Postprint: Performance Study of a 3D Lifting and Rotating Stage in Imaging LiDAR Calibration System

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Abstract

The three-dimensional lifting and rotating platform is a core component of the imaging lidar calibration system for the Wide Field-of-view Cherenkov Telescope Array (WFCFA) at the Large High Altitude Air Shower Observatory (LHAASO), primarily consisting of a slow control subsystem, a mechanical subsystem, and a standard zero-point subsystem, used for precisely controlling the emission direction of the laser beam. This paper employs high-precision digital image processing techniques to study the performance of the three-dimensional lifting and rotating platform, with results indicating that its rotational and lifting positioning accuracies are 0.005° and 0.056 mm respectively, and repeatability accuracies are 0.003° and 0.075 mm respectively, meeting the experimental requirements of the imaging lidar calibration system. The automatic control and cruising function of the three-dimensional lifting and rotating platform effectively reduces manual intervention and enhances the reliability and efficiency of remote system operation. The calibration function of the standard zero-point can effectively monitor the positioning accuracy of the three-dimensional lifting and rotating platform and, in case of misalignment, enables remote calibration to ensure its long-term high-precision and stable operation.

Full Text

Performance Study of a Three-Dimensional Rotating and Lifting Platform in an Imaging Lidar Calibration System

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Abstract

The three-dimensional rotating and lifting platform (RLP) is the core component of the imaging lidar calibration system for the Wide Field of View Cherenkov Telescope Array (WFCTA) of the Large High Altitude Air Shower Observatory (LHAASO). The RLP consists primarily of a programmable logic controller (PLC) subsystem, a mechanical subsystem, and a standard zero subsystem, designed to precisely control the beam pointing of the imaging lidar system. This paper employs a high-precision digital image processing method to investigate the performance of the RLP. Our results reveal that the rotational and lifting positioning accuracies are 0.005° and 0.056 mm, respectively, while the corresponding repeatabilities are 0.003° and 0.075 mm. These outcomes fulfill the experimental requirements for the calibration system. The automatic cruise function of the RLP not only minimizes manual intervention but also improves both the reliability and efficiency of remote operation. The standard zero calibration function enables effective monitoring of the RLP' s positional accuracy and implements remote calibration in case of misalignment, thereby ensuring long-term stable operation with high precision.

Keywords: three-dimensional rotating and lifting platform; PLC; digital image processing method; standard zero; automatic cruise function

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The Large High Altitude Air Shower Observatory (LHAASO) is a national major scientific infrastructure focused on cosmic ray observation research. The Wide Field of View Cherenkov Telescope Array (WFCTA), one of LHAASO's primary detectors, comprises 18 wide-field Cherenkov light telescopes with the main scientific objective of measuring the energy spectrum of cosmic ray components from 10^{13} eV to 10^{18} eV. The telescopes infer the energy and composition of primary cosmic rays by measuring fluorescence or Cherenkov light produced by charged particles in extensive air showers. To obtain accurate primary cosmic ray energies, absolute calibration of the photon count received by the telescopes is required.

The imaging lidar calibration system is a precision optical calibration system that achieves end-to-end calibration through the coordinated operation of a laser source, laser pointing device, laser receiving device, and auxiliary components. As the transmitting end, the laser pointing is controlled by the three-dimensional rotating and lifting platform. N_0 photons emitted by the laser enter the atmosphere, undergo Rayleigh and Mie scattering, and N_1 photons are subsequently received by the WFCTA reflector, forming an image of the laser event on the silicon photomultiplier array at the focal plane. Absolute calibration of the telescope is realized by comparing the photoelectron count from the laser event with N_1. This end-to-end laser calibration method imposes clear precision requirements on the three-dimensional rotating and lifting platform: the pointing accuracy must be less than 0.05°.

The Pierre Auger Observatory' s fluorescence telescope detector employs a similar laser calibration system, consisting of a laser source and mirrors on two orthogonal rotation axes that can direct the laser beam to any direction above the horizon, including vertical. The absolute pointing accuracy of the vertical beam is 0.04°, the scanning absolute pointing accuracy is 0.2°, and the relative pointing accuracy is 1/80°. The High Resolution Fly' s Eye detector, comprising HiRes1 and HiRes2 telescopes, uses atmospheric fluorescence technology to detect ultra-high-energy cosmic rays. Its laser scanning system consists of a laser and a series of rotatable optical mirrors, achieving absolute pointing accuracy of less than 0.1° in any direction, horizontal relative pointing accuracy of 0.03°, and pitch direction relative pointing accuracy of 0.005°. The laser scanning system used by two WFCTA prototypes operating at the Yangbajing Cosmic Ray Observatory can point to any direction above the horizon with angular resolution better than 0.1°.

In the LHAASO-WFCTA imaging lidar calibration system, the PLC-controlled three-dimensional rotating and lifting platform can precisely control the laser beam direction and enables automatic cruise control across the entire sky region. Experimental measurements yield the following parameters: for horizontal rotation, positioning accuracy of 0.005°, repeatability of 0.003°, and backlash error of 0.013°; for pitch rotation, positioning accuracy of 0.004°, repeatability of 0.003°, and backlash error of 0.087°; for lifting motion, positioning accuracy of 0.056 mm, repeatability of 0.075 mm, and backlash error of 0.200 mm. These results demonstrate that the platform' s pointing accuracy meets the requirements of LHAASO-WFCTA laser calibration and atmospheric monitoring experiments, provides a basis for accurate automatic cruise operation, and ensures long-term stable performance when combined with standard zero monitoring and calibration.

2. Design and Composition

LHAASO is located at Haizi Mountain in Daocheng County, Sichuan Province, at an average altitude of 4410 m on the edge of the Tibetan Plateau, where weather conditions change rapidly. Based on the field environment at the LHAASO site and laser calibration requirements, an imaging lidar calibration system was designed with the three-dimensional rotating and lifting platform as its key component. The overall layout of the platform is shown in [Figure 1: see original paper], consisting primarily of three parts: the PLC subsystem, the mechanical subsystem, and the standard zero subsystem.

(1) PLC Subsystem: The programmable logic controller (PLC) implements programmable logic control of the three-dimensional rotating and lifting platform, ensuring stable execution of all-day cruise tasks while simultaneously storing operational status and environmental information to a local computer in real time. An Actel FPGA control chip drives the stepper motors controlling the platform, with high-precision encoder feedback enabling closed-loop control. The FPGA connects to the local computer via RS422 for remote operation. The PLC supports 20 different automatic cruise schemes, each configurable for multi-angle scanning, with the ability to switch between schemes during operation. The PLC control software achieves precision better than 0.01°, which provides the basis for precision settings in the independently developed image processing software used for standard zero calibration.

(2) Mechanical Subsystem: This subsystem mainly comprises the three-dimensional rotating and lifting platform and a flip-cover door. The platform consists of a horizontal motorized rotational stage (0–360°, Figure 2: see original paper), a pitch motorized rotational stage (-10° to 90°, with horizontal defined as 0°, Figure 2: see original paper), and a motorized lifting stage (0–510 mm, Figure 2: see original paper). The center load capacities are 100 kg, 50 kg, and 45 kg, respectively, with all components constructed from aluminum alloy. Detailed specifications are provided in . The flip-cover door automatically opens before automatic cruise operation and closes afterward, protecting the three-dimensional rotating and lifting platform and the laser.

(3) Standard Zero Subsystem: This subsystem consists primarily of a CCD camera, 0.01% attenuator, coordinate paper, and other components for daily monitoring and calibration of the platform' s pointing direction.

3.1 Digital Image Processing Technology

To investigate the platform' s performance characteristics, including positioning accuracy, repeatability, and two-dimensional angle, we employed a high-precision digital image processing technique. First, as shown in Figure 3: see original paper, the experimental setup was constructed: a He-Ne laser with stable pointing and Gaussian intensity distribution, fixed atop the three-dimensional rotating and lifting platform, served as the light source, projecting its spot onto coordinate paper at distance L. To prevent image overexposure and stray light effects, the CCD camera required a 0.01% attenuator in front of its lens and imaged the spot in a dark room. Second, the CCD camera was calibrated: photographs were used to calculate the ratio K between pixel length in the image and physical length on the coordinate paper (units: m/pixel), enabling determination of the spot' s precise position on the coordinate paper, as shown in Figure 3: see original paper. The intensity distribution of the spot projected onto the horizontal coordinate yields the spot' s central horizontal coordinate x through Gaussian function fitting of the mean value, with similar processing applied to obtain the vertical coordinate. Finally, the platform' s rotation angle was calculated: platform rotation causes a displacement Δx of the spot center, which can be converted to angular displacement through geometric relationships. The measurement precision of this technique depends on factors including the distance L between the light source and coordinate paper, the distance d between the CCD camera and coordinate paper, and the pointing stability of the laser source. As shown in Figure 3: see original paper, when L = 214.5 cm and d = 35.6 cm, processing 153 spot images yielded measurement precisions of 0.0009° in the horizontal direction, 0.0009° in the pitch direction, and 0.041 mm in the lifting direction, satisfying the experimental precision requirements for the three-dimensional rotating and lifting platform design specifications.

LxKΔ

3.2 Performance of the Three-Dimensional Rotating and Lifting Platform

The above technique was used to measure the platform's performance, characterized by parameters including backlash error, positioning accuracy, repeatability, and two-dimensional angle. The measurement process utilized five variables: Δ (rotation angle set by the PLC software), $\Delta\phi$ (actual rotation angle), $\Delta\omega$ (feedback value from the encoder on the stepper motor), Δz (lifting displacement set by the PLC software), and Δz (actual lifting displacement). Experimental measurements were conducted for Δ = 0.01°, 0.04°, 0.10°, 0.15°, 0.20°, 0.25°, 0.30°, 0.35°, 0.40°, 0.45°, and 0.50°. When Δ ≥ 0.2°, Δ and $\Delta\omega$ were equal; when Δ < 0.2°, discrepancies occurred due to stepper motor missed steps or platform inertia.

Platform performance studies were conducted only when Δ and $\Delta\omega$ were equal. Therefore, the minimum control step size was set to Δ = 0.2° for both horizontal and pitch directions, and Δz = 2 mm for the lifting direction.

3.2.1 Backlash Error

The PLC software controls the three-dimensional rotating and lifting platform by first rotating a stage clockwise, then stopping (without any operation), and subsequently rotating counterclockwise. During this process, a gear gap exists, known as backlash. The same phenomenon occurs in the reverse sequence. As shown in [Figure 4: see original paper], the minimum control step size was set to 0.2° in the PLC software, with the horizontal direction set angle Δ as the horizontal axis and the actual rotation angle $\Delta\phi$ as the vertical axis. Linear fitting was applied to these coordinate points, where P_0 represents the intercept and P_1 represents the slope of the fitted line. A slope value closer to 1 indicates better consistency between Δ and $\Delta\phi$. In Figure 4: see original paper, the blue line shows the fitting result for counterclockwise data points in the horizontal direction, while the red line shows the fitting result for clockwise data points. The difference between the initial values P_0 of these two fitted lines represents the backlash error, measured as 0.004°. Similarly, Figure 4: see original paper shows a backlash error of 0.087° in the pitch direction. Figure 4: see original paper presents the backlash error in the lifting direction, measured as 0.20 mm with a motion step size of 2 mm. The linear relationships for all three directions are 0.99. Backlash error is a critical factor affecting the pointing accuracy of the three-dimensional rotating and lifting platform and must be considered when designing automatic cruise schemes.

3.2.2 Repeatability and Positioning Accuracy

Repeatability is expressed as the standard deviation (Std Dev) of the distribution of deviations ($\Delta\phi$-Δ) between multiple actual rotation angles $\Delta\phi$ and the set angle Δ , with similar definition for the lifting direction. In the experiments, the 0 (relative position) served as the initial set position, with the platform rotated to 20° or lifted to 40 mm before returning to the initial position. This process was repeated 29 times to determine the platform' s repeatability. As shown in [Figure 5: see original paper], the repeatability is 0.003° in both horizontal and pitch directions, and 0.058 mm in the lifting direction. The relative pointing accuracy of the three-dimensional rotating and lifting platform is 0.004°, meeting experimental requirements.

Positioning accuracy is defined as the mean value of deviations between multiple actual rotation angles $\Delta\phi$ and the set angle Δ (with similar definition for the lifting direction). Two test scenarios were conducted. The first scenario involved large-angle rotation: $\Delta = 20°$ and lifting displacement $\Delta z = 40$ mm. The positioning accuracy results are shown in [Figure 5: see original paper], with 0.005° in the horizontal direction, 0.002° in the pitch direction, and 0.058 mm in the lifting direction. The second scenario measured performance using the minimum control step size $\Delta = 0.2°$ in the horizontal and pitch directions and $\Delta z = 2$ mm in the lifting direction. The positioning accuracy was 0.002° in the horizontal direction, 0.002° in the pitch direction, and 0.022 mm in the lifting direction. When designing automatic cruise schemes, angles should be minimized but must exceed the minimum control step size.

3.2.3 Two-Dimensional Angle

In LHAASO-WFCTA imaging lidar calibration experiments, the PLC controls the three-dimensional rotating and lifting platform to scan the WFCTA field of view. The two-dimensional angle between the horizontal rotation plane and the pitch rotation plane must be precisely measured during cruise operation. If this angle deviates significantly from 90°, it will cause increased angular errors in either the horizontal or pitch direction. Using digital image processing technology, measurements were performed for both unloaded and loaded conditions. With the pitch angle maintained at 0°, the trajectory of the spot was recorded for horizontal rotation steps of 0.2°. Similarly, with the azimuth angle at 0°, the rotation trajectory in the pitch direction was obtained. The combined "cross" spot trajectory is shown in [Figure 6: see original paper], where the trajectory nearly parallel to the x-axis represents the intersection line between the horizontal rotation plane and the coordinate paper plane, and the trajectory nearly parallel to the y-axis represents the intersection line between the pitch rotation plane and the coordinate paper plane. Since the coordinate paper plane is perpendicular to both the horizontal and pitch rotation planes, the angle between the trajectories equals the angle between these two rotation planes. Fitting the measurement data for both horizontal and pitch directions yielded a two-dimensional angle of 89.96° ± 0.12° under no-load conditions (Figure 6: see original paper) and 89.68° ± 0.12° under loaded conditions (Figure 6: see original paper). The loaded two-dimensional angle value is applied in the laser calibration simulation program.

This experiment measured four three-dimensional rotating and lifting platforms located in the university laboratory and the L2, L3, and L4 laser calibration laboratories at the LHAASO site. The measurement results for one unit are shown in , where the load (greater than 10 kg) refers to the laser and incubator on the three-dimensional lifting stage. These results demonstrate that the platform' s accuracy under loaded conditions remains consistent with that under no-load conditions.

4. Standard Zero Calibration and Long-term Monitoring

To determine the precise geographic pointing of the three-dimensional rotating and lifting platform, the standard zero is defined as the pointing direction at a specified lifting height, true north orientation, and level pitch. A level with 0.02 mm/m resolution was used to adjust the levelness of the platform support frame and the three-dimensional rotating and lifting platform: first, the support frame was leveled, then the three-dimensional rotating and lifting platform was adjusted from bottom to top to ensure the initial pitch direction was level (pitch angle = 0°). The solar shadow method was employed to determine geographic true north, defined as 0°, with true east as 90°, simultaneously establishing the initial horizontal direction angle as 0° for the three-dimensional rotating and lifting platform. A lifting position of 60 mm above the lowest position was designated as the initial lifting position.

Long-term operation of the three-dimensional rotating and lifting platform may cause deviations in the initial pointing. To avoid frequent on-site calibration, a standard zero monitoring system was developed. This system employs the same digital image processing technology described in [Figure 3: see original paper] to calibrate the standard zero position by determining the laser spot location. A nitrogen laser serves as the light source, with a self-developed image processing software calculating the spot position in real time. The deviation of the three-dimensional rotating and lifting platform' s initial direction angle is determined by comparing this position with the standard zero position. When the horizontal deviation angle $\Delta\alpha$ is less than 0.01° and the pitch deviation angle $\Delta\beta$ is less than 0.01°, the position is considered the standard zero. Otherwise, the PLC software fine-tunes the platform pointing until the standard zero is achieved. The standard zero calibration process is illustrated in the flowchart [Figure 7: see original paper].

The nitrogen laser spot position represents the average of 20 laser pulse positions, yielding a spot position accuracy of 0.004° in the horizontal direction and 0.0003° in the pitch direction, which satisfies experimental requirements. Long-term monitoring results for the standard zero are shown in [Figure 8: see original paper], where red triangles represent horizontal deviations $\Delta\alpha$ and black triangles represent pitch deviations $\Delta\beta$. [Figure 8: see original paper] presents continuous monitoring results over 45 days, during which 14 days required no zeroing operation while 31 days necessitated standard zero calibration.

5. Automatic Control Cruise

To meet the requirements of LHAASO-WFCTA laser calibration and atmospheric monitoring, the laser beam must scan the field of view of each telescope during WFCTA operation. To address frequent errors in manual laser beam pointing control during long-duration, multi-angle operations, an automatic cruise scheme using PLC control of the three-dimensional rotating and lifting platform was implemented. This scheme enables fully automatic operation and increases field-of-view scanning time.

First, based on the positions of the three-dimensional rotating and lifting platform and each telescope, along with the telescope pointing directions, the required angles for platform calibration and monitoring of each telescope were determined. Second, to avoid backlash error effects, all cyclic rotation angles in the cruise scheme follow an ascending order: a fixed pitch angle is set, horizontal scanning is performed from small to large angles, then the platform moves to the next larger pitch angle and repeats the horizontal scanning process, continuing cyclically. Each angle position requires a dwell time to reduce vibrations caused by platform rotation and to allow sufficient time for telescope data acquisition. Finally, the single-cycle time is controlled within 20 minutes to meet atmospheric monitoring requirements.

To ensure consistent initial pointing for each laser cruise, standard zero calibration and monitoring must be performed before initiating the automatic control cycle. The three-dimensional rotating and lifting platform then ascends from the initial position to the laser emission position to begin the automatic cycle. After telescope observation concludes, the automatic cycle terminates and the platform returns to the initial position, completing the cruise. During cruise operation, the automatic cruise can be terminated at any time in case of unexpected circumstances such as extreme weather.

The measured performance parameters of the three-dimensional rotating and lifting platform—including positioning accuracy, repeatability, and backlash error—ensure pointing accuracy during automatic cruise operation.

6. Conclusions and Outlook

This paper addresses the high pointing accuracy and automatic cruise requirements of the LHAASO-WFCTA imaging lidar calibration system by designing and studying a three-dimensional rotating and lifting laser platform. A digital image processing technique was developed and applied to measure the platform' s performance parameters. Experimental results demonstrate rotational and lifting positioning accuracies of 0.005° and 0.056 mm, respectively, and rotational and lifting repeatabilities of 0.003° and 0.075 mm, respectively. These measurement results for positioning accuracy, repeatability, and backlash error provide the basis for accurate pointing control of the three-dimensional rotating and lifting platform via PLC automatic control. Furthermore, the application of standard zero calibration and monitoring in the imaging lidar calibration system ensures long-term laser pointing precision.

The three-dimensional rotating and lifting platform in the imaging lidar calibration system has achieved automatic control, meeting the precision requirements of LHAASO-WFCTA imaging lidar calibration experiments. This guarantees accurate measurement of absolute photon number calibration for LHAASO-WFCTA, LHAASO weather monitoring, and LHAASO aerosol distribution, providing valuable experience for other telescope observation experiments.

Future work will involve further analysis and monitoring of the three-dimensional rotating and lifting platform' s precision through studies of laser events observed by the telescopes.

References

[1] CAO Z, CHEN M, CHEN S Z, et al. Introduction to Large High Altitude Air Shower Observatory (LHAASO) [J]. Chinese Astronomy and Astrophysics, 2019, 43(4): 457-478.

[2] JI F, ZHANG J X, CHEN M J, et al. Water quality monitoring analysis based on WCDA [J]. Astronomical Research & Technology, 2020, 17(2): 252-257.

[3] WU W X, ZUO X, XIAO G, et al. The performance test of LHAASO-MD photomultiplier [J]. Astronomical Research & Technology, 2020, 17(2): 258-264.

[4] FICK B, MALEK M, MATTHEWS J, et al. The Central Laser Facility at the Pierre Auger Observatory [J]. Journal of Instrumentation, 2006, 1(1): 1-17.

[5] ABU-ZAYYAD T, Al-SEADY M, BELOV K, et al. The prototype high-resolution Fly' s Eye cosmic ray detector [J]. Nuclear Inst & Methods in Physics Research A, 2000, 450(2): 253-269.

[6] WIENCKE L R, GRAY R C, MUMFORD J R, et al. Steerable laser system for UV atmospheric monitoring at the High-Resolution Fly' s Eye [C]. Spies International Symposium on Optical Science. International Society for Optics and Photonics, 1999, 3818: 56–6.

[7] LIU J L, ZHU F R, JIA H Y, et al. A calibration of WFCTA prototype telescopes using N_2 laser [J]. Nuclear Instruments & Methods in Physics Research A, 2018, 877: 278-287.

[8] PI W X, HUANG M, ZHU F R, et al. Extinction coefficients of surface atmospheric aerosol above LHAASO [J]. Chinese Physics C, 2019, 43(8): 117-123.

[9] YE W R, SUN Z B, GENG B M. Three freedom degrees precision laser turntable control system based on FPGA [J]. Electronic Design Engineering, 2014, 22(11): 15-18.

[10] LÜ H K. LHAASO-KM2A electromagnetic particle detector wide dynamic range design and array calibration research [D]. University of Chinese Academy of Sciences, 2019.

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