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Expected acceptance of the KLYPVE/K-EUSO space-based mission for the observation of ultra-high energy cosmic rays

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KLYPVE/K-EUSO is a space-based observatory of ultra-high energy cosmic rays on the international space station to study anisotropy with higher statistics. The collaborative work has begun in 2013 between the original KLYPVE collaboration and the JEM-EUSO collaboration to utilize the lens technology developed for JEM-EUSO in the KLYPVE mission. The baseline optics of KLYPVE/K-EUSO consists of a mirror, a corrective Fresnel lens and a focal surface detector. The full acceptance will be about twice larger than that of Pierre Auger Observatory, and about 20% of JEM-EUSO's. The trigger threshold energy of KLYPVE/K-EUSO was found to be possibly twice lower than that of JEM-EUSO.

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1. Introduction

More than 50 years have passed since the first 10^{20} eV candidate was registered[1], but the origin of cosmic rays with energy above 50 EeV is still a mystery. At present, two observatories for the observation of ultra-high energy cosmic rays (UHECRs) are in operation. One is the Telescope Array Project (TA) in the northern hemisphere and the other is the Pierre Auger Observatory (Auger) in the southern hemisphere. TA reported a "hot spot" (excess regions of cosmic rays above 57 EeV in the celestial sphere) with a significance larger than 5σ[2]. Auger reported a dipole anisotropy and correlation with nearby Active Galactic Nuclei (AGNs)[3, 4] in the similar energy range, although the significance is smaller than the hot spot reported by TA. These results give us a hint about their origin, but the statistics are not enough to make it clear because of the very low flux above 50 EeV, ~ 1 event/km^2/100years. To overcome the difficulty of low statistics, several observations from a satellite orbit have been proposed, among them JEM-EUSO[5] and KLYPVE[6] projects. Both projects are space-based missions under development. The idea is to launch onto the International Space Station (ISS) a telescope to observe tracks of fluorescence and Cherenkov light in near ultra-violet band from Extensive Air Showers of UHECRs with large acceptance. Thanks to the orbit of ISS, the whole celestial sphere can be observed with a single detector with a flat exposure, which is one of the advantages for the large-scale anisotropy study. The acceptance of KLYPVE was found to be able to be improved considerably by utilizing the Fresnel lens technology developed for JEM-EUSO[6]. Collaborative work between the KLYPVE and JEM-EUSO collaborations has started in 2013[6, 7], which is called KLYPVE/K-EUSO hereafter. KLYPVE/K-EUSO is a first step to prove the ability of UHECR observation from space and of the anisotropy study with statistics higher than that of TA. Successful KLYPVE/K-EUSO mission will lead to space-based experiments with larger acceptance such as JEM-EUSO and Super-EUSO[8] to identify UHECR sources and to study their production mechanism.

2. Baseline Optics of KLYPVE/K-EUSO

The baseline optics for KLYPVE/K-EUSO consists of a mirror of 3.4 meter diameter, a double-sided Fresnel lens of 1.7 meter diameter and a focal surface of 1.4 meter diameter (Figure 1). The lens is made of UV-PMMA (Ultra-Violet-transparent Poly methyl methacrylate) of 10 mm thickness and reduces the effect of comatic aberration especially for a large field angle. Absorption loss in the lens material is less than 10% for the wavelength longer than 320 nm. Diffractive optics is adopted on the focal surface side of the lens to correct chromatic aberration. There are several ways to realize diffractive surfaces in general. For KLYPVE/K-EUSO, it will be realized by a Fresnel surface with groove depth of 700 nm. The other side of the lens is a Fresnel surface with groove depth of 1 mm. The focal surface consists of 1,900 multi-anode photomultiplier tubes with 64 pixels each with pixel size of $\sim 3 \times 3$ mm^2. Each photomultiplier has a BG3 band-pass filter[9] on top to select photons in the wavelength range between 290 nm and 430 nm where main lines of Nitrogen fluorescence exist. The total number of pixels are 120,000. The data acquisition system works in photon counting mode with intelligent trigger to discriminate shower tracks[10]. The designed field of view is $\pm 14^\circ$ for the whole optics and $\sim 0.058^\circ$ for a pixel which corresponds to 0.4 km on the ground from the ISS altitude of 400 km.

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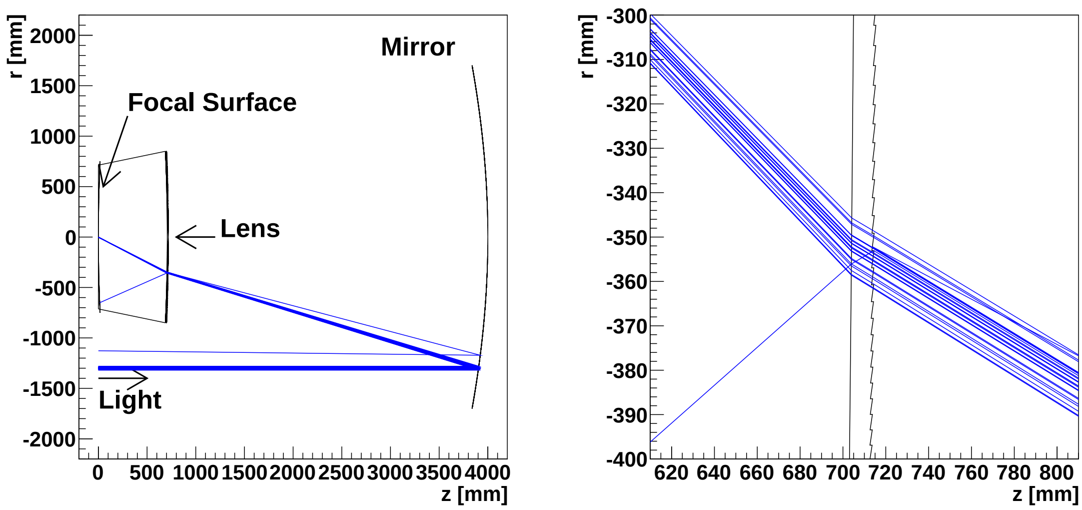

Figure 1: Schematic view of the KLYPVE/K-EUSO optics. General view of the optics is shown in the left panel and enlarged view of the lens with rays refracted and scattered by the lens in the right. Several examples of light paths are drawn with blue lines.

A dedicated raytracing code was developed to evaluate the performance of the optics. Sample rays traced by the code are shown in Figure 1. In the calculation, 90% was used for the mirror reflectivity as a realistic number and the behavior of the rays at the diffractive surface was calculated with an optical path difference function. Figure 2 shows the shapes of the spots for three main lines of Nitrogen fluorescence (337, 357 and 391 nm) and five different angles of incidence from the optical axis between 0 and 14 degrees. The photons make very complicated shapes on the focal surface depending on the wavelength and the angle of incidence. Most of the photons were concentrated at the expected position, but widely scattered photons were also observed all over the focal surface. The ratio of the scattered photons outside of the area of 20 mm$\times$20 mm is 4% for the field angle 0 degree and increases up to 7% at 14 degrees.

In order to evaluate the performance of the optics more quantitatively, root-mean-square spot radius is plotted as a function of angle in the left panel of Figure 3. The size is comparable to the pixel size up to 14 degrees. Taking into account the tail of the point spread function outside of the pixel size, the trigger will be issued based on the signal-to-noise ratio in 3$\times$3 pixels.

The transmittance of the optics is plotted in the right panel of Figure 3. Here we define the transmittance as the ratio of the number of photons which reach area within 3.5 mm radius on the focal surface to those incident onto the area within 1,700 mm radius at the entrance of the optics which is at $z = 0$ in Figure 1. The center of the incident area was translated in the plane perpendicular to the optical axis according to the angle so that maximum number of photons reached the focal surface. In the calculation, we assumed 5% loss due to the manufacturing error of the lens and 95% as the diffraction efficiency, which will be verified and tuned in the future by comparing with measured values of prototype optical elements. The transmittance is about 50% for 0 degree and decreases with larger angle, because more photons will miss the lens at larger angle. Larger the lens diameter becomes, more photons will be obscured by the lens and less photons will miss the lens at large angle. We have decided 1.7 meter as an optimum diameter of the lens taking into account the both effect. The budget of the photon loss in the optics for 357 nm and 0 degree for example is as follows. 25% of incident photons will be blocked naturally by the focal surface - lens structure. 10% will be lost at the mirror and about 13% will be scattered or reflected by the Fresnel lens structure. The overall transmittance was estimated as 47% after taking into account other smaller factors such as absorption in the material, diffractive efficiency and the loss due to the manufacturing error of lens.

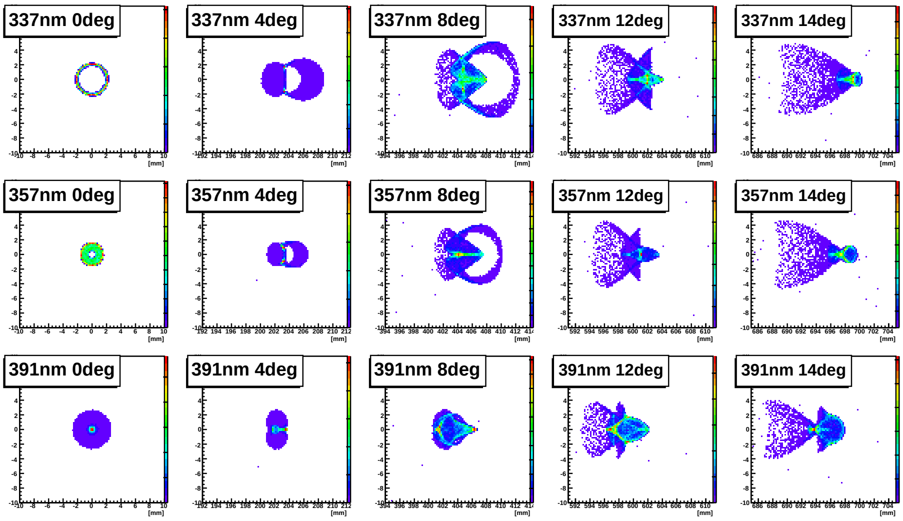

Figure 2: Spot diagram of the KLYPVE/K-EUSO optics. The panels in each row show the diagrams for the wavelength 337, 357, and 391 nm, respectively and those in each column show for the light with incident angle from the optical axis, 0, 4, 8, 12 and 14 degrees. The size of each frame is 20 mm×20 mm. The arrived number of photons are more intense as the color changes from blue to red.

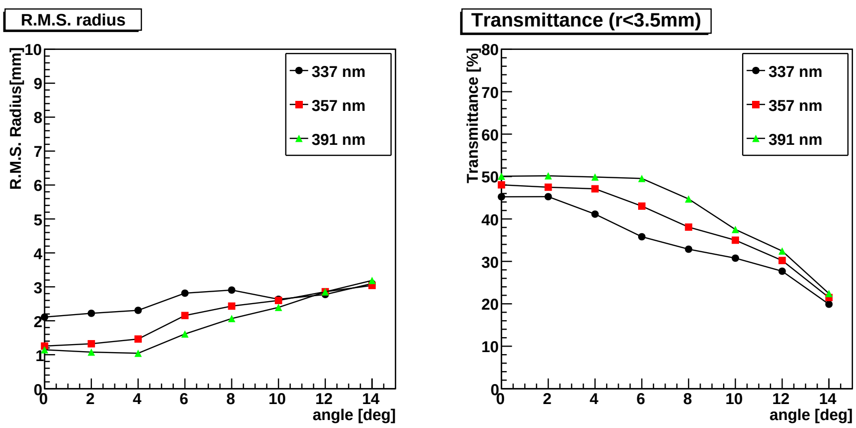

Figure 3: Root-Mean-Square (RMS) spot radius (left) and optics efficiency (right) of the KLYPVE/K-EUSO optics as a function of incident light angle for the wavelength 337 (dots), 357 (squares) and 391 nm (triangles).

3. Acceptance of KLYPVE/K-EUSO for UHECR observation

The raytracing code of the KLYPVE/K-EUSO has been implemented into the Euso Simulation and Analysis Framework (ESAF)[11] to evaluate the performance of the cosmic ray observation. ESAF adopted a modular structure, so that user can choose one of the implemented models in each part. In this paper, we used a parametrized shower generation according to the Greisen-Ilina-Linsley (GIL) function[10, 12], fluorescence production following the Nagano's result[13], photon propagation based on LOWTRAN[14], the raytracing code for the KLYPVE/K-EUSO optics of this work and the electronics described in Ref.[10]. The background photon rate was assumed as 500 photons/m^{2}sr ns which we assume as a typical number above a dark part of the earth[10].

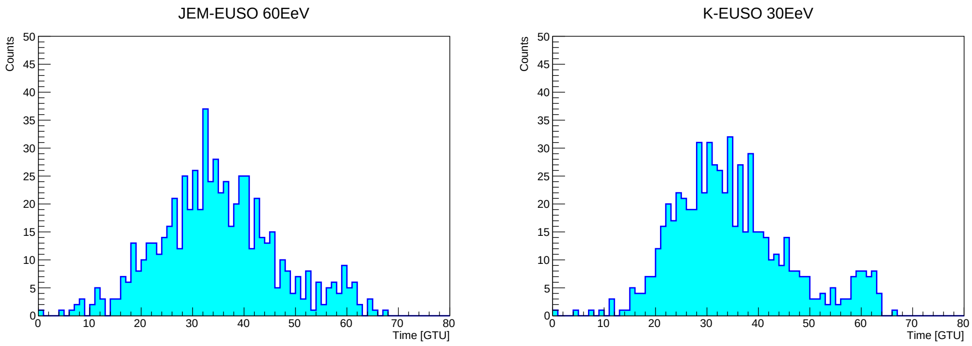

Figure 4: Samples of shower development curves observed by JEM-EUSO (left) and K-EUSO (right). Detected number of photo-electrons from a shower is plotted as a function of Gate Time Unit (GTU) which is 2.5 μs. Proton primary of 60 EeV for the JEM-EUSO observation and 30 EeV for the K-EUSO observation were injected into atmosphere. Only signals from the extensive air showers are plotted.

In Figure 4, two samples of shower longitudinal developments observed by JEM-EUSO and KLYPVE/K-EUSO are shown. The number of photo-electrons will be counted every Gate Time Unit (GTU, 2.5μs) in the electronics. Proton primary at 60 EeV landing at the center of the field of view with zenith angle of 60 degrees was simulated for the JEM-EUSO observation, while proton at 30 EeV with the same geometry as for the JEM-EUSO case was simulated for KLYPVE/K-EUSO. As can be seen from the figure, almost same number of photo-electrons are detected for both observations. This means that the threshold energy of KLYPVE/K-EUSO will be lower than that of JEM-EUSO and the reconstruction error will be similar for 30 EeV event by KLYPVE/K-EUSO and for 60 EeV event by JEM-EUSO[16, 17]. More detailed study on reconstruction is in progress and the result will be reported in other papers. A nominal background rate on orbit at the altitude of 400 km was assumed as 500 photons/m^2·sr as in Ref.[10]. This number corresponds to the detected background rate, 0.68 counts/pixel/μs, after taking into account the KLYPVE/K-EUSO detector response.

Since KLYPVE/K-EUSO observes UHECR only in dark nights, annual exposure will be better to describe its expected performance than acceptance. The annual exposure for triggering KLYPVE/K-EUSO was estimated as a function of energy with the following function:

$$< \text{Annual exposure} > = A(E) \cdot \eta_0 \cdot \kappa_C \cdot (1 - f_{\text{loc}}) \cdot (1[\text{yr}]) \,, \tag{3.1}$$

where $A(E)$ is the trigger acceptance of KLYPVE/K-EUSO in the case of the nominal background rate, η_0 is the reference duty cycle due to high background rate by the sun light and the moon light, κ_C is the observation efficiency where there is no cloud or extensive air showers are observable above cloud, $f_{\rm loc}$ is the ratio of too bright area to observe cosmic rays where a big city exists or lightning happens. We chose $\eta_0 = 20\%$, $\kappa_C = 72\%$ and $f_{\rm loc} = 10\%$ as in Ref.[10]. The annual trigger exposure increases with energy and becomes constant above $\sim 3\times10^{19}$ eV (Figure 5). The maximum exposure can be determined by the field of view for space-based experiments and will reach 1.2×10^4 km^2·sr·yr/yr in case of nadir observation by KLYPVE/K-EUSO. This number agrees well with a simple estimation using the ratio of the field of views of KLYPVE/K-EUSO to of JEM-EUSO. It is only $\sim 1/5$ of the JEM-EUSO's annual exposure, but about twice of the Pierre Auger Observatory's. It should be noted that the exposure is comparable or above the JEM-EUSO's at energy smaller than 2×10^{19} eV owing to the larger optics area. It is a good feature for a space-based mission of the first generation. At the first stage, the results of ground-based experiments like Auger, TA can be confirmed with the space-based mission. And then at the next stage, the instrument will be tilted for the observation at the highest energy end with high statistics.

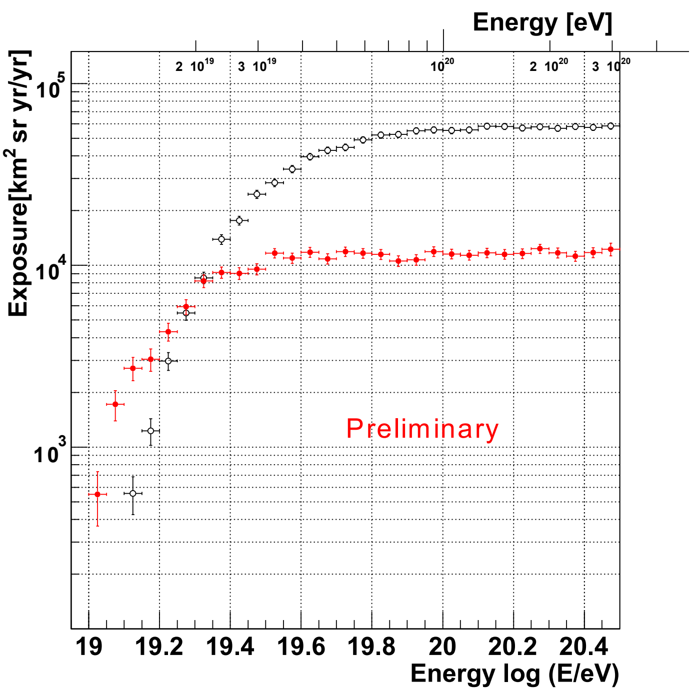

Figure 5: Annual trigger exposure of KLYPVE/K-EUSO (red solid circles) compared with JEM-EUSO's (black open circles)[10]. See the text for detailed conditions.

The integral number of cosmic rays triggering KLYPVE/K-EUSO observing towards the nadir during the mission period (6 years) is shown in Figure 6. The power law spectrum with smooth suppression based on the observation at the Pierre Auger Observatory, which was reported at the 33rd International Cosmic Ray Conference, was used to estimate the number[15]. About 1,000 cosmic rays will trigger KLYPVE/K-EUSO above $\log E > 19.5$ during the mission period. Considering the flux reported by the Auger collaboration is lower than that by TA within systematic error, this is a conservative estimate.

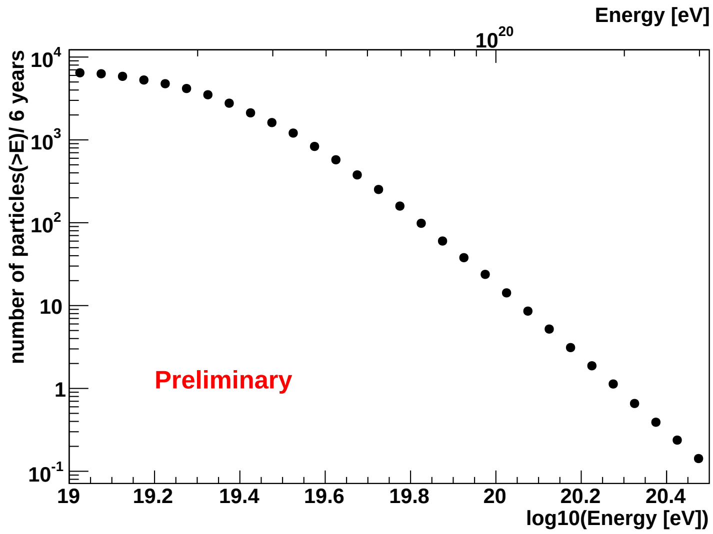

Figure 6: Integral number of triggering cosmic rays during the mission period (6 years) of KLYPVE/K-EUSO observing towards the nadir. The energy spectrum reported by the Pierre Auger collaboration at ICRC2013 was used as input[15].

4. Conclusions

KLYPVE/K-EUSO will be a UHECR observatory on ISS in the near future. Its optics consists of a mirror, a corrective Fresnel lens and a focal surface. In this paper, a dedicated raytracing code has been developed to study the performance. The spot radius on the focal surface was found to be $\sim$3 mm or smaller for all over the field of view, $\pm 14^{\circ}$. The optics efficiency was $\sim$50% for photons parallel to the optical axis. The performance for cosmic ray observation was evaluated with the full simulation framework for EUSO, ESAF, with the raytracing code implemented. The annual trigger exposure will be 1.2×10^{4} km$^{2}\cdot$sr$\cdot$yr/yr. The threshold will be lower than that of JEM-EUSO and the annual exposure at 2×10^{19} eV will be comparable. This feature will be good for the establishment of space-based experiments in connection with the ground-based experiments. As soon as the spectrum is confirmed, the instrument will be tilted to increase the exposure to observe UHECRs at the high energy end with higher statistics. KLYPVE/K-EUSO will open the era of UHECR observation from space. It will be followed by the experiments with larger exposure like JEM-EUSO, Super-EUSO to study “Particle Astronomy”.

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