Calibration of the Telescope Array Experiment Fluorescence Detectors

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***Abstract*. The Telescope Array (TA) experiment has three stations of Fluorescence Detectors (FDs). Two stations (Black Rock Mesa "BR" and Long Ridge "LR") consist of 24 new detectors (12 each). The third station (Middle Drum "MD") consists of 14 detectors that were reconditioned and redeployed from the High Resolution Fly's Eys experiment (HiRes). In this paper, we describe the detector calibration process for the BR and LR FD stations. The telescope calibration includes the measurement of (1) mirror reflectances, (2) absolute gains of reference photo-tubes, (3) "relative gains" of the clusters of 256 tubes, (4) (non-)uniformity of photo-cathode sensitivity of the tubes, and (5) transmittance of the UV filters on the photo-tubes and acrylic windows on the cameras. The reflectances of mirrors, transmittance of the UV filters and the acrylic windows are measured using a spectrophotometer. The absolute gains and non-uniformity of photo-cathode are measured with a simple pulsed UV light calibration systems and a large XY stage with UV LEDs. The relative gains are monitored hourly during observations with a Xe flasher and an alpha-ray scintillator pulsar called YAP. We discuss the qualities of the calibration data, and we evaluate systematic uncertainties in air shower reconstruction and energy determinations.**

***Keywords*: Ultra-high energy cosmic rays, Fluorescence light, Telescope Array Experiment**

I. INTRODUCTION

The Telescope Array (TA) experiment started to observe the ultra-high energy cosmic rays (UHECRs) in the northern hemisphere[1]. This experiment uses the hybrid observation with three stations of Fluorescence Detectors (FDs)[2] and 507 Surface Detectors (SDs)[3]. Each of FD station consists of the two-tiered rings with six telescopes for each. The upper and lower ring cover 3°-33° in elevation and 108° in azimuth. Each telescope has a 256 pixel photo-tube camera and a spherical mirror with a diameter of 3.3m which consists of 18 segment mirrors. The camera has two types filters, an acrylic window on the camera and UV filters on each photo-tube.

For precise measurement of UHECR properties, we have to understand the efficiencies of telescope optics, mirror reflectance, filter transmission, photo-tube quantum efficiency and electronics sensitivity. Here we describe how we calibrate the mirror reflectance and optical filter transmittance of the cameras which are measured using a spectrophotometer, and absolute gains and uniformities of the tubes which are measured and monitored hourly for every camera with a tiny stable light source and a Xe flasher as an uniform light source. Moreover we report the calibration for the non-uniformity of photo-cathode sensitivity measured by a large XY stage attached to a camera window.

II. MIRROR REFLECTANCES

A mirror of TA FDs are the spherical segmented mirror with a diameter of 3.3m which consists of 18 hexagonal segment mirrors. Each segment mirror is selected with a condition of the spot size at the focal plane less than 30mm. We have the spectral reflectances for all the segment mirrors above 250nm measured by the production company (SANKO SEIKOJYO Co.). Moreover, the reflectances are measured and monitored regularly with the spectrophotometer (KONICA MINOLTA CM-2500d). The handling of this spectrophotometer is easy for a compact (w69mm×h96mm×d193mm) and light weight (670g excluded the battery) body. However, the minimum of wavelength of the sensitive range is 360nm. Therefore, we use the data measured by the company as an absolute spectral reflectance and we monitor their time variations and degradations.

At the time of installation of the mirrors, we had measured the reflectances for all the mirrors in order to know an individual difference (Fig. 1). While the maximum difference is about 5%, almost all the mirrors are within ±1% difference. Until Jun. 2008, we monitored the mirror reflectances only for lower mirrors every half year. Then, in July 2008, all mirrors are washed with pure water and measured the reflectances before and after washing. After this, we have decided to monitor the reflectances for same 4 telescopes of each station every one or two months. Fig. 2 shows the time variation of the averaged mirror reflectances for each layer of the LR station lower telescopes. Notice that the spectrophotometer has 1% systematic fluctuation for each measurement. The magnitude of degradation depends on the height of the mirrors, and that is about 3% per half year for the lowest layer and less than 1% per half year for the highest layer.

The absolute spectral reflectance for every mirrors can be calculated with an individual difference (Fig. 1) and its time variation(Fig. 2) and an absolute reflectance at its production. Fig. 3 shows an examples for a telescope. The systematic errors of measured reflectances are estimated about 3% by the systematic on the spectrophotometer and by interpolations of time variations.

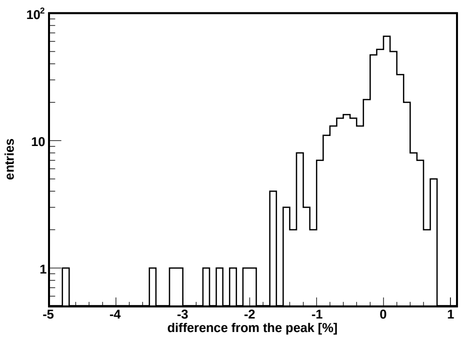


Fig. 1: The individual difference measured at the time of installation.The total number of mirrors is 432 at the BR and the LR stations. The horizontal axis shows the difference from the peak reflectance.

III. Transmittance of the UV filters on the photo-tubes and the camera

As important optical components, TA FDs have two types of optical filters. In order to reduce incident night sky back ground light, a UV transparent filter (SCHOTT BG3) with 4mm thickness is mounted on each phototube. On each camera, there is UV transparent acrylic panel (KURARAY PARAGLAS-UV00) for protecting photo-tubes from the dust. The spectral transmittances of the filters and panels are measured with a spectrophotometer (HITACHI U-1100). Fig. 4 is the result for 99 UV filters measured before installations, and Fig. 5 is the result for 3 tiny fragments of acrylic panels.

Additionally, we checked the transmittance of every acrylic panel by comparing the Xe flash intensity[4] through the window with that without the window. The individual difference is smaller than 3%.

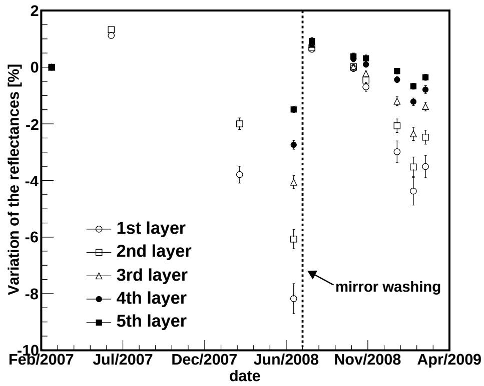


Fig. 2: The time variations of the averaged mirror reflectance for each layer of LR the station lower telescopes. Each data point corresponds to an average over mirrors of same height (the 1st layer is lowest). Open circles are of the 1st layer (lowest), and open squares, open triangles, filled circles and filled squares are 2nd, 3rd, 4th and 5th layers, respectively. Error bars indicate standard deviations for each layer. The vertical axis is the difference from the first mirror reflectance measured at the time of installation.

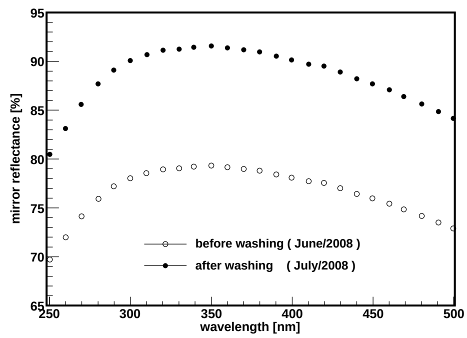


Fig. 3: The spectral reflectance of camera #06 of the BR station. Open circles are the reflectance before washing and filled circles are after washing.

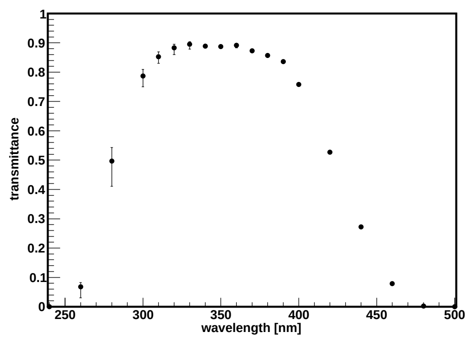


Fig. 4: A typical transmittance of the UV filter on phototubes. Data point is the median for all the sampled filters with 1 σ error bar.

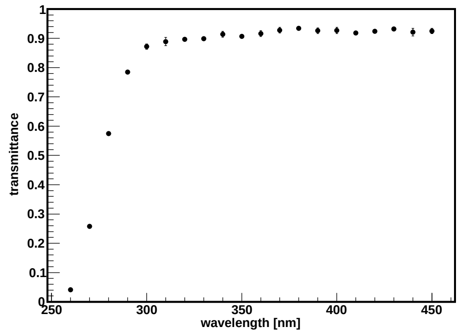


Fig. 5: The typical transmittance of the acrylic window panel on the camera. Filled circles are the median value for three samples. Error bars indicate the differences between the median and the other two samples.

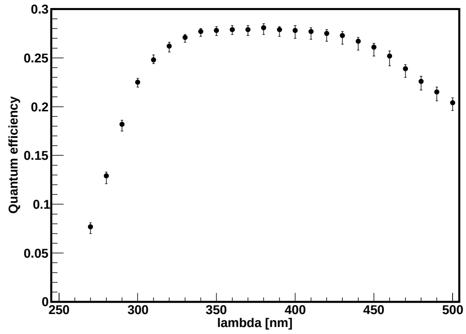


Fig. 6: The typical quantum efficiency of photo-tubes. Data point is the median with 1 σ error bar of all the measure photo-tubes by HAMAMATSU PHOTONICS.

IV. NON-UNIFORMITY OF PHOTO-CATHODE SENSITIVITY

The quantum efficiency (QE) and the collection efficiencies (CE) for several photo-tubes have been measured by production company, HAMAMATSU PHOTONICS. Fig. 6 is the result of averaged QE for 32 samples. The measured averaged CE for five samples is $0.909^{+0.005}_{-0.002}$. In general, however, these efficiencies are not uniform over the photo cathode.

The spot size of our telescope optics is less than 30mm at the focal plane. On the other hand, the photo-tubes has 2in. diameter hexagonal photo sensitive area. Therefore, output signals of photo-tubes are affected by that non-uniformity.

In order to measure this, we developed a large XY stage attached on the camera window (XY-scanner)[4]. This module has eight light sources which consist of UV LEDs (NICHIA-NSHU590B) with a peak wavelength of 365nm and the spot size of 4mm×4mm. The number of measurement points per photo-tube is about 200 with 4mm spacing.

Fig. 7 is an averaged non-uniformity map over 253 photo-tubes (excluded the three standard photo-tubes with YAP) on the camera #05 at the BR station. This is normalized with the bins inside circle with 36mm diameter. This condition corresponds to the effective area for the absolute gain calibration(Section V).

HAMAMATSU have also measured the non-uniformities along two cross-sectional axis. Fig. 8 is the comparison between the results by HAMAMATSU and that of XY-scanner, and they are in good agreement.

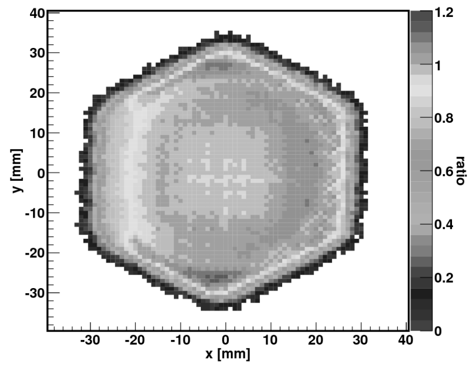


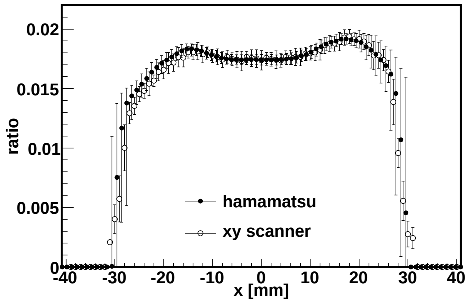
Fig. 7: The typical non-uniformity map with 1mm×1mm resolution of the photo-cathode of our photo-tube. The non-uniformity map is normalized with the bins inside circle with 36mm diameter.

V. ABSOLUTE AND RELATIVE CALIBRATION OF PHOTO-TUBES

The FD camera consists of 256 (16×16) hexagonal photo-tubes (HAMAMATSU R9508). Currently, the calibration process of photo-tube gain is divided into three steps, namely the absolute gain measurement for the standard photo-tubes, the relative gain measurement for a camera and the correction for the temperature characteristics of photo-tubes.

In ICRR, we developed a simple pulsed UV light calibration systems called CRAYS (Calibration using RAYleigh Scattering)[5]. The light source is a scattered photons of nitrogen laser light with 5% absolute intensity error with pure nitrogen gas molecules. By the system, three photo-tubes per camera are sampled, and for each sample the absolute relation between the number of injected photons of 337.1nm and a sum of the ADC counts by the electronics used in TA FDs are recorded as the conversion factor. It should be noticed that the measured absolute response by CRAYS includes the transmittance of UV filters, and effective photo-cathode area is limited within the circle with a diameter of 36mm.

This calibrated absolute gain of every standard photo-tube is monitored hourly by a tiny stable light source called YAP pulsar. This is a UV pulsed light source with a diameter of 4mm and a height of 2mm consists of a 50 Bq alpha-ray sources (Am^{241}) and a YAP scintillator ($YAlO_3$:Ce). The temperature dependence of an intensity is about -0.2 %/degree from -10 to 40



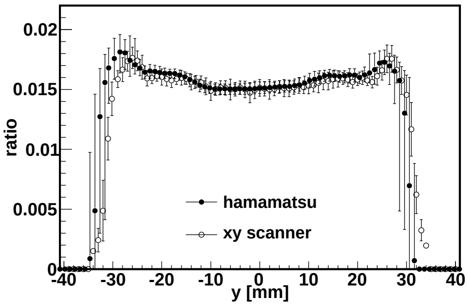


Fig. 8: The result of comparison HAMAMATSU data with measured data by XY-scanner. Upper and lower figure are corresponded the difference measured axis.The definition of the coordinate of x and y axis is same as Fig. 7. Filled circles are the HAMAMATSU data, and open circles are XY-scanner's.

degrees[6]. Each standard photo-tube has this pulsar on the center of photo-cathode, and its gain is regularly monitored comparing outputs with the YAP pulsar intensity. The typical intensity is equivalent to 450p.e. with a fluctuation of 10% and an individual difference of 5%. The relation between the absolute gain and the intensity of the YAP pulsar is also calibrated by CRAYS for all of the standard photo-tubes.

The uniform light source called Xe flasher is mounted on the center of each mirror, and it is faced to the camera center. Xe flasher, consists of Xe lamp and diffuser, emits pulsed photons with an intensity equivalent to $2{\times}10^4$p.e. and a width of 2μs. We adjusted the gains of all of the photo-tubes to that of standard photo-tubes, and we monitored once per an hour during observations with this light source. The standard deviation of the adjusted relative gains for each camera is about 1%[4].

In general, responses of the photo-tubes and the pre-amplifiers depend on temperature. We prepared a measurement system for temperature characteristics for photo-tubes, the pre-amplifiers and YAP pulsars. Several standard photo-tubes were tested, and the typical measured temperature coefficient of the photo-tubes including that of pre-amplifiers is about -0.7%/degree[6]. Moreover temperatures of each camera are measured every minute with a thermometer mounted in each camera box. Therefore, we can correct measured temperature effects for all the observation terms.

Currently, we calculated the absolute gains for all the photo-tubes with these absolute and relative gain measurement and temperature coefficient. Fig. 9 shows an example of the averaged absolute gains for 256 phototubes in camera #06 of BR station at Mar/2008.

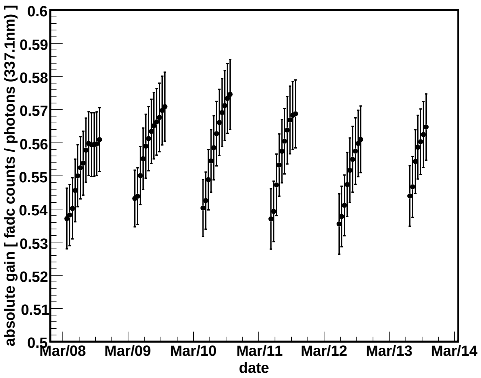


Fig. 9: The hourly variation of absolute gain at Mar/2008. Filled circles are averaged gains for 256 photo-tubes in camera #06 of BR station. Error bars are the standard deviations for 256 photo-tubes.

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