Calibration of JEM-EUSO photodetectors

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Abstract: The calibration of the JEM-EUSO focal surface (FS) about 5000 photomultipliers (PMTs) will be made in two steps: a) on earth, PMTs will be sorted out according to their gain and efficiency. Then identical PMTs will be used to make the Photo Detector Modules (PDM) consisting of 36 PMTs (2304 pixels). Immediately after the PDM assembly, the gain and absolute efficiency of each pixel will be measured with the PDM's own front end electronics working in single photo-electron mode. A X-Y-Z-θ-φ (PDM has a spherical shape) movement will support the illuminating device consisting of UV LEDs with wavelength of 330-430 nm inside an integrating sphere whose exit port will feed a collimator with 0.3 mm holes. The light will be monitored with a NIST photodiode mounted on a third port of the sphere. This set-up will be calibrated by replacing the PMT with another NIST. b) in space, during the day, when the JEM-EUSO lid is closed, the focal surface will be illuminated in a uniform way by a set of 1 inch spheres set on the periphery of the last lens (at one meter from the FS). The spheres will be equipped with LEDs and monitored by NIST photodiodes. Another set of identical spheres will be put at the FS periphery and will illuminate the lenses. The light will bounce back on the lid covered with diffusive reflector, to reach the FS which has been previously calibrated. Other means of in flight calibration will use ground sources (Xenon flashers) and finally the moon light reflected by earth albedo.

Keywords: Ultra high energy cosmic ray, International space station, JEM-EUSO, Calibration

1 Introduction

JEM-EUSO is a mission to observe ultra high energy cosmic rays (UHECRs) above 10²⁰ eV[1, 2]. The JEM-EUSO telescope will be attached to the International Space Station (ISS) and will detect fluorescence photons from extensive air showers (EASs) induced by UHECRs. It is necessary to understand the instrument very well to discuss its origins. The JEM-EUSO instrument consists of Fresnel lens optics with a diffractive lens and the focal surface detector with photon counting capability[3, 4].

The number of observed photo-electrons (ΔS) from a luminous phenomena (with emitting number of photons of ΔQ) at distance r is expressed as:

\[ ΔS = \frac{εηκT_lT_fT_rT_aA}{4πr^2} ΔQ, \]

where,
ε quantum efficiency of the detector
η collection efficiency of the detector
κ the probability to be contained in a pixel
T_l throughput of the Fresnel lens system
T_f transmission of the optical filter
T_r trigger efficiency of the electronics
T_a atmospheric transmission
A aperture of the telescope.

The terms related to the instrument among above are ε, η, κ, T_f, T_r and T_a. Here, let’s consider the calibration of the instrument with the following four cases.

- Pre-flight calibration
- On-board calibration
- In-flight Calibration with ground light sources
- Atmospheric monitor

For the atmospheric monitor, a dedicated subsystem is organized[5]. A ultraviolet(UV) LASER and an infrared camera are under preparation to measure the cloud coverage in the field of view and the cloud heights. The other three calibrations are included in the “calibration system” and are being prepared by the collaboration of Japan, France, United States, Italy and Mexico.

The energy of 10²⁰ eV has not been reached until now artificially, so that it is difficult to determine the absolute energy scale directly by any calibration. However, JEM-EUSO is expected to detect more than 1000 UHECRs in the mission period. If there are sources in our vicinity, the energy spectrum for each source will be obtained. Since ultra
high energy cosmic rays interact with cosmic microwave background photons and lose energy, the spectrum will be suppressed above \( \sim 4 \times 10^{19} \) eV (GZK suppression). If the suppression threshold energy is obtained as a function of distance, the absolute scale might be determined.

2 Pre-flight calibration

2.1 Outline

The JEM-EUSO optics consists of two Fresnel lenses, a diffractive lens and a focal surface[3, 4, 6]. The focal surface is covered with about 5000 pieces of 1” multi-anode photomultiplier tubes (MAPMTs) developed for JEM-EUSO[7, 8]. The focal surface detectors are grouped, to make it easy for manufacturing and the data handling. A module of four PMTs is called “Elementary Cell” (EC) and a photo-detector module (PDM) consists of 9 ECs. Each PDM has a capability to detect EASs induced by cosmic rays by itself. The stand-alone performance and the functions of optics, electronics, etc. will be checked in each dedicated subsystem in principle. The calibration subsystem is in charge to measure the efficiency of the focal surface, especially efficiency of the MAPMTs.

2.2 Calibration of MAPMTs

The gain of a MAPMT will be measured at various voltages to determine an appropriate voltage for the input to the front-end electronics. As shown in Figure 1(a), LED light will be diffused with an integrating sphere to illuminate the photo-cathodes of 5-10 MAPMTs. Three kinds of wavelength will be used in the range of 330 nm and 430 nm. Pulse height distribution will be taken with photon-counting method with the electronics developed for night glow measurement by the EUSO Italy group. All the PMTs will be sorted out by their gain and efficiency, and every four PMTs with similar characteristics will be packed as an EC.

2.3 Calibration of PDMs

In order to measure the position and angular dependences of the photon detection efficiency of PDMs, an integrating sphere with UV LED at 375 nm and a monitor photodiode is mounted on a XYZ\( \theta \phi \) stage and the PDM surface will be scanned with 1 mm step with various incident angles (Figure 1(b)). The light is collimated to 1 mm in diameter. The photo-diode is calibrated precisely by the manufacturer. The efficiency of not only MAPMTs but the whole system (=quantum efficiency\times collection efficiency\times electronics efficiency) can be obtained. In this measurement, the variation of the intensity is monitored by a well-calibrated photo-diode, and that the attenuation of light to single photo-electron level is determined by the geometrical factor of the collimator. Therefore, the efficiency can be obtained better than a few percent.

Next, to check the trigger efficiency of PDM, fluorescence image from a cosmic ray air shower will be emulated with an array of UV LEDs. UV beam reflected by a rotating mirror is another candidate to emulate EAS image. The rotating speed will be adjusted to reproduce the light spot speed of EAS on the focal surface.

2.4 End-to-End calibration

The total performance of the instrument will be checked at this stage. One of the possible methods is that EAS image generated with a LED array for the PDM calibration is projected to the entrance pupil by a large parabolic mirror(Figure 1(c)). UV LASER light reflected by a rotating mirror is another candidate light source at this stage, too.

3 In-flight calibration

3.1 Outline

Absolute values of efficiency, gain, etc. will be measured on ground before launch, and only the relative changes will be monitored in flight in principle. Several light sources will be put in the JEM-EUSO instrument to monitor the efficiency and the detector gain. Ground light sources and the reflection of the moonlight by the Earth will also be utilized to make the calibration more reliable.

3.2 On-board calibration

The light source consists of a small integrating sphere equipped with UV LED in 330-430 nm and a NIST photodiode to monitor the variation of the light intensity. Several identical light sources will be settled behind the rear lens and illuminate the whole focal surface (Figure 2 (a)). The intensity will be set at single photo-electron level and the photon detection efficiency of the system and the gain of MAPMT will be measured. If large change of gain is found, the threshold level for the counting will be adjusted. Other several light sources will be set along the edge of the focal surface to illuminate the rear lens. The light passes through the lenses and is reflected back at the diffuse surface on the lid. A certain amount of the emitted light will be detected by the focal surface detector. The time variation of the efficiency of the optics and the detector will be obtained in this measurement. Therefore, after subtracting the degradation of the detector itself, the decrease in the optics throughput will be obtained.

3.3 From-ground calibration

3.3.1 Ground light source (Flasher)

There will be a dozen ground-based units deployed at host stations in different geographical locations to cover various atmospheric conditions, and one airborne unit. ISS will fly
Figure 1: Apparatus for the pre-flight calibration. (a) Uniform light made with an integrating sphere illuminate ten MAPMTs. Single photo-electron spectrum will be taken with photon counting and MAPMTs will be sorted according to the gain and the efficiency. (b) A light source made of an integrating sphere is mounted on a stage to measure the PDM efficiency at various positions and with various incident angles. (c) An emulate air shower image with a LED array will be seen with the JEM-EUSO instrument to check total performance.

Figure 2: On-board calibration system. Diffused UV light sources made of integrating spheres will be set at the position shown in the panels (a) and (b), and the time variation of the efficiency of the optics and the detector will be monitored. (a) Several light sources will be set along the edge of the rear lens to illuminate the focal surface directly. The relative change of the detector efficiency will be taken. (b) The same light sources are placed along the edge of the focal surface to illuminate the rear lens. The light is reflected back at the diffuse surface on the lid and is detected by the focal surface detector. Here, convolution of the efficiency of the optics and that of the detector will be obtained.

over one flasher in average every night, the lamp will be lit by remote control for the cross-check of the JEM-EUSO photon detection efficiency, atmospheric transmittance, focusing quality of the JEM-EUSO optics. The airborne unit is to be installed on an upward directed portal of a P3B research aircraft stationed at NASA Wallops Flight Facility. It flies under the orbit of ISS at the altitude of 1-6 km above both land and sea every month during the JEM-EUSO mission. The Hamamatsu flash lamp L6404 has an light intensity of 2J per flash. The expected signal detected by JEM-EUSO is about 500 photo-electrons for clear nights. The maximum flash-to-flash variation for this lamp is 3% and the spatially non-uniformity is less than 5% over a 60° field of view. The duration of over-flights range from 5 to 70 seconds, so that typically 100 flashes per over-flight will be observed by JEM-EUSO. Atmospheric transmittance will be determined with a few percent accuracy by repeating measurements. Each ground flasher consists of four lamps with band pass filters at 337 nm, 357 nm and 391 nm, which corresponds to the wavelength of main N₂ fluorescence lines, and one broad band filter similar to that on JEM-EUSO. The intensity of the lamps is monitored by
Figure 3: In-flight calibration with ground light sources. JEM-EUSO will fly over one of the 10-20 Xe flasher stations in average every night, and atmospheric transmittance and the JEM-EUSO efficiency will be checked. Artificial extensive air showers generated by LIDAR will be used to study the reconstruction accuracy experimentally.

3.3.2 Ground LIDAR

Since we can emulate EASs with the third harmonic of NdYAG Laser (355 nm), ground LIDARs may be an effective tool for calibration. In order to emulate the EAS of $3 \times 10^{20}$ eV with an elevation angle of $\sim 20^\circ$, we need the output of 50 mJ at least. Once the power and the elevation angle of the Laser are fixed, we can determine the size of the receiver (1 m in diameter). The signals back-scattered at 30 km and 60 km are about 800 photo-electrons and 20 photo-electrons in GTU (2.5 $\mu$s). If we shoot 100 times, for example, more than 1000 photo-electrons will be observed and the atmospheric properties are determined well. We can measure the transparency with an accuracy of 5-10% after 100 shots. As a ground light source the shot in the elevation angle of 20-30$^\circ$ is optimum and probably the fixed directional Laser may be robust and minimize the maintenance of the mechanical parts of the system. The Laser can be tunable up to 10-30 Hz. In these horizontal shots, the Laser beam reaches the top of the atmosphere after traveling 30 km, where the Rayleigh scattering is dominant. The beam travels in pure molecular region for another 30 km and we can get the boundary condition for the LIDAR equation, because we can know the ratio of the back-scattered intensity to the beam intensity in the pure molecular region. Then we can solve the LIDAR equation to obtain the transmittance of the atmosphere as a function of height. The Laser beam with an elevation angle of $20^\circ$ can be seen as a track of 30-50 km long from JEM-EUSO.

If the scattering is dominated by the Rayleigh process, the number of photons at the entrance of JEM-EUSO can be calculated. The scattering angles of photons that JEM-EUSO will receive are always larger than $40^\circ$. In such large scattering angles, Rayleigh process usually dominates under good weather condition. We will use photons scattered above 3 km where the scattering is better described only by the Rayleigh process. Simultaneous operation of the on-board LIDAR system and the ground LIDAR system gives us more detailed information about the atmosphere and more redundant measurements. It will also reduce the systematic error in the measurement significantly. The systematic errors and the resolutions of arrival direction and energy determinations by JEM-EUSO can be evaluated experimentally by reconstructing LIDAR events.

4 Summary

Calibration of the instrument plays a key role to open a new era of “Particle Astronomy” by JEM-EUSO. In order to achieve better than a few % accuracy, several methods for pre-flight and in-flight calibrations are proposed and the preparation is in progress.

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References