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Accurate Reflectance Measurement of Spherical Mirror at Multi-wavelength on LHAASO-WFCTA

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The Wide Field of view Cherenkov Telescope Array (WFCTA) is an important part of the Large High Altitude Air Shower Observatory (LHAASO) project. WFCTA consists of 18 Cherenkov telescopes, and its main scientific objective is to measure the spectrum of cosmic rays. Each Cherenkov telescope is equipped with a large aperture spherical reflector consisting of 25 small spherical mirrors. In the process of cosmic ray detection and analysis, the reflectance of the telescope will directly affect the measurement of Cherenkov light. In the long-term use of mirror, the reflectance will experience varying degrees of attenuation. A reflectance measurement system of spherical mirror is presented in this paper. The system includes a light source and a measuring instrument for measuring the intensity of the reflected light. The multi-wavelength reflectance measurement system employed lasers with wavelengths of 405 nm, 450 nm, 488 nm, 520 nm, and 650 nm. The lasers exhibited fluctuation amplitudes of 0.06%, 0.01%, 0.02%, 0.01%, 0.06%, respectively. Additionally, the systematic errors when using different lasers were carefully assessed and found to be 0.2%, 0.2%, 0.1%, 0.2%, 0.3%, respectively. After performance tests in the laboratory, the measurement system was taken to on-site measure the reflectance of the spherical mirror of the telescope. A total of 175 different measuring points were selected for reflectance measurements, covering all 18 telescopes. The average reflectance is 78.5% (405 nm), 78.5% (450 nm), 78.5% (488 nm), 78.0% (520 nm), and 76.3% (650 nm). These measurements provide a reliable experimental basis for LHAASO-WFCTA.

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1. Introduction

Extensive air shower (EAS) is a phenomenon that occurs when cosmic rays penetrate the atmosphere, producing Cherenkov light that can be detected by particle physics experiments[1, 2]. Over the past few decades, many experiments on Cherenkov light have been constructed worldwide, aimed at reconstructing cosmic ray energy and analyzing cosmic ray composition[3, 4]. Cherenkov light can be reflected, and has continuous spectrum of 400 to 700 nm. Cherenkov light reaches the ground and is detected in the spectral range of approximately 200 nm to 700 nm. Cherenkov telescopes are typically the scientific equipments used to detect Cherenkov light[5]. Spherical mirrors are commonly used in Cherenkov telescopes, such as HESS[6, 7], MAGIC[8], VERITAS[9], LHAASO-WFCTA[10], CTA[11], etc.
Cherenkov telescopes aim to achieve the spectrum of cosmic rays and study their composition[12]. Astrophysical experiments must consider cost so that use aluminum film mirrors. However, the reflectance of spherical mirrors can vary depending on the wavelength and position due to the interference of light reflected from the aluminum surface layers[13].
The spherical mirror of Cherenkov telescope is typically made up of a patchwork of sub-mirrors.

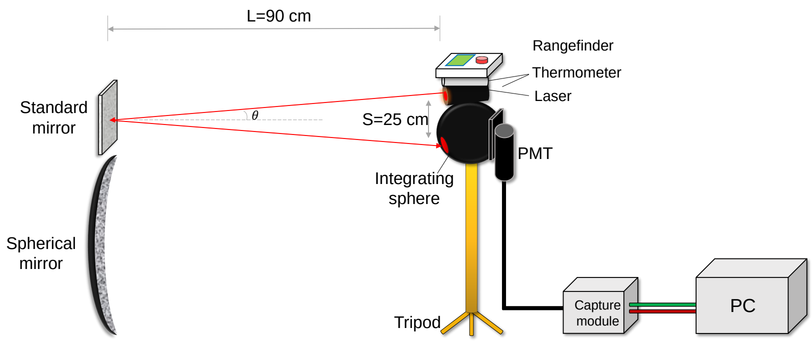


Figure 1: The schematic of the reflectance measurement system. The system includes a standard mirror, a laser, an integrating sphere, a photomultiplier tube (PMT), a capture module, a thermometer, a rangefinder, a tripod, and a computer. The standard mirror is used to calibrate the reflectance of the spherical mirror, as it has a known reflectance value. The laser serves as a stable light source for the system. The function of the integrating sphere is to change the incident light into a uniform light field in the integrating sphere. The PMT is fixed on the integrating sphere, and the window receiving light is exposed to a uniform light field within the integrating sphere. The electrical signal at the PMT is converted into a digital signal by the capture module and finally transmitted to the PC. The thermometer monitors the temperature during the measurement, the rangefinder controls the distance between the laser and the mirror, and the tripod maintains the stability of the integrating sphere.

Hi-Res uses four sub-mirrors to form a complete spherical mirror[14], and MAGIC-I uses 964 sub-mirrors[15, 16] to form a complete one. The absolute reflectance of the spherical mirror is the main parameter for measuring luminous flux of Cherenkov light[17]. The energy of cosmic rays is directly related to the absolute reflectance of the spherical mirror. Due to aging, the reflectance may attenuate over time. The reflectance of spherical mirrors varies with different wavelengths[18], and the reflectance of different Cherenkov telescopes need to be measured. Additionally, the reflectance provided by mirror manufacturers is not sufficient for accurate long-term calibration of the photon number of Cherenkov telescope. Therefore, reflectance measurements at different wavelength are necessary[19]. However, measuring and monitoring this parameter for Cherenkov telescopes placed in the wilderness of plateau is difficult.

In the past, the reflectance of spherical mirrors utilized in Cherenkov telescopes was not well-defined[20]. The relationship between specular reflectance and wavelength is typically measured using a spectrophotometer or reflectometer in commercial and industrial fields. There are two primary methods for measuring the reflectance of astrophysical experiments. The first method is a single-point reflectance measurement used by MAGIC telescopes, which focuses on a single-point reflectance measurement and uses it to represent the overall reflectance[21]. The second method is the reflectance measurement used by VERITAS IACTs, which takes advantage of the telescope's maneuverability to measure the reflectance of the spherical mirror by changing the angle and direction of the telescope's pitch to track starlight[22].

However, the telescope studied in this paper lacks a maneuvering device for azimuth adjusting, making real-time starlight tracking impossible. In order to achieve a more precise representation of mirror reflectance and measure any location on the mirror with greater accuracy, a novel measurement system has been developed to gauge the reflectance of Cherenkov telescopes. This paper introduces the research process of the reflectance measurement system and method, including the work to ensure the performance of the measurement system. Finally, the results of the measurements made on the spherical mirror are summarized.

2. Measurement System Setup and Performance

Since the measurement process requires visual observation, this study focuses on wavelengths within the visible spectrum that are easily discernible. The selected wavelengths for measurement are 405 nm, 450 nm, 488 nm, 520 nm, and 650 nm. Of particular importance, reflectance at 405 nm is regarded as most relevant for research in the field of cosmic ray experiments[12].

2.1 System Setup

A detailed depiction of the reflectance measurement system is shown in Figure 1. A standard mirror is a square with a side length of 7.5 cm and an aluminized reflection area of 56.35 cm^2. The reflectance of the standard mirror was calibrated by National Institute of Metrology (China) using the hemispherical reflection method at the incidence angle of 8°, the calibrated wavelength is from 250 to 900 nm. Semiconductor lasers with output power of 100 mW serve as light sources, with five different wavelengths (405 nm, 450 nm, 488 nm, 520 nm and 650 nm). Each laser has a wavelength error of 5 nm. The laser is fixed on a rotating bracket, which is then attached to the integrating sphere. The integrating sphere features an inner diameter of 150 mm, with a 5 mm thick inner layer coated in polytetrafluoroethylene, and a 5 mm thick aluminum alloy shell. The diameter of the integral ball opening measures 2 cm. The PMT model utilized in the reflectance measurement system is the CR131, which is manufactured by Hamamatsu Corporation[23]. This particular model boasts a wide spectral coverage and is less susceptible to temperature fluctuations. A thermometer and a rangefinder are placed around the laser, with the positioning of both devices

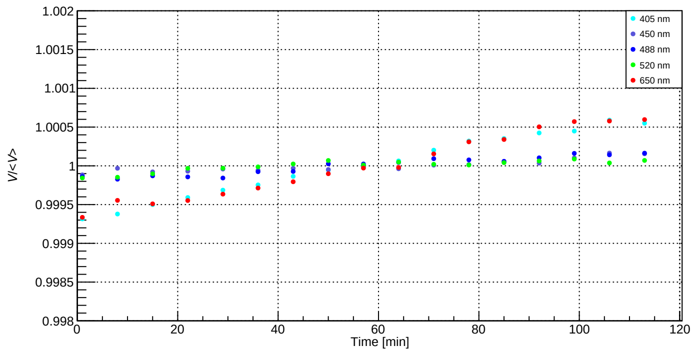
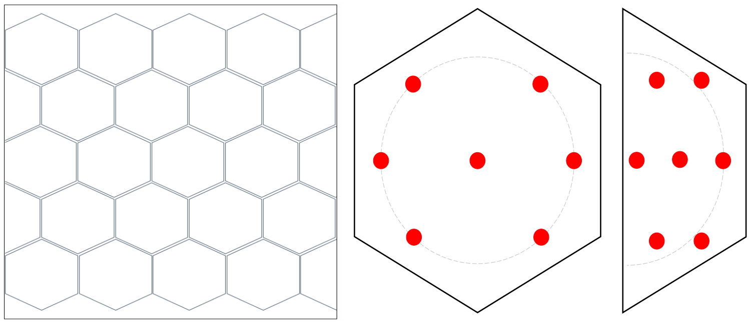


Figure 2: The stability of the system mainly depends on the stability of the laser energy, which is tested by irradiating the laser's light on the standard mirror and injecting the reflected light into the integrating sphere. After removing the preheating data, The relative ADC value of the reflected light intensity is measured every seven minutes in two hours. V is the relative ADC value of each measurement, <V> is the mean of relative ADC value in two hours, and the stability of laser energy can be measured by their ratio. The error bar comes from the statistical error caused by the measurement, the temperature in the lab fluctuates between 15 °C and 20 °C.

carefully considered to avoid any potential interference with the experiment.
The distance S between the laser and the integrating sphere is fixed, so the distance L between the system and the spherical mirror is important for controlling the incidence angle θ. The rangefinder controls the distance L between the system and the measured mirror. Due to the high sensitivity of the PMT to light, the entire measurement system is kept in a dark environment to prevent interference from external light sources. The measured distance L is controlled at 90 cm by the rangefinder, the distance S between the integrating sphere and the laser is 25 cm. Given by geometric relations, the calculated incidence angle θ is 8°.

2.2 Performance

To ensure the stability of the measurement system, it is crucial to conduct performance tests of the measurement system. The performance of the system was tested on the optical table in the laboratory. The light from the laser is reflected into the integrating sphere by the standard mirror, and the light intensity is recorded and analyzed. It is worth noting that during the preliminary experiment, it was found that in order to achieve good stability, the system needs to be preheated for two hours. After preheating, the reflectance measurement system was tested for 2 hours to evaluate its stability. Figure 2 shows that the fluctuation amplitude of the lasers are 0.06% (405 nm), 0.01% (450 nm), 0.02% (488 nm), 0.01% (520 nm), 0.06% (650 nm). A full on-site measurement takes about one hour and the temperature does not change more than 3 °C. As a result, the performance is deemed sufficient to meet the requirements of on-site experiments.



(a) (b)

Figure 3: (a) The spherical mirror of the telescope measured consists of 25 sub-mirrors with the same radius of curvature, the spherical mirror is composed of five rows of sub-mirrors, each row consists of four hexagonal sub-mirrors and one isosceles trapezoidal sub-mirror; (b) The schematic diagram of measuring sites. The reflectance of each sub-mirror is obtained by averaging the reflectance of three measuring sites at the top, middle and bottom. Seven measurement sites selected on each sub-mirror, a spherical mirror has 175 measuring sites. These sites were selected for subsequent studies to analyze the relationship between reflectance and the height of the sub-mirrors.

3. Method of Reflectance Measurement

Figure 3 (a) shows the spherical mirror measured in this paper consists of 25 sub-mirrors. Throughout the measurement, the standard mirror is placed in the same horizontal position of the spherical mirror, and the integral sphere can be moved to any position within the measuring space. This allows for the measurement of reflectance at any site on the same mirror. The laser is directed towards the mirror, with the emission direction adjusted to enable the reflected beam to fully enter the integrating sphere. Once the system has stabilized, the light intensity of the mirror is measured and recorded for further analysis. After measuring the mirror, the distance L is kept unchanged and the light intensity of the standard mirror is measured. The measurement sites selected on each sub-mirror is shown in Figure 3 (b).

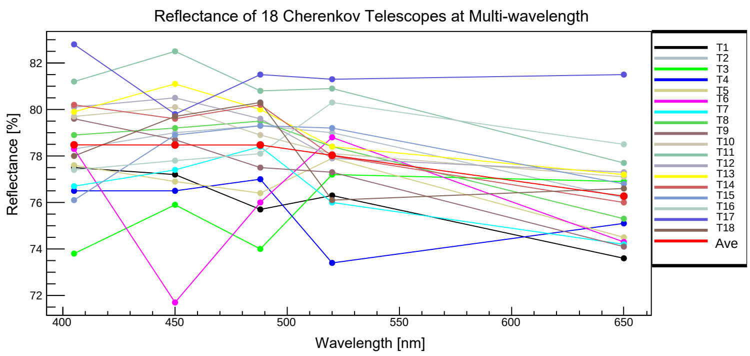


Figure 4: The average surface reflectance of the spherical mirror was measured with different usage period. The average surface reflectance is obtained by averaging the reflectance of all measuring sites on the spherical mirror.

4. Results

Following specular reflection, the light is incident into the integrating sphere, with the light evenly distributed within the sphere to form a uniform light field. The reflectance is calculated by the following formula:

$$R_1(\lambda) = \frac{I_1(\lambda) - B}{I_0(\lambda) - B} \times R_0(\lambda)$$

Here, λ represents different wavelengths, with the PMT detecting the light intensity of the uniform light field in the integrating sphere as $I(\lambda)$, reflectance of the standard mirror at different wavelengths is represented as $R_0(\lambda)$, while $I_0(\lambda)$ denotes the light intensity data after the light is illuminated to the standard mirror reflection. Similarly, $I_1(\lambda)$ presents the light intensity data after the light is illuminated to the spherical mirror reflection, and B is the measured baseline.
Use one half of the standard mirror as the reference mirror and the other half as the measuring mirror. After 50 measurements of the reference mirror and the measuring mirror, the average relative ADC values of the two light intensities were obtained. The average relative ADC value of the reference mirror corresponds to the calibration results of National Institute of Metrology (China), so the systematic errors of the measuring system under five different wavelengths are obtained. The systematic errors of the measurement system by different lasers are 0.2% (405 nm), 0.2% (450 nm), 0.1% (488 nm), 0.2% (520 nm), 0.3% (650 nm) respectively. The reflectance of the spherical mirror in the optical system of a Cherenkov telescope is evaluated through the use of the reflectance measurement system. Reflectance measurements are carried out under the reflection condition with an incidence angle of 8° using the above system. We measured the reflectance of the spherical mirror with different usage period. By employing the above measurement and data processing methods, the average surface reflectance of the spherical mirror at different wavelengths is obtained. The average surface reflectance of the spherical mirror are 78.5% (405 nm), 78.5% (450 nm), 78.5% (488 nm), 78.0% (520 nm) and 76.3% (650 nm).

5. Summary

In any particle astrophysics experiment utilizing Cherenkov telescopes, the state of primary mirror is a crucial factor influencing the detector's performance. Cherenkov telescopes are exposed to air, which exposes its mirrors to the harmful effects of the atmosphere (wind and dust). The pervasive presence of dust further diminishes its optical properties. This paper seeks to evaluate the reflection performance of Cherenkov telescopes in astroparticle physics experiments. To achieve this objective, a reflectance measurement system is designed, with the system's stability and accuracy meeting the necessary measurement requirements. The system outlined in this paper enables the capture, transmission, and processing of original reflectance data. The reflectance measurement of the Cherenkov telescope's spherical mirror is not limited to the result, our aim is to investigate the cause of the reflectance decline over a long period of time, and discuss the effect of the reflectance decline on the telescope's detection efficiency. We plan to measure the reflectance of spherical mirrors at more wavelengths in the future. The reflectance measurements of the spherical mirror will be made at a annual frequency.

Acknowledgments

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