WCDA-Based Water Quality Monitoring Analysis Postprint

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Abstract

The Water Cherenkov Detector Array (WCDA) is one of the principal detectors of the Large High Altitude Air Shower Observatory (LHAASO). Since water serves as the sole detection medium of the detector, its purity directly impacts the detection efficiency for Cherenkov light. To ensure the achievement of WCDA' s physics objectives, real-time measurement and monitoring of water attenuation length is essential and represents one of the critical tasks for detector operation and calibration. This study separately introduces the operational principles of the water attenuation length measurement apparatus and the UV-Vis spectrophotometer, and performs measurements on various water samples using LEDs of different wavelengths. Through comparative analysis of the data obtained from the two methods, the measurement uncertainties of the two devices are determined to be 0.22 m and 0.18 m, respectively, along with the correlation between the industrial metric of absorbance and the scientific metric of water attenuation length. Furthermore, a Querry water quality model is identified for GEANT4 simulations, thereby enhancing the realism of the simulations. By validating the water attenuation measurement device for WCDA Pool No. 1 and analyzing data from water quality monitoring during the period from initial water filling to stable operation, a robust and reliable water quality monitoring protocol is established, providing a solid foundation for the monitoring efforts of Pools No. 2 and No. 3.

Full Text

Water Quality Monitoring and Analysis Based on WCDA

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Abstract

The Water Cherenkov Detector Array (WCDA) is one of the principal detectors of the Large High Altitude Air Shower Observatory (LHAASO). As water serves as the sole detection medium, its transparency directly affects the detector' s efficiency in observing Cherenkov light. To ensure the realization of WCDA's scientific objectives, real-time measurement and monitoring of water attenuation length is critically important and constitutes one of the key tasks for detector operation and calibration. This paper introduces the working principles of both the water attenuation length measurement device and the ultraviolet-visible spectrophotometer. Measurements were performed on various water samples using LEDs of different wavelengths, and the results from both methods were compared and analyzed. The measurement errors of the two devices were determined to be 0.22 m and 0.18 m, respectively, and the correlation between the industrial index (absorbance) and the scientific research index (water attenuation length) was established. A Querry water quality model was identified for GEANT4 simulation, further advancing the realism of simulations. Through verification of the WCDA No. 1 pool water attenuation measurement device and analysis of water quality monitoring data from the water injection phase to stable operation, a stable and reliable water quality monitoring scheme was developed, providing a solid foundation for the monitoring of Pools No. 2 and No. 3.

Keywords: LHAASO; water quality monitoring; water attenuation length; absorbance

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The primary scientific objective of the LHAASO-WCDA experiment is to achieve all-weather observation of very-high-energy gamma-ray astronomy, including the detection and monitoring of very-high-energy gamma-ray sources, energy spectrum measurement, and studies of extended source morphology [1]. The WCDA covers a total area of 78,000 square meters with an effective water depth of 4 m, consisting of three water pools that require 350,000 tons of purified water in total. Each pool is divided into multiple detector units by black light-blocking curtains, comprising 3,120 units in total, with each unit measuring 5 m $\times$ 5 m. In Pool No. 1, an 8-inch photomultiplier tube (PMT) with its photocathode facing upward is installed at the bottom center of each unit to detect Cherenkov light produced by secondary particles from extensive air showers in water. Based on the number of photons received and their arrival times at each PMT, the shower core position, energy, and direction of the primary particle can be reconstructed [2]. A 1.5-inch PMT placed beside each 8-inch PMT serves to expand the dynamic range for measuring the shower core region, thereby enabling high-precision measurements of high-energy cosmic rays [3].

As the key detection medium for the WCDA detector, water quality is crucial for long-term operation of the detector array. Water attenuation length directly affects detection efficiency—the greater the attenuation length, the better the water quality and the higher the photon detection efficiency. Different experiments have varying requirements for water quality. The CHIPS experiment measured the attenuation length of Cherenkov light as a function of filtration time, studying the transmission characteristics of 405 nm laser light with attenuation lengths reaching up to 100 m [4]. The Daya Bay neutrino experiment in China required water attenuation lengths above 30 m [5]. The LArTPC detector experiment measured the reaction cross-section between nitrogen molecules and scintillation light in liquid argon as $(7.14 \pm 0.74) \times 10^{21}$ $cm^2 \cdot molecule^{1}$. A doping concentration at the parts-per-billion level (ppm level) corresponds to an attenuation length of 30 m $\pm$ 3 m [6]. The KM2A muon detector [7] (MD) group developed a measurement apparatus that installs multiple light sources in an 8 m long water tank to achieve rapid measurement of water attenuation length. Measurements of ultra-pure water samples from the mountain site and various water qualities verified that the apparatus achieves 20% measurement precision for attenuation lengths of 100 m [8].

The water attenuation length measurement method employs a straightforward and practical straight-tube approach, where the water level height in the measurement device is varied to change the optical path length, thereby obtaining the water attenuation length [9]. In earlier WCDA engineering array prototype experiments, data analysis revealed a method for monitoring water quality using the peak position variation of the second peak in the single-channel counting spectrum [10]. This method requires comparative analysis with results from direct measurement devices. GEANT4 simulations require water attenuation length parameters at different wavelengths, necessitating a water quality model that closely approximates experimental conditions. Literature review identified two water quality models: Smith and Querry [11], and experimental measurements were needed to determine an appropriate model to provide reliable parameters for simulation.

This study employs the straight-tube method to determine water attenuation length at specific wavelengths and compares the results with those from a UV-Vis spectrophotometer to calibrate the attenuation length of the detection medium. Further analysis of measurement results from different wavelength LEDs provides a set of reliable water quality model parameters for GEANT4 simulation.

2.1 Working Principle of the Measurement Device

The water attenuation length measurement device consists of an LED light source, optical tube, main water pipe, and photomultiplier tube (PMT). At a given LED wavelength, the signal amplitude received by the PMT is measured at different water levels (h), where A represents the LED emission intensity. According to the definition of water attenuation length:

$$A = A_0 e^{-h/\lambda}$$

Taking the natural logarithm of both sides yields:

$$\ln(A) = \ln(A_0) - \frac{h}{\lambda}$$

This establishes a linear relationship between the logarithm of the PMT signal amplitude and the water level height h, from which the water sample' s value (the attenuation length) can be obtained as the reciprocal of the absolute value of the slope.

2.2 WCDA Water Attenuation Length Measurement Device

[Figure 1: see original paper] shows the water attenuation length measurement device designed by WCDA based on this principle. The measurement procedure is as follows: First, the measurement device is automatically rinsed with the water sample to be tested to reduce experimental error. Second, the corresponding electric water valve and water pump are opened to begin water injection; when the water level reaches 1.1 m, the electric valve and pump are closed, and the LED and PMT power supplies are activated to collect LED emission signals. Third, the drain valve is controlled to vary the water height h in the measurement device, the signal amplitude A received by the PMT is measured, and experimental data are recorded and saved. Fourth, the water attenuation length of the sample is obtained through fitting according to the calculation formula.

Water attenuation length measurement can be performed in either automatic or manual mode. Under the control of the slow control system, automatic measurement is achieved, with each water sample measurement completed every 2 hours to enable water quality monitoring.

2.3 Stability Analysis and Measurement Results of the WCDA Device

Before formal measurements, we conducted a stability verification analysis of the device. Using the apparatus, water quality in the pool was monitored for 27 days, and daily measurement errors were analyzed to demonstrate system stability. [Figure 2: see original paper] shows the measurement errors over 27 days, revealing that error fluctuations remain within 0.22 m, indicating stable measurement performance.

[Figure 3: see original paper] presents the results of pool water samples measured using this device with a 400 nm wavelength LED. Figure (a) shows the water attenuation length obtained from a single measurement fit, with measurement error less than 3%; Figure (b) displays long-term measurement results, showing that the current water quality in the pool remains essentially at 7.53 m ± 0.21 m, with overall measurement error less than 5%.

For comparative study with the direct measurement device, this experiment also employed a UV-Vis spectrophotometer to measure the same water samples, establishing the correspondence between absorbance and water attenuation length.

3.1 Working Principle of the UV-Vis Spectrophotometer

The Lambert-Beer law, also known as the fundamental law of light absorption, describes the relationship between absorption intensity and both optical path length and absorber concentration when a substance absorbs incident light. This law provides the theoretical basis for quantitative analysis in UV absorption and infrared spectroscopy:

$$A = \lg \frac{I_0}{I} = \lg \frac{1}{T} = KCL$$

where A is absorbance, T is transmittance, K is the absorption coefficient, C is sample concentration, L is optical path length, I is incident light intensity, and I is transmitted light intensity.

A UV-Vis spectrophotometer consists of a light source, monochromator, sample chamber, detector, amplification control system, and display system. This experiment employs a dual-beam configuration with two optical paths and a single detector. Reference and sample cuvettes are placed in the two paths, and light from the monochromator passes through a chopper to sequentially measure the reference and sample. The detector is a photomultiplier tube that, when irradiated, absorbs photon energy and converts it into measurable physical quantities, with results displayed and saved on a PC. This method measures the relative absorbance of water samples.

3.2 WCDA UV-Vis Spectrophotometer

The UV-Vis spectrophotometer used for WCDA water quality measurement is a Cary 300 model manufactured by Agilent Technologies. The procedure involves first powering on the computer Scan software and Cary 300 equipment for 1 hour of warm-up, then setting the measurement wavelength range to 300–700 nm, sampling time to 0.2 s, and sampling interval to 1 nm. A pure water sample is placed in the sample chamber for baseline correction, followed by measurement of the water sample. Results from each water sample measured by the UV-Vis spectrophotometer are expressed as absorbance (Abs):

$$\mathrm{Abs} = \lg \frac{I_0}{I}$$

According to the Beer-Lambert law for light attenuation, if the water attenuation length is , then the intensity of incident light I after passing through a water sample of length L becomes:

$$\frac{I}{I_0} = e^{-L/\lambda}$$

During spectrophotometer measurement, L is taken as 0.1 m, allowing calculation of the water attenuation length at each wavelength:

$$\lambda = \frac{1}{10^{\mathrm{Abs}} \ln 10}$$

3.3 Stability Analysis of the UV-Vis Spectrophotometer

Before formal measurements, we similarly monitored water quality in the pool for 27 days using this device, analyzing daily data errors. [Figure 4: see original paper] shows the measurement errors converted from daily absorbance values to water attenuation length over 27 days, verifying the stability of the apparatus. The error fluctuations remain within 0.18 m, demonstrating equally stable measurement performance.

[Figure 5: see original paper] shows the absorbance of various water samples measured by the UV-Vis spectrophotometer at 400 nm wavelength. Pure water exhibits essentially zero absorbance; smaller absorbance values indicate higher water transparency and larger water attenuation length. During initial water injection, absorbance decreases rapidly due to dilution of contaminants in the pool by the increasing water volume. The absorbance of water treated by the circulation station is lower than that of pool water, indicating that the circulation station treatment has some water purification capability, though not yet meeting design requirements.

4 Results Analysis

The error analysis of the two measurement devices shows that both still exhibit certain errors. We attribute this to instability in the current WCDA water purification and circulation equipment, which affects the measured water samples. Additionally, the UV-Vis spectrophotometer measurement itself involves equipment errors, and unavoidable contamination of cuvettes during each sampling leads to slight variations in results. However, the data errors from both devices are very small and within acceptable ranges. Subsequently, we performed measurements and comparative analysis on identical water samples using both devices.

[Figure 6: see original paper] shows the monitoring results for WCDA pool water over 18 days using the water attenuation length measurement device, yielding an attenuation length of 7.41 m ± 0.21 m. Simultaneously, monitoring the same water sample with the UV-Vis spectrophotometer and converting the results yields an attenuation length of 6.79 m ± 0.37 m. The water attenuation lengths obtained by the two methods are consistent within error margins.

We calculated water quality models from data measured by both devices. Table 1 presents the water attenuation lengths of pool water samples measured by both the water attenuation length measurement device and the UV-Vis spectrophotometer at LED wavelengths of 365 nm, 385 nm, and 400 nm. The slopes of the relationship between water attenuation length and wavelength derived from three data points are 0.08 ± 0.04 and 0.10 ± 0.02, respectively. [Figure 7: see original paper] shows the relationship between water absorption length and wavelength, presenting two water absorption length models based on different experimental results. The slopes for the Smith and Querry water quality models under the same conditions are 0.79 ± 0.05 and 0.16 ± 0.01, respectively. The slopes calculated from data measured by both devices clearly demonstrate that the pool water sample more closely matches the Querry water quality model. Therefore, the Querry water quality model was selected for GEANT4 simulation.

This paper validates the stability of both the water attenuation length measurement device and the UV-Vis spectrophotometer, determining measurement errors of 0.22 m and 0.18 m, respectively. Comparative measurements of identical water samples using both devices demonstrate that the monitoring results are consistent within error ranges. By analyzing water attenuation lengths of pool water samples at different LED wavelengths measured by both devices, and through calculation and comparative analysis, the Querry water quality model was identified for use in GEANT4 simulation.

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