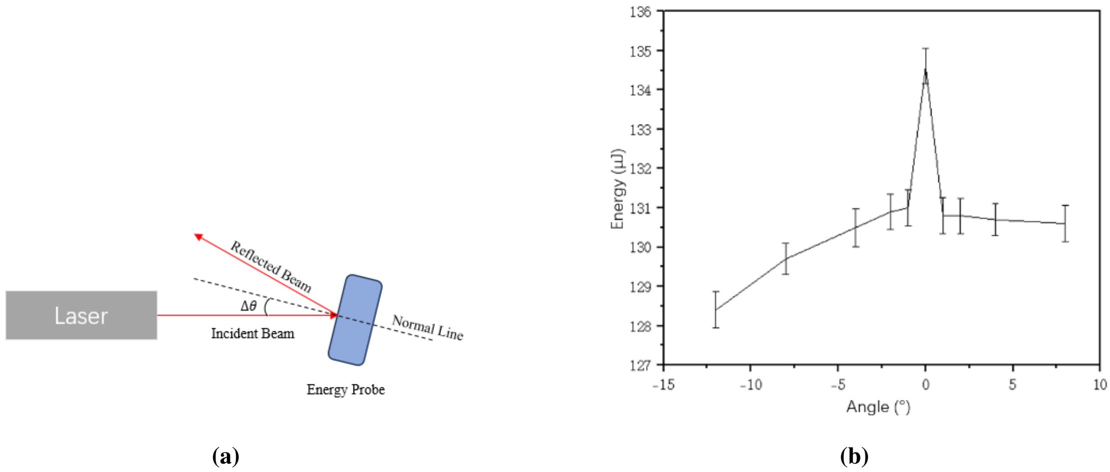

Figure 5: Experimental setup illustrating the relationship between the incidence angle of the laser beam and the corresponding readings from the energy sensor.

4. Summary

This paper presents an energy measurement system for laser calibration systems and details the results obtained from relative calibration and performance testing of the energy sensor employed within the system. By performing relative calibration among multiple energy sensors, we were able to mitigate the measurement errors associated with laser energy assessments across different sensor batches. In conclusion, this study further refines the calibration process established in earlier work. Moreover, it was observed that the energy probe's response to laser beams incident at varying angles is a significant factor that cannot be overlooked. The experimental findings of this investigation also offer valuable insights for the analysis of laser calibration experimental data.

5. Acknowledgments

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