Pointing Calibration Study for the HADAR Experiment

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Abstract

HADAR is an ultra-wide-angle atmospheric Cherenkov telescope that employs a water-lens optical system, offering significant advantages in detecting gamma-ray sources, including burst, transient, and extended sources. Given its implementation of an innovative transmissive optical technology, the precise pointing accuracy of both the telescope and imaging system is critical, as it directly influences the reconstruction accuracy of gamma-ray events based on Cherenkov light detection. Consequently, rigorous calibration is essential. In this study, we present a calibration method to determine the optical axis orientation of the HADAR imaging system. This method leverages the distinct signal variations observed in the imaging system's pixel units when bright stars transit through the water-lens field-of-view, thereby enabling the precise calibration of the telescope's geometric properties. Applying this method to the 0.9-meter HADAR prototype system, we analyzed the imaging characteristics induced by bright stars and performed an accurate calibration of the prototype's imaging system alignment. Our results confirm the effectiveness of this calibration approach. This technique will be further employed for the alignment and calibration of future large-aperture water-lens telescopes in the HADAR experiment.

Full Text

Pointing Calibration Study for the HADAR Experiment

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HADAR is an ultra-wide-angle atmospheric Cherenkov telescope that employs a water-lens optical system, offering significant advantages in detecting gamma-ray sources, including burst, transient, and extended sources. Given its implementation of an innovative transmissive optical technology, the precise pointing accuracy of both the telescope and imaging system is critical, as it directly influences the reconstruction accuracy of gamma-ray events based on Cherenkov light detection. Consequently, rigorous calibration is essential. In this study, we present a calibration method to determine the optical axis orientation of the HADAR imaging system. This method leverages the distinct signal variations observed in the imaging system's pixel units when bright stars transit through the water-lens field-of-view, thereby enabling the precise calibration of the telescope's geometric properties. Applying this method to the 0.9-meter HADAR prototype system, we analyzed the imaging characteristics induced by bright stars and performed an accurate calibration of the prototype's imaging system alignment. Our results confirm the effectiveness of this calibration approach. This technique will be further employed for the alignment and calibration of future large-aperture water-lens telescopes in the HADAR experiment.

Keywords: Water-lens, Imaging system, Bright star, Star trajectory

INTRODUCTION

Imaging Atmospheric Cherenkov Telescopes (IACTs) constitute a powerful technique for detecting very-high-energy (VHE) gamma rays by capturing atmospheric Cherenkov radiation. This approach relies primarily on telescope cameras to record images of Cherenkov light produced in the atmosphere. The IACT technique offers two key advantages: (1) it enables highly efficient gamma/hadron discrimination, significantly reducing interference from cosmic-ray (CR) background events; and (2) it employs stereoscopic imaging technology with high angular resolution, substantially enhancing the reconstruction accuracy of primary gamma-ray events.

IACTs can be broadly classified into two categories based on their optical system: reflective and refractive telescopes. Reflective IACTs are further divided into imaging and non-imaging types, depending on how they collect Cherenkov light. Imaging reflective Cherenkov telescopes position cameras at the focal plane of a mirror system to capture Cherenkov light, as demonstrated in experiments such as HEGRA [?], H.E.S.S. [?], MAGIC [?], VERITAS [?], and CTA [?]. These telescopes achieve high angular resolution but are often constrained by a limited field-of-view (FoV). Conversely, non-imaging reflective Cherenkov telescopes utilize the "wavefront sampling technique [?]," which employs an array of segmented mirrors with sub-meter apertures and high-speed electronics operating at sub-nanosecond precision to record Cherenkov light waveforms. By precisely measuring the arrival times of Cherenkov pulses at different detector units, these systems can reconstruct the trajectory of the primary particle. Additionally, pulse amplitude and spatial distribution provide further gamma/hadron discrimination. Notable experiments that have employed this technique include THEMISTOCLE [?] in France and the PACT [?] experiment in India.

The FoV is a critical parameter in astronomical observations, particularly in detecting gamma-ray sources such as bursts, transients, and extended sources. A broader FoV enhances the detection efficiency of such sources. To expand the FoV, researchers have explored lens-based refractive IACT technologies, exemplified by the GAW [?, ?] and JEM-EUSO [?, ?] experiments, which employ Fresnel lenses as their primary optical components. Fresnel lenses offer a large FoV and high transmittance in the near-ultraviolet to blue-light spectrum (290–430 nm). However, their fabrication is complex and costly, and their imaging performance degrades significantly at large off-axis angles.

In general, stereoscopic IACT technology offers several observational advantages, including high angular resolution, energy resolution, and effective gamma/hadron discrimination, making it particularly well-suited for studying gamma-ray sources with rapid temporal variations. However, its relatively narrow FoV (3.5° to 5.0°) and low duty cycle (< 10 %) limit its ability to observe multiple sources simultaneously, restricting its effectiveness for tracking burst, transient, and extended sources. In contrast, traditional Extensive Air Shower (EAS) arrays and water Cherenkov telescopes offer a wide FoV and all-sky monitoring capabilities. Nevertheless, these systems suffer from high energy thresholds and relatively poor gamma/hadron discrimination, angular resolution, and energy resolution in the sub-TeV energy range.

Inspired by the Fresnel lens concepts of the GAW and JEM-EUSO experiments, Chinese researchers have proposed an innovative ultra-wide FoV atmospheric Cherenkov telescope experiment based on water-lenses: the High Altitude Detection of Astronomical Radiation (HADAR). This novel IACT array employs refractive lenses to focus atmospheric Cherenkov light produced by CRs and gamma rays, enabling the detection of gamma-ray radiation in the energy range from 10 GeV to 10 TeV. The water-lens has a hemispherical structure and consists primarily of a glass (or acrylic) spherical shell with high transmittance in the blue-violet spectrum, filled with high-purity water. This design addresses the limitations of traditional reflective telescopes, including restricted FoV and degraded off-axis imaging performance, while offering advantages such as a large FoV, uniform imaging quality, and cost efficiency. Further details on the HADAR experiment can be found in Chen et al. [?], Xin et al. [?], Qian et al. [?], Yao et al. [?], and Zhang et al. [?].

The feasibility of the hemispherical thin-lens concept was validated in 2016 through the construction of a 0.9-meter diameter prototype, which successfully detected CR events [?, ?]. Future research will focus on scaling the technology to 2-meter and 5-meter hemispherical lenses.

In the HADAR experiment, the telescope's imaging capabilities are primarily determined by its geometric properties (e.g., structural configuration, pointing accuracy, and photomultiplier tube (PMT) array positioning) and optical parameters (e.g., focal length, image spot, and FoV). The physical placement of the PMT imaging system (i.e., the orientation of PMT pixels) determines the location of the Cherenkov light's image, necessitating precise calibration.

In this study, we propose a stellar-based calibration method to determine the telescope's geometric properties using ultraviolet-bright stars. While monitoring Cherenkov light from air showers, the telescope is also highly sensitive to stellar light passing through its FoV. Given their well-documented positions, stars serve as ideal reference sources for calibrating the telescope's pointing direction. Using the 0.9-meter prototype of the HADAR experiment, we analyzed the imaging characteristics of stellar light and performed a pointing calibration of the telescope. This method is expected to be applicable in future HADAR experiments.

The structure of this paper is as follows: Section II introduces the HADAR prototype; Section III discusses stellar signals and their imaging characteristics; Section IV describes the calibration methodology and results; and Section V presents a summary and discussion of the study's findings.

II. THE WATER-LENS PROTOTYPE OF HADAR

A. Design and Optical Performance

In 2016, the HADAR experimental group successfully installed and operated a prototype at the Yangbajing Cosmic Ray Observatory in Tibet, China (4300 m above sea level, 90.522° E, 30.102° N, atmospheric depth of 606 g/cm^2). The prototype consists of a thin hemispherical lens made of Poly-Methyl-Methacrylate (PMMA) and filled with high-purity water. The hemispherical lens has an aperture of 900 mm, an outer diameter of 664 mm, and an inner diameter of 650 mm, as illustrated in Fig. 1 [Figure 1: see original paper]. During testing, the water-lens was mounted within a steel frame (1.2 × 1.2 × 3.5 m), while the imaging system was housed in a dark chamber beneath the frame, which was opened during experiments. The surface roughness of the lens is maintained below 0.8 µm. The total mass of the lens is approximately 30 kg, while the injected high-purity water contributes an additional 70 kg.

The optical properties of the water-lens were evaluated under controlled laboratory conditions. The focal length of the lens was measured to be 168.0(15) cm when illuminated by collimated light. The imaging quality of the lens varies slightly with the incident angle of incoming light. The point spread function (PSF) of the imaging system, defined as the radius containing 80 % of the total energy (r_{80}) \cite{19–21}, is used to quantify imaging performance. Simulations indicate that for normal incidence (0°), the PSF spot size measures 30.6 mm, with a divergence angle of 1.0°. When light enters at an angle of 7.5°, the PSF spot size increases to 38.9 mm, with a divergence angle of 1.3°, in close agreement with experimental results. Fig. 2 [Figure 2: see original paper] presents PSF spot images under collimated light illumination. The observed spot exhibits a distinct annular structure, with the innermost region appearing white, followed by a blue intermediate region, and outer rings transitioning from yellow to orange and red. The structural irregularities in the spot are primarily attributed to spherical aberration, coma, and chromatic aberration. Another critical optical parameter of the lens is its light transmittance in the blue-violet spectral range, which is influenced by two primary factors: absorption losses due to the PMMA material and high-purity water, and energy losses caused by interface reflections, which can be estimated using Fresnel equations. The prototype lens demonstrates an optical transmittance of approximately 89 % at a wavelength of 420 nm. For further details on the parameters of the water-lens prototype, please refer to Chen et al. [**?**].

B. Imaging System

The lens imaging system is positioned at the focal plane of the lens and consists of 48 pixel units. The arrangement of these units is illustrated in the lower right section of Fig. 1, while their specific numbering is shown in Fig. 6 [Figure 6: see original paper]. Each pixel unit integrates a Hamamatsu R7725 PMT with a bialkali photocathode, featuring a quantum efficiency of 26 % at 420 nm and a spectral response range of 300–650 nm. Each PMT has a diameter of 51 mm, corresponding to an approximate FoV of 1.7°. The pixel units, including their external protective rings, are arranged in a regular hexagonal pattern with a center-to-center spacing of 57.8 mm, resulting in an FoV of approximately 2.0° per unit. The entire camera system covers a total FoV of approximately 15° × 13°.

C. Electronics and Data Acquisition

Since atmospheric Cherenkov radiation pulses are extremely short (10 ns), the data acquisition (DAQ) system must be equipped with high-speed triggering and storage capabilities while effectively suppressing starlight background interference, reducing accidental triggers, and improving the efficiency of prototype testing. The telescope prototype employs three parallel high-speed waveform digitizers—Switched-Capacitor Digitizers (SCDs) (CAEN DT5742B)—to record signals from 48 channels. These digitizers operate at a sampling rate of 2.5 GHz, corresponding to a sampling interval of 0.4 ns. Each event consists of 1024 sampling points, yielding a total sampling window of 409.6 ns per event [**?**].

To minimize the impact of night-sky background noise, the telescope prototype is triggered when at least one channel detects a signal amplitude exceeding 10 photoelectrons (p.e.). Upon triggering, all three SCDs simultaneously record data from the 48 channels. Each SCD transmits its data via a dedicated DAQ card (A2818) and optical fiber to an independent DAQ computer for subsequent processing. Further analysis is performed on threshold-exceeding signals to extract key physical parameters, including amplitude, charge, and peak arrival time.

For coincidence detection of CRs with the scintillator detector, the prototype was strategically positioned near an array of 75 scintillator detectors [?]. The telescope prototype's trigger signal is directly integrated into the scintillator array's DAQ system to enable coincidence measurements. If a trigger signal is registered within a predefined time window along with signals from at least four scintillator detectors, the event is classified as a CR detection by both the Cherenkov telescope prototype and the scintillator array.

III. DETECTION OF THE BACKGROUND LIGHT AND STARLIGHT

A. Night Sky Background Light

Within a sampling time window of 409.6 ns, the telescope primarily records three types of data: dark noise, night sky background light, and Cherenkov light. Excluding dark noise, the majority of the effective signals detected by each PMT originate from night sky background light. This background light consists of two primary components: a diffuse component and a contribution from relatively bright stars, which have fixed positions and flux. When a star enters the FoV of a given PMT, its emitted photons superimpose on the diffuse background light, leading to an increase in the overall intensity of the night sky background light. Additionally, the intensity of this background light is influenced by external factors such as weather conditions and atmospheric transparency. A representative signal of the night sky background light within a given time window is illustrated in Fig. 3 [Figure 3: see original paper].

Before the experiment commenced, gain calibration was performed for each PMT to minimize variations in signal amplitude among different units. The calibrated gain was set to 1×10^7, corresponding to a single p.e. amplitude of approximately 13 mV. The experiment was conducted on clear, moonless nights from November 3 to 6, 2016, with each night's observation lasting approximately eight hours.

B. Bright Stars

The presence of bright stars within the telescope's FoV can interfere with atmospheric Cherenkov light observations. However, these stars also serve as valuable reference points for calibrating both the telescope's pointing accuracy and the alignment of its pixel units. When a bright star enters the FoV of a PMT under operational gain conditions, it induces significant fluctuations in the event rate. If a bright star transits directly through the diameter of a PMT, it can remain within the single-pixel FoV (1.7°) for approximately six minutes, assuming negligible effects from Earth's precession and atmospheric refraction.

The calibration principle is illustrated in Fig. 4 [Figure 4: see original paper].

When light from a bright star passes through the water-lens, it undergoes refraction at the lens surface and forms an image on the focal plane. This process significantly enhances the event rate of the corresponding pixel unit (i.e., the pixel that “fires” due to the incident star’s light). As the star moves across the sky, it traces a trajectory on the imaging system of the water-lens, where the event rate of each pixel along this path first increases and then decreases.

It is assumed that the event rate reaches its maximum when the bright star’s trajectory precisely intersects the center of a given pixel. However, due to the relatively large size of the PMTs, the actual sensitive photocathode surface is smaller than its external glass envelope, and mechanical gaps exist between adjacent PMTs. Additionally, as discussed in Section II A, the image spot itself has a finite size. Consequently, this assumption introduces a certain degree of deviation.

By identifying which pixel unit is activated at a specific moment, it can be inferred that this pixel is aligned with the bright star. Analyzing the activation sequence of different pixels over time enables the precise determination of the overall pointing direction of the imaging system. The use of multiple pixels further minimizes systematic pointing errors.

For our analysis, we employ the TD1 Stellar Ultraviolet Fluxes Catalog[4], derived from the all-sky survey conducted by the TD1 satellite of the European Space Research Organization (ESRO) [?]. This catalog provides absolute stellar fluxes in four passbands (1565 Å, 1965 Å, 2365 Å, and 2740 Å), along with visual magnitudes (Vmag) and celestial coordinates. Since the telescope prototype operates within the blue-to-near-ultraviolet spectral range, we specifically focus on the 2740 Å band in our study. Additionally, we select relatively bright stars (flux $> 1 \times 10^{-11}$ erg/cm^2/s/Å) as reference sources for analysis.

The telescope prototype scans a region of the sky in the equatorial coordinate system, covering a Right Ascension (RA) range of (0°, 120°) and a Declination (Dec) range of (22°, 38°). Our analysis primarily considers relatively bright stars, particularly those with Vmag exceeding 2.5. The four brightest stars identified within the telescope’s FoV, as cataloged in TD1, are listed in table 1 . These include β Geminorum (Pollux), α Geminorum (Castor), β Taurus (Elnath), and Andromeda (Alpheratz), with their corresponding Henry Draper (HD) catalog numbers being HD 62 509, HD 60 179, HD 35 497, and HD 358, respectively.

IV. CALIBRATION OF THE WATER-LENS IMAGING SYSTEM

A. Method

The positional accuracy of stars in the sky is exceptionally high. By converting between the horizontal coordinate system (azimuth and zenith angles) and the equatorial coordinate system (right ascension and declination), the azimuth and zenith angle information of bright stars can be precisely mapped to the groundbased telescope's FoV during operation. The red dots represent the trajectory of HD 358 in the horizontal coordinate system, indicating that the star continuously traverses the imaging system for approximately 1.58 hours, beginning at 22:26:17. The blue squares denote the fired times of the three PMTs shown in Fig. 5 [Figure 5: see original paper]. In Fig. 6, the x-axis represents the east-west direction, with the coordinate origin set at the lens center. It is apparent that the optical axis of the lens does not perfectly align with the center of the imaging system but instead exhibits a slight deviation. Specifically, the optical axis intersects the imaging system near pixel unit 26.

Following calibration, the pointing direction of the imaging system is determined to be offset by approximately 18° relative to the east-west direction, thereby establishing its precise orientation. Finally, by incorporating the known mechanical relative positions of different PMTs in the imaging system, the absolute position of the entire system within the horizontal coordinate system can be accurately determined. This calibration approach is referred to as the "star trajectory method."

B. Calibration Results

Fig. 5 illustrates the variation in the normalized event counts detected by pixels 37, 27, and 21 as a function of local sidereal time from the night of November 3 to the early morning of November 4, 2016. The three prominent peaks in the event rate correspond to the entry of the bright star HD 358 into the telescope's FoV. It is evident that for different pixel units, the event rate initially increases before subsequently decreasing over time. By fitting the event rate distribution, we determine the precise times at which the bright star reaches the center of each pixel's trajectory (referred to as the "fired time") to be 22:42:59, 23:21:26, and 23:34:13, respectively.

Due to factors such as the imaging spot size of the bright star, the width of the event rate distribution provides an estimate of the duration for which the star's signal remains within a fired pixel. This duration is observed to be slightly greater than the expected 6 minutes.

Fig. 6 depicts the actual spatial distribution of the camera's PMTs, calibrated based on the trajectory of the bright star. The x-axis represents the east-west direction in the horizontal coordinate system. Numbered circles denote the PMT pixel units, while red dots trace the trajectory of the bright star HD 358 as captured by the imaging system, where it remains within the lens's FoV for approximately 1.58 hours. Blue dots indicate the fired times of pixels 37, 27, and 21. Following calibration, the pointing direction of the imaging system is determined to be offset by approximately 18° relative to the east-west axis.

As discussed in Section II, the telescope prototype operates in conjunction with a scintillator-based EAS array. During actual observations, the telescope detects atmospheric Cherenkov light generated by CRs, while the scintillator array detects the EAS produced by these CRs. This setup enables the calibration of the telescope's pixel unit pointing accuracy using coincidence CRs observed by both instruments. The calibration process involves reconstructing the EAS using the scintillator array to determine the CR zenith and azimuthal angles. By leveraging the experimentally established relationship between the direction of Cherenkov light and the CR zenith and azimuthal angles, the direction of the Cherenkov light associated with coincident CR events can be accurately inferred [**?**]. This directional information is then used to calibrate the pointing accuracy of the telescope's pixel units. The CR directional data provided by coincident events in the scintillator array is highly precise, making it a reliable reference for validating the star calibration method. The results indicate that the calibration obtained through starlight is highly consistent with that derived from the scintillator array, confirming the reliability and accuracy of our calibration approach.

C. Discussion

The star calibration method for the water-lens prototype detector is subject to various sources of error stemming from mechanical structures and other influencing factors. The primary sources of error are as follows: (1) The relatively large dimensions of the PMTs introduce inaccuracies in star imaging. To address this limitation, the upcoming HADAR experiment will utilize smaller PMTs or silicon photomultipliers, thereby enhancing the precision of star calibration and improving the imaging accuracy of atmospheric Cherenkov light. (2) The optical characteristics of the lens, particularly its aberrations and imaging spot size, affect calibration precision. (3) The discrepancy between the camera curvature and the image plane curvature. While the current camera is designed as a flat imaging surface, the actual image plane exhibits curvature. Future experimental designs will incorporate modifications to mitigate this inconsistency and optimize imaging performance. (4) The mechanical structure of the entire telescope can also affect calibration accuracy to some extent. These issues will be systematically addressed and minimized in subsequent HADAR experiments.

V. CONCLUSION AND SUMMARY

HADAR is an atmospheric imaging Cherenkov telescope that employs a novel transmissive optical technology. A critical parameter of the water-lens telescope is the pointing accuracy of both the overall system and its individual pixel units, as it directly impacts the precision of gamma-ray event reconstruction using Cherenkov light. Therefore, rigorous calibration is essential.

HADAR has a relatively large FoV, allowing bright stars traversing its field to generate strong vibrational signals within the imaging system. Consequently, stellar signals serve as an effective tool for telescope pointing calibration. Based on this principle, we propose a novel calibration approach for determining the optical axis orientation of the HADAR imaging system, referred to as the "star trajectory method." By analyzing the response of bright stars across different pixels, we extract stellar signals from background noise to determine the pointing direction of individual PMTs and, subsequently, the overall pointing accuracy of the telescope's imaging system.

Using this method, we analyzed data from the 2016 HADAR prototype detector and determined the optical axis orientation of the imaging system, specifically its precise position within the horizontal coordinate system. The results were then compared with direction measurements obtained via the scintillator array calibration method, confirming the validity and reliability of our approach. Given the relative stability of stellar signals, this calibration technique also facilitates the assessment of non-uniformities across different PMT pixel units and enables long-term monitoring of operational stability. Thus, it provides a straightforward yet robust approach for evaluating the telescope system's stability.

Looking ahead, the HADAR 2-meter and 5-meter lens experiments will be progressively implemented. This calibration methodology will serve as a crucial technical reference for the alignment and calibration of future large-aperture water-lens telescopes.

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