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Calibration and monitoring of the air fluorescence detector for the Telescope Array experiment

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Abstract: The air fluorescence detectors (FDs) of the Telescope Array (TA) experiment have been constructed in a dessert of Utah, USA. We can measure the longitudinal developments of EASs directly with the FDs by detecting air fluorescence lights and determine the primary energies of ultra-high energy cosmic rays. In order for accurate observation and measurements of EASs, elaborate detector calibrations and monitoring systems are required. We will present the result of calibration and monitoring systems for the reflectance and curvature radius of segment mirrors, the characteristics of PMT (absolute gain, linearity, temperature dependence of gain), and the uniformity of the camera surface, etc.

Introduction

The AGASA energy spectrum of the primary cosmic rays shows that there is no indication of GZK cut-off expected by the photo-pion production of the ultra high energy cosmic rays [1]. In contrast, HiRes group reported that there is a GZK cut-off in their observed energy spectrum [2]. It seems that a part of the inconsistency is due to the systematic error of both experiments in the determination of primary cosmic ray energies. In order to make clear the difference, and to get definite answer on the origin of ultra high energy cosmic rays, we plan to observe extensive air showers EAS with an AGASA type surface detector (SD) array and with HiRes type air fluorescence detectors (FD) simultaneously. It is located in the west Desert of Utah, USA. There are three air Fluorescence stations surrounding the SD array. The separation of the station is 30 km.

Fluorescence Detectors measure the fluorescence light generated by Extensive air showers (EASs) particles. The observation of the whole shower longitudinal development in the atmosphere enables the unbiased determination of the primary energy from the total absorption calorimetry. A telescope consists of upper/lower pairs of camera and spherical mirror. The mirror with a diameter 3.3 m, and with a radius of curvature R=6067 mm is composed of 18 hexagonal shape segment mirrors. The spot size on the focal plane is smaller than 30 mm in FWHM. The camera consists of 256 hexagonal shape PMT (R9508 HAMAMATSU) with 60 mm opposite side distance and each PMT has 1.1×1 field of view (FOV). The FOV of one telescope unit is 18.0° in azimuth 15.5° in elevation, and total FOV of station is 108° in azimuth, 3° – 33° in elevation.

To obtain a result from FD with high accuracy we have to study the air fluorescence light yield, atmospheric monitoring, absolute calibration (which includes performance monitoring) of FD equipment carefully. The construction of the fluorescence detectors has been completed in Mar 2007. After that construction, calibrations and adjustments of FD are now in progress. In June 2007, stereo observation has been started with 10 cameras at the first station, and 6 cameras at the second station. In addition 2 cameras were adjusted and taking data at the first station in July 2007. Other telescopes are calibrated and adjusted continuously in summer 2007. The third station have been constructed. HiRes-I mirror and electronics were transfered from HiRes site to the third station[3], and assembled. The performance check of equipments and test run is now in progress.

PMT camera calibration

The FD camera consists of 256 hexagonal shape PMT (R9508 HAMAMATSU). To reduce Night Sky Background (NSB) PMT are equipped with an optical filter, Schott BG3 with 4mm thickness (transmittance=95% at 350 nm). Photo-cathode is impressed negative voltage typical -900 V with absolute gain 8×10^4. Pre-amplifier mounted on PMT outputs a semi-differential signal into electronics via 20 m twist pair cable. Each channel of the electronics (Signal Digitizer/Finder SDF) has a differential receiver and a stretcher. Total SDF gain is $\times$ 1. Signals are digitized by the SDF with 10MHz, 12 bit resolution and 14 bit dynamic range.

The items of PMT calibration are input-output linearity, PMT-gain, 2-dimensional uniformity of the surface. All PMT will be checked its DC input-output linearity etc. by HAMAMATSU before making delivery. We use a stable light source for checking the absolute PMT gain at the experimental site. As the stable light source we use YAP light pulser (Radiation Instruments and New Components Ltd.) [4, 5]. YAP light pulser consists ($YAlO_3$: Ce) + Am^{241} alpha radiation source (50 Bq) in an aluminum cylinder with 4 mm diameter and 1 mm thickness, and radiates UV light. Its peak wave length is 370 nm. A light intensity is 500 - 800 p.e.. FWHM is 20 ns. The deviation of that light intensity is typical 10 %. In our operational temperature range from -20 degree to 40 degree, YAP has some temperature dependence which is $\pm$1% from -20 to 10 degree, and temperature coefficient is -0.2%/degree from 10 to 40 degree [4]. To compensate the temperature dependence the ambient air temperature is monitored.

To calibrate PMT gain and YAP pulser in lab, we made an absolute light source which called CRAYS. CRAYS has a scatter box suffused with molecular nitrogen. Light of laser (N_2 laser 337.1 nm 300 μJ, VSL-337ND-S, Laser Science) goes through the box, and that light is scattered by Rayleigh scattering of nitrogen in the box. We measure the laser intensity using Silicon energy probe (RjP-465, Laser Probe Inc.). This probe has an accuracy is $\pm5\%$ for the laser pulse absolutely. The intensity of Rayleigh scattering light can be calculated by theoretical simulation and ray tracing calculation. Using CRAYS PMT gain is adjusted, and light intensity of YAP pulse is measured. The following is the procedure of the PMT gain adjustment. First PMT gain is adjusted using known light intensity from CRAYS. Second signal of the YAP pulser are measured with the adjusted PMT gain using SDF. The relation of the gain and SDF output counts is conserved anywhere. After that PMT gain can be adjusted using this relation at our stations in the desert. Three PMTs with YAP pulser will be install on each camera.

We have to monitor PMT-gain on the fluorescence light observation, because PMT gain is affected by the variation of temperature, NSB, and PMT aging. We have installed Xenon-flasher covered with Teflon diffuser (light intensity is $\sim4\times10^4$ p.e. and FWHM 2 μs, the deviation of the light intensity is typical 1%) at the center of the mirror. All PMT can be measured relative gain using Xenon-flasher and these also can be compared absolute gain from the PMT with YAP pulser. Figure 2 shows the relative PMT gain at the first station. Median value of the relative PMT gain is 1.00, and $1\sigma = \pm0.01$. PMT absolute gain are adjusted with $\sim\,\pm\,10\ \%$ accuracies from our preliminary estimation.

We make a XY-scanner to measure 2-dimensional relative uniformity of PMT gain. This XY-scanner consist of 8 UV LEDs (wave length λ =360 nm, NSHU590B NICHIA) with optical lens for light source and a XY-stage mounted on the front of camera. 8 PMTs will be measured at the same

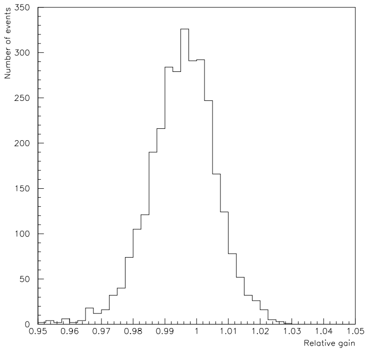

Figure 1: Histogram of 3072 relative PMT gains at BRM.

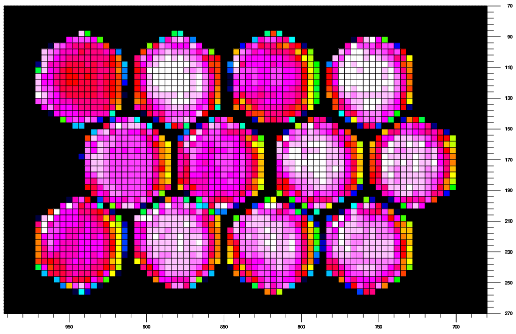

Figure 2: Contour map of 2-dimensional uniformity of QE×CE for 12 PMT in arbitrary unit., unit of axes is mm

time, and the measuring time is 3 hours for one camera. The sources make ∼4 mm diameter spot on the PMT surface. Relative PMT gains calculated using XY-scanner compare with the relative PMT gains adjusted by Xe. Figure shows that the difference between the gain by Xe and XY-scanner is ± 2 %. This means negligible the wavelength dependence of PMT gain between Xe and XY-scanner.

Mirror calibration, monitor

The telescopes in the first staion and second station have 12 spherical mirrors on each station. These mirrors with a radius of curvature R=6067 mm

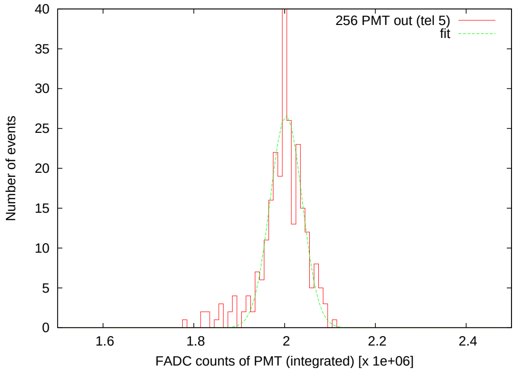

Figure 3: The difference of relative PMT gain between Xe and XY-scanner

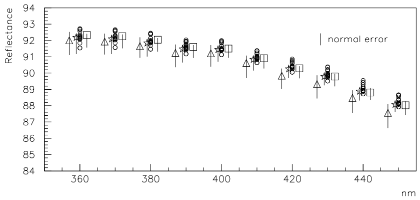

Figure 4: A typical Mirror reflectance at the first staion, Entry: 18 segment mirrors, Error bar: 1-σ

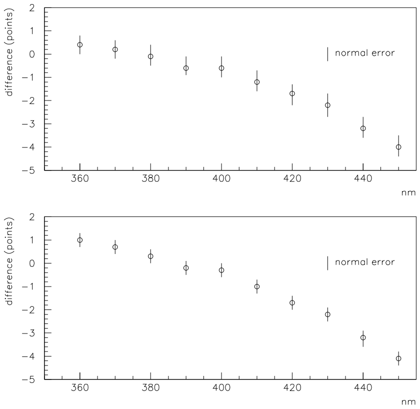

Figure 5: Difference of the Mirror reflectance, Upper: after 1 year at the first station, Lower: after 6 monthes at the second station, Error bar: 1-σ

which is composed of 18 hexagonal shape segment mirrors. The surface of segment mirrors have been anodized, and the estimated degradation of the reflectivity is ~ 1 %/year. From our ray-tracing calculation, it is necessary that curvature radius and the diameter of minimum spot implement the following specification: curvature radius is 6067 ± 100 mm, and the diameter of the minimum spot is less than 20 mm. This spot size is sufficiently small because it is half of the PMT dimension. The spot size of the reflected light at 6067 ± 100 mm, and the curvature radius have been measured for acceptance test. we confirmed that all mirrors implement their specifications.

The reflectivity of the 450 segment mirrors have been measured using Spectrophotometer (CM-2500d, KONICA-MINOLTA) on the wave length from 360 nm to 450 nm when mirror was installed (on 2005, 2006, 2007). The reflectivity of these mirrors is more than 90% at 360 nm (*e.g.* Fig.), and its deviation by location dependency on the mirror surface is less than ± 1 % for typical one. The reflectivity was remeasured in June 2007. The differences of reflectivity are smaller than 1 % at wavelength shorter than 400 nm (Fig.). Those differences are in reproducibility error. We make a reflect-meter for measuring shorter wave length from 200 nm.

End To End calibration

The construction of the first and second FD station has been finished. Calibrations and performance monitoring for individual FD equipments in situ will be started. End to end (the mirrors to SDF) calibration is also important to understand our FD system totally. We are studying the various light sources for this calibration. A steerable laser at the center of our experimental site will be installed. It aims for monitor of the atomospheric condition between CLF to each FD site, and GPS timing calibration between each FD sites and SDs [6]. That has a potential to be assumed calibrated light source if Mie-scattering is not dominant. Moreover, we have a plan to use air fluorescence lights generated by low energy electrons radiated by Linac [7]. Reported fluorescence light yield [8, 9] are different from each other. There are various efforts to determine the yield and to parameterize a lot of measurement conditions. In contrast, we can obtain the relation between $\mathrm{d}E/\mathrm{d}x$ and SDF counts includes fluorescence light yield using calibrated EASs on site. From these end to end calibration, accuracy of energy estimation by FD will be progressive.

Acknowledgments

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