On-board calibration system of the JEM-EUSO mission

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Abstract: In order to unveil the mystery of ultra-high energy cosmic rays (UHECRs), JEM-EUSO (Extreme Universe Space Observatory on-board Japanese Experiment Module) will observe extensive air showers induced by UHECRs from the International Space Station (ISS) orbit with a huge acceptance. Calibration of the JEM-EUSO instrument, which consists of Fresnel optics and a focal surface detector with 5,000 multi-anode photomultiplier tubes (MAPMTs), 300,000 channels in total, is very important to discuss the origin of UHECRs precisely with the observed results. The performance of the detector should always be monitored on orbit. Since the on-board resource is very limited, on-board calibration is in principle a relative one. For that purpose, a few uniform light sources with UV-LEDs and integrating spheres will be settled along the edge of the lens facing the focal surface (FS). Very uniform light is available thanks to the integrating sphere and the light intensity will be monitored in real-time by a photo diode attached to each sphere. The same light sources will be put along the edge of the FS and will illuminate the entrance pupil to monitor the transmission of the optics. The performance of the detector itself and the optics will be measured in the ISS days as required. The present development status of the calibration device will be reported together with the expected performance.

Keywords: JEM-EUSO, UHECR, space instrument, fluorescence, International Space Station, calibration, reference light source

1 Introduction

The Extreme Space Observatory on-board the Japanese Experiment Module (JEM-EUSO) is an UV-fluorescence telescope that will be installed at the International Space Station (ISS) in 2017 [1]. The JEM-EUSO telescope consists of three Fresnel lenses and a focal surface (FS) and has a field of view of 60°. From the ISS-orbit (≈ 400 km altitude) the JEM-EUSO telescope will be able to observe a surface area of around 1.4 × 10^5 km^2. The FS consists of roughly 5,000 Multi-anode photomultiplier tubes (MAPMTs) of which each has 8 × 8 pixels and is glued with an UV-filter that transmits UV-light from 330 – 400 nm. Four MAPMTs form one elementary cell (EC) and nine ECs form one photodetector module (PDM). 137 of these PDMs form the whole FS of the telescope.

The main function of the JEM-EUSO telescope is the observation of extensive air showers (EASs) induced by ultra-high energy cosmic rays (UHECRs) with energies above 5 × 10^19 eV [2]. The main component of EASs are electrons which excite Nitrogen molecules of the atmosphere and thus produce isotropic fluorescence light. The particles in EASs also travel faster than the speed of light in air and thus produce Cherenkov light directed towards the Earth. The ultraviolet fluorescence light as well as reflected and scattered Cherenkov light will be detected by the JEM-EUSO telescope.

To estimate the energy of the primary particle the fluorescence yield from electrons which has been measured formerly [3] will be used. Furthermore there are also several quantities related to the detector itself [4]: quantum efficiency and collection efficiency of the detector, probability for a photon to be contained in a pixel, transmission of the Fresnel lens system and of the optical filter, trigger efficiencies of the electronics, atmospheric transmission and the aperture of the telescope.

These quantities have to be measured very precisely before the mission start and have to be monitored throughout the whole mission to have a good understanding of the detector performance at all times. Therefore several systems will be used: pre-flight calibration [4], on-board calibration, in-flight calibration with external light sources [5] and an on-board atmospheric monitoring system (AMS) [6]. The AMS will be attached to the telescope and will consist of an IR-camera [7] to measure the cloud coverage in the field of view and an UV-laser to measure the height of these clouds. The other three subsystems are included in the calibration system of JEM-EUSO.

2 Calibration system

The calibration system consists of three subsystems that are prepared by collaborators from Japan, Germany, France, United States of America, Italy and Mexico. Since an absolute calibration is very difficult to maintain for the whole mission time of JEM-EUSO, it is imperative to monitor changes in the detector. Therefore the on-board calibration system will be used to do a relative calibration of the detector with respect to the absolute pre-flight calibration [4]. It is also planned to use external light sources like the Moon for further in-flight calibration [8]. There will also be on-ground lasers to check the trigger efficiency and the error in the reconstruction of the arrival direction. Xe-flashers will
be used in combination with the AMS devices to measure local atmospheric conditions, e. g. absorption of photons in the atmosphere.

2.1 On-ground reference light source
In order to measure changes in the detection efficiency of the JEM-EUSO detector a reference light source with known optical output is needed. Therefore a prototype on-ground reference light source was built. It consists of a 3-port 13.5 cm (5.3 inch) diameter integrating sphere, with two 2.54 cm (one inch) exit-ports and a 6.35 cm (2.5 inch) entrance-port. An UV-LED-array is mounted light-tight to the entrance-port and a NIST-calibrated photo diode and a collimator are mounted light-tight to the exit-ports (Fig. 1).

The UV-light (≈ 375 nm) from the LED-array is diffusely reflected inside the integrating sphere and distributed uniformly over the inner surface of the sphere. The sphere’s inside is made of Spectralon [9] which reflects 98% of UV-light in the region of 300 – 430 nm. The integrating sphere behaves as a beam splitter and a diffuser. The fraction of photons leaving the sphere from one port is proportional to the area of the port itself [10]. Therefore both exit-ports emit the same number of photons \( N_{\text{Sphere}} \). This is measured at one exit-port with a NIST-calibrated photo diode (Photo Diode 1). The collimator at the second exit-port is there to reduce the photon flux from the exit-port. This is necessary because the light source will illuminate MAPMTs and their gain is around a factor of 10\(^6\) bigger than the gain of the photodiode.

The optical output of the light source is measured by a second NIST-calibrated photo diode (Photo Diode 2) as the number of photons \( N \) that are emitted by the light source. The ratio of both photon numbers gives the collimator factor \( R \) of about 10\(^{-6}\). Because of the low gain of the photo diode and the strong collimator reduction the whole LED-array is set to continuously emit light. Because the collimator factor \( R \) only depends on the collimator geometry and was measured very precisely with the second NIST-calibrated photo diode, the number of photons \( N \) emitted by the reference light source can be calculated via the measurements of the number of photons \( N_{\text{Sphere}} \) inside the sphere. With this the number of emitted photons \( N \) is known and the light source can be used to illuminate one or more MAPMTs. For high-gain sensors in front of the reference light source, only one LED of the LED-array will be used while being pulsed by a LED-driver. Then the number of detected photons by this sensor is \( N_{\text{Port}} \).

With this set-up the number of photons emitted by the reference light source can be calculated via the collimator factor and the signal from the first NIST-calibrated photo diode. The ratio of the number of photons detected by the pixels of the MAPMTs and the total number of photons leaving the reference light source at the collimator gives the detection efficiency of every pixel of the MAPMTs. The gain can be obtained by measuring the single photo-electron spectra of every MAPMT [4].

2.2 On-board calibration system
The on-board calibration system will be installed into the JEM-EUSO telescope to monitor changes in the detection efficiency of the detector and in the transmission of the optics. This calibration will be relative to the absolute calibration that was done pre-flight. The on-board system will consist of several small identical diffuse light sources that will be placed at different locations inside the telescope (Fig. 3).

The on-board light sources will be built with an integrating sphere with a diameter of 2.54 cm (one inch), one or more UV-LEDs with 300 – 430 nm, a LED driver and a NIST-calibrated photo diode to monitor variations of the light intensity (Fig. 3). The coating on the inside of the integrating sphere will be Spectralon. The optical output from one source will be a Lambertian distribution with a maximum emitting angle from the optical axis of the source. This maximum angle is dependent on the shape and size of the pinhole that will be put on the exit-port of the sphere. The on-board light sources will be characterised pre-flight with the on-ground calibration system shown above.

To measure the detector calibration change, several identical diffuse light sources will be placed at the edge of the third Fresnel lens to achieve a direct illumination of the FS (Fig. 3(a)). The intensity will be set to single photo-electron mode and the relative change of the detection efficiency will be measured while the gain of the MAPMTs will be measured absolutely. The threshold level for the counting will be adjusted if a large variation in gain is found.

Figure 1: Sketch of the on-ground reference light source. The number of photons before and after the collimator is measured via two NIST-calibrated photo diodes. The emitted number of photons by the reference light source is calculated via the signal from the first NIST-calibrated photo diode.

Figure 2: Schematic view of the on-board light source. The light source consists of one ore more UV-LEDs, a monitor photo diode, LED driver electronics, readout electronics and an interface circuit to a cluster control board (CCB).
The efficiency of the optics will be measured with identical light sources placed at the edge of the FS facing the rear side of the third lens (Fig. 3(b)). The UV-light from the light sources will pass the optics, be reflected at the diffuse lid (sand-blasted Aluminium) and pass the optics a second time. The MAPMTs at the FS will detect a fraction of the emitted photons. The time variation of the performance of the optics and the detector will be obtained at the same time in this measurement. Changes in the optical system can be obtained after subtracting the degradation of the detector.

2.3 Expected performance

In order to gain a better understanding of the requirements for the on-board calibration system, raytracing simulations where made for the direct illumination and the illumination through the optics. The goal was to achieve a very uniform illumination pattern on the FS. For both cases different set-ups were used. The required intensities for the sources were estimated to operate the on-board system in the single photo-electron regime.

Direct illumination: Four light sources were placed at the centres of the four edges of the rear lens. Each light source faced the FS and had a Lambertian optical output. The maximum emitting angle from the optical axis of the source was set to 60°. The inclination of the optical axis of the source from the optical axis of the telescope was set to 50°. The resulting illumination pattern is very uniform (Fig. 3). Additional simulations where done with a single source failing, resulting in a non-uniform illumination pattern on the FS. However the resulting ratio of the intensity was about a factor of two and is still acceptable for the on-board calibration. With four light sources, the on-board calibration with direct illumination will be redundant.

Illumination through optics: For this simulation one light source was placed at the centre of the bottom edge of the FS facing the rear lens. The optical output of this source was again a Lambertian distribution. The maximum emission angle was narrowed to 10°. Therefore a suitable pinhole will be designed. The inclination of both optical axes was set to 10°. The material of the lenses is PMMA with the respective optical properties. The reflectivity of the diffusive lid was set to 50%. The resulting illumination pattern on the FS is composed of three bunches at different arrival times (Fig. 5). The first two bunches result from reflections at the rear and middle lenses. The last bunch is a superposition of reflections at the front lens and the lid. Raytracing showed that photons which were reflected only from the lid create a diffuse image on the FS. A discrimination of these photons is not possible, however one can choose photons that arrive near the center of the FS. These have a higher probability to have been reflected only by the lid.

Light source intensity: First the light intensity estimation for the direct measurement will follow. A typical UV-LED with light emission at 380nm and an optical output power of 1 mW is attached to an integrating sphere with a diameter of 25 mm and Spectralon coating. The exit-port of the sphere is a pinhole of 1 mm diameter. The resulting light intensity follows from [10]:

\[
\Phi = \Phi_i \cdot \frac{A_{\text{port}}}{A_{\text{sphere}}} \cdot \frac{\rho}{1 - \rho} \left(1 - \frac{\Sigma A_{\text{port}}}{A_{\text{sphere}}}\right) \cdot \sin^2 \theta
\]

with the input flux \(\Phi_i\), the exit-port area \(A_{\text{port}}\), the internal sphere area \(A_{\text{sphere}}\), the reflective index \(\rho\) and the emission angle \(\theta\) of the port. With the reflective index \(\rho = 0.98\) for Spectralon and an emission angle of 60° (Lambertian distribution), one source will emit about \(10^{13}\) photons/s. The raytracing simulation results (Fig. 5) gave approximately \(3 \times 10^{-4}\) photons/PMT for the detection probability on the FS. Combining these two results gives for the number of photons per pixel (px) and gate time unit (GTU) (\(GTU = 2.5 \mu s\)):

\[
10^{13} \times 3 \times 10^{-4} \frac{\text{ph}}{64 \text{px}} \times 2.5 \times 10^{-6} \frac{\text{ph}}{1 \text{GTU}} = 120 \frac{\text{ph}}{\text{GTU} \cdot \text{px}}
\]

A conservative assumption of 20% for the detector detection efficiency results in 24 p.e./GTU/px. In order to avoid overlapping of single photo-electron pulses we require \(\approx 1\) p.e./GTU/px. This can be achieved by reducing the intensity of the LED via the LED-voltage or the reduction of the duty cycle via the LED driver. For higher intensities (> 300 p.e./GTU/px) one LED with 1 mW is not enough. Here a more powerful LED (15 mW) or several LEDs are necessary.

The light intensity estimation for the optics transmittance is similar to the estimation above with a 1 mW LED. Here the emission angle was reduced to 10° and the detection probability was reduced to about \(10^{-7}\) ph/GTU/px. This
leads to 0.025 p.e./GTU/px that are detected. For this calculation, the photons which hit the wall were assumed to be absorbed completely. In the real case with a finite reflectivity of the walls, the discrimination of reflected photons from the lid becomes very difficult.

3 Summary

The calibration system of JEM-EUSO with the focus on the on-board calibration was presented. The on-board calibration is very important to monitor changes in the detector throughout the whole mission time. It consists of several UV-light sources that are placed at different positions inside the telescope. Raytracing simulations have pointed out that the direct illumination of the focal surface produces a very uniform illumination with four light sources. The calibration can still be continued if one light source fails. The indirect illumination through the optics needs further investigation. Furthermore other configurations like a light source on the lid will be studied in detail. Intensity calculations showed that the desired photo-electron/GTU levels can be achieved with 15 mW LEDs. After completion of the light source prototype it will be tested with the on-ground calibration device.

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Figure 4: Light intensity distribution on the focal surface (FS) with four light sources at (0 mm, ±945 mm) and (±1320 mm, 0 mm). The upper left panel shows the 2-dimensional illumination. The colour scale shows the photon detection probability in a 1 cm² area, when the light sources emit one photon. The upper right panel shows the projected histogram of a vertical 5 cm wide stripe at x=0. The vertical axis shows the probability of a photon reaching a 5 × 1 cm² area. The lower left panel shows the same histogram for a horizontal 5 cm wide stripe at y=0.

Figure 5: Light pattern on the focal surface (FS) for the optics transmittance measurement configuration. The upper left panel shows the 2-dimensional illumination pattern on the FS, the upper right projection along y-axis and the lower left projection along x-axis, as described before. The lower right panel shows the arrival time distribution of photons at the FS.

References