Simulation System and Performance Estimation for JEM-EUSO

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Abstract. The JEM-EUSO (Extreme Universe Space Observatory) on board of the ISS is a science mission to investigate the nature and origin of Extremely-High-Energy Cosmic-Rays (EHECRs) with primary energies $> 7 \times 10^{19}$ eV. The End-to-End simulation generates the Extensive Air Shower (EAS) in atmosphere induced by EHECR with the zenith angle of 0°-90° and the energy region of $> 10^{19}$ eV. The air fluorescent and Cherenkov photons produced by charged particles in EAS development are the quantities to be measured. The hardware responses of the optics module, the focal surface detector and the signal control circuit in the JEM-EUSO, have been included in the simulation. The triggering efficiency for EAS detection is 86% at 10^{20} eV and the EAS threshold energy at a triggering efficiency of 50% is 5×10^{19} eV by the nadir mode observation. The EAS reconstruction code determines EAS parameters (arrival direction, X_{max} and primary energy) to evaluate the JEM-EUSO telescope performance. The resolutions of arrival direction, X_{max} and energy for EASs with energies of 10^{20} eV, $10^{20.5}$ eV and 10^{21} eV, are presented as a function of zenith angle. They are almost filling the required performances of the JEM-EUSO telescope to accomplish the scientific objectives.

Keywords: cosmic-ray, air shower, satellite mission, astrophysics

I. INTRODUCTION

The JEM-EUSO [1] aims at performing the charged-particle astronomy with a large statistic of >1000 EAS events above 7×10^{19} eV in five years' observation. An EHECR interacts with an atmospheric nucleus and produces an EAS in atmosphere. The JEM-EUSO at an altitude of 430 km, captures the moving track of the fluorescent photons emitted isotropically along the trajectory of EAS. The telescope consists of high-transmittance Fresnel lenses(a side-cut shape with a 2.65 m major axis), a cluster of multianode photomultipliers(MAPMT) as the photo-sensitive detector at the focal surface and the suitable signal control electronics. The JEM-EUSO records an EAS image with a time resolution of 2.5 μs and a spatial resolution of 0.75 km at ground. This time-segmented EAS image allows us determining EAS energy, arrival direction and EAS longitudinal profile.

II. THE END-TO-END SIMULATION

The JEM-EUSO telescope was designed to lower the threshold energy down to 3×10^{19} eV by some advances in hardware and software: (i) the improved optical design and new lens material, (ii) the MAPMT with a higher quantum efficiency, (iii) the improved event trigger algorithm.

The End-to-End simulation code consists of three components as EAS generation, telescope simulation and EAS event reconstruction part, as shown in the simulation scheme (Fig.1).
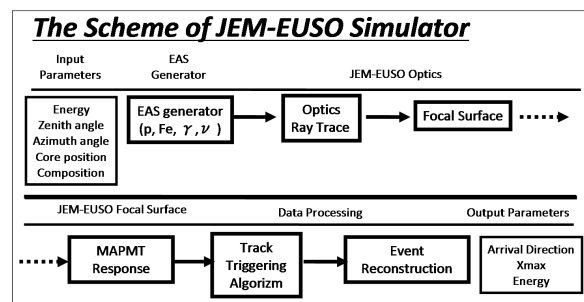

Fig. 1. The scheme of JEM-EUSO simulation package

The EAS generation code generates EAS longitudinal profile in atmosphere (the US standard atmosphere[2]) initiated by assumed composition of EHECRs with zenith angles of 0-90° and energies fixed between 10^{19} eV and 10^{21} eV at logarithmically equally spaced values (ten energies per decade). 500 EAS profiles at each energy have been pooled as the EAS library. The air fluorescent and Cherenkov photon emissions are calculated with their yields [3][4], and their scattering (Rayleigh and Mie) processes in atmosphere are also included in the code. The characteristics of arrival photons (wavelength, arrival time and spatial position of emission) at the optical lens are evaluated from this generation code.

In the telescope simulation code,the characteristics of the hardware responses to incident photons, photoelectrons and analogue/digital signals have been taken into account in the data flow process between the optics module and the signal control circuit, and then the simulated output data is generated.

In addition, the EAS event reconstruction code de-

termines EAS energy, arrival direction and longitudinal profile from the simulated data generated by the former two processes, and it is used for evaluating the telescope performance. This code also contributes to the development of hardware improvements and analytical algorithms aiming at the optimization of the telescope's capability.

To fulfill his goals, the JEM-EUSO has set the following requirements on the experimental accuracies:

- the expected number of EAS events: > 1000 with energies above 7×10^{19} eV;
- the threshold energy: 5×10^{19} eV;
- the angular resolution: $< 2.5°$;
- the energy resolution: $< 30\%$;
- the depth of EAS maximum (X_{max}) resolution: $< 120 \ g/cm^2$;

According to the conceptual design of the JEM-EUSO optics module, the lens has a side cut shape with 2.65 m in diameter and 1.9 m in width. The Field of View (FoV) of the optics is $60° \times 48°$ and the spot size at the focal surface is 2.5 mm which is enough smaller than the pixel size of MAPMT.

The focal surface detector should have the single photon counting capability to avoid systematic errors, which may be introduced through the gain drift. It should be reliably and stably operational in space environment for at least five years' mission period. The MAPMT(Hamamatsu R8900-03-M36)[5] with 36 pixels is a baseline model.

The observation will be carried out with a duty cycle of 19%. Two years' observation is planned by the nadir mode operation to observe events in the lower energy region, and the tilted mode operation with a tilt angle of 38° will accomplishes successively to accumulate larger statistics in the highest energy region $> 10^{20}$ eV by three years' observation.

III. RESULTS

A. *Triggering efficiency*

The JEM-EUSO will observe the fluorescent photons from EAS together with the background photons emitted from ground and airglow sources. Therefore, the optimized EAS triggering method has been studied to acquire the EAS events efficiently with the best S/N avoiding fake triggers[6].

The energy dependence of the triggering efficiency at different tilt angles is shown in Fig.2. Here, we assume proton-induced EASs and the background photon intensity of 500 photons $m^{-2} \cdot sr^{-1} \cdot ns^{-1}$. The triggering efficiency at 10^{20} eV is estimated as 86% for the nadir mode observation, and the EAS threshold energy is 5.0×10^{19} eV at a 50% triggering efficiency level. The threshold energy of EASs hitting within a radius of 100 km from the center of FoV, becomes 3.7×10^{19} eV because of better performance of the optics module and the smaller impact parameters to the EAS axes. The triggering efficiencies for the tilted mode observation

with tilt angles of 30°, 35° and 38° are also shown in the same figure. The efficiencies become smaller with angle due to a longer distance from the EAS axis to the telescope, however, the increase of acceptance by the tilted mode observation has an important advantage over the decrease of triggering efficiency in the energy range of $> 10^{20}$ eV.

The energy dependence of the effective acceptance derived from the combination of triggering efficiencies and increase of the FoV is shown in Fig.3. The relative advantage of the tilted mode observation could be seen as 1.8 times and 2.4 times larger effective acceptance at 10^{20} eV and $10^{20.5}$ eV, respectively, as compared to the nadir mode observation.
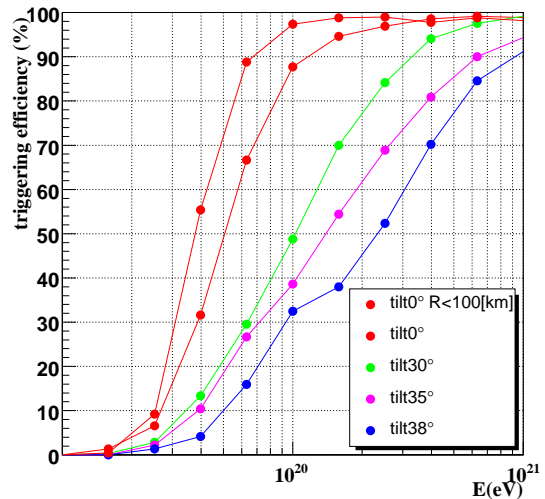
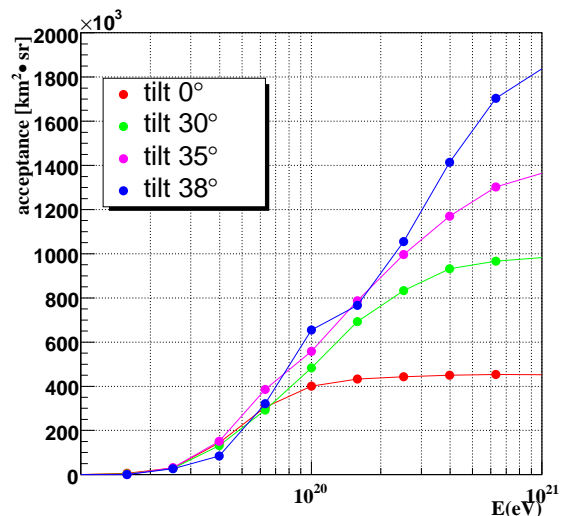Fig. 2. The energy dependence of the triggering efficiency at different tilt angles.

Fig. 3. The JEM-EUSO effective acceptance for EASs with different tilt angles as a function of energy.

B. Resolutions

The resolutions of arrival direction, X_{max} and energy have been evaluated from the reconstructed EAS time profiles. The intensity of background photon intensity is required but it is not included in the current stage of EAS reconstruction to interpret the best telescope performance.

The arrival direction of triggered EAS is determined by reconstructing the EAS longitudinal profile in atmosphere from the positions of detected photoelectrons and their time transitions in the focal surface. The image length in the focal surface changes depending on EAS energy and zenith angle. The angular resolutions for proton-induced EASs hitting within the JEM-EUSO FoV are shown in Fig.4 as a function of zenith angle. Here, the angular resolutions is defined as the opening angle between the real and the reconstructed arrival direction, in which 68% EASs are included. The angular resolutions become better for EASs with larger zenith angles because longer EAS images could be detected at the focal surface. The required resolution of $< 2.5°$ is satisfied according to the present result for EASs with energies of $> 10^{20}$ eV and zenith angles of $> 30°$.
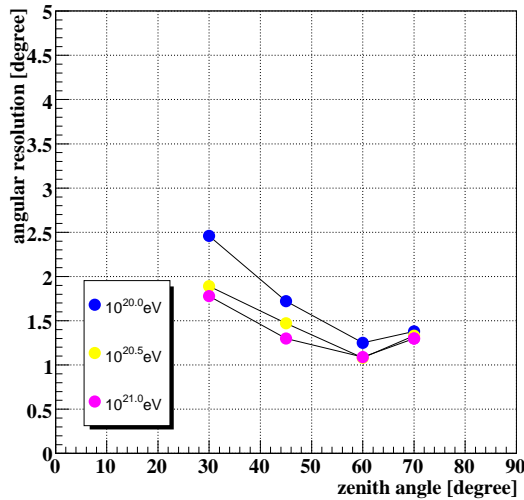

Fig. 4.   The angular resolution for EASs triggerd within the JEM-EUSO FoV as a function of zenith angle.

After the determination of the EAS axis, primary energy and X_{max} are derived from the reconstructed longitudinal profile. The EAS profile is estimated from the transition curve of photons produced in atmosphere taking into account the fluorescent photon yield and the scattering/absorbtion in their propagations. X_{max} resolutions for EASs of 10^{20} eV, $10^{20.5}$ eV and 10^{21} eV are shown in Fig.5. The triggered EASs hitting within the JEM-EUSO FoV are analyzed to reconstruct their profiles. The resolution is shown by the RMS of the distribution of $|X_{max}(real) - X_{max}(reconstructed)|$. The resolution does not depend so much on zenith angle, and X_{max} resolution of 60100 g/cm^2 are expected.
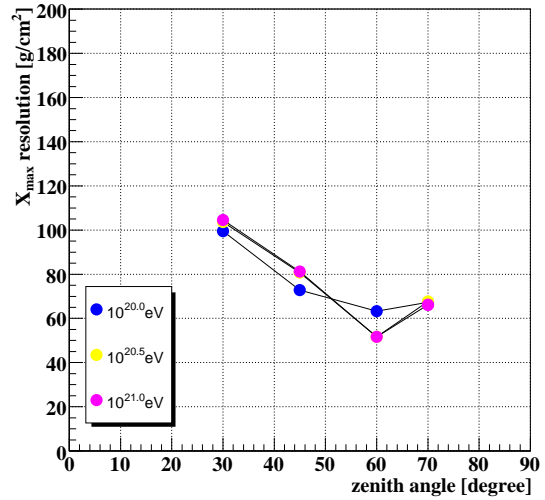

Fig. 5.   The X_{max} resolution for EASs triggered within the JEM-EUSO FoV as a function of zenith angle.

EAS energy has been temporary estimated by the maximum number of EAS particles (N_{max}) from the reconstructed longitudinal profile. Energy resolutions for EASs of 10^{20} eV, $10^{20.5}$ eV and 10^{21} eV are shown in Fig.6 as a function of zenith angle. Energy resolution is improved with increase of zenith angle and 1528% is expected for EASs with the zenith angles of $> 30°$.
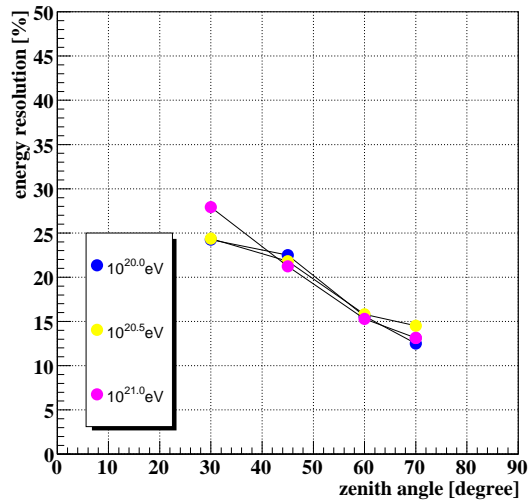

Fig. 6.   The energy resolution, as a function of zenith angle, for EASs triggered within the JEM-EUSO FoV.

C. The expected number of triggered events

The expected number of triggered EAS events are estimated by taking into account the geometrical acceptance (5.8×10^5 $km^2 \cdot sr$) of JEM-EUSO, a duty cycle of 19% and the triggering efficiency which depends on energy and zenith angle. In this estimation, the energy spectrum is assumed as an intensity J(E)E^3 of 2.0×10^{24}

$eV^2 \cdot m^{-2} \cdot s^{-1} \cdot sr^{-1}$ at 2×10^{19} eV and an index of γ = -2.75 up to 5×10^{19} eV. At energy $> 5 \times 10^{19}$ eV (cutoff energy), an index $\gamma = -4.5$ is assumed.

The integrated numbers of triggered events ($> E$) are listed in Table I. The expected numbers of events with energies of $> 7 \times 10^{19}$ eV and $> 10^{20}$ eV are 460 and 58 events per year in the nadir mode observation, respectively.

The study in the lower energy region is also important for what concerns the cross calibration with the Auger energy spectrum and the newly results on EHECR anisotropy. The JEM-EUSO has enough potential to study on EHECRs around 3×10^{19} eV with the statistic more than 1000 events per year.

TABLE I
THE EXPECTED NUMBERS OF TRIGGERD EVENTS IN 1 YEAR.

>Log(E)	nadir	tilt38°	nadir $\times$ 2yrs + tilt38° $\times$ 3yrs
19.7	930	970	4770
19.8	400	570	2500
20.0	58	95	400
20.2	11	20	80
20.4	4	9	35
20.6	2	5	20
20.8	0.8	2	8
21.0	0.2	0.6	2

Moreover, the tilted mode observation with a tilt angle of 38° will provide us the larger statistic in the energy of $> 10^{20}$ eV as shown in Table I. 95 events with region energies of $> 10^{20}$ eV could be expected in a year.

We plan the nadir mode and the tilted mode observation for two years and three years, respectively. The expected numbers by both observations, will be 1950 and 400 events with energies of $> 7 \times 10^{19}$ eV and $> 10^{20}$ eV, respectively, in five years' observation. Furthermore, $\sim$20 events with energies of $> 10^{20.6}$ eV will be also expected according to the assumed energy spectrum. The JEM-EUSO will be able to detect the events and to study on the unknown structure of energy spectrum in the extreme high energy region.

IV. CONCLUSION

The End-to-End simulation on behalf of the JEM-EUSO has been developed to estimate the telescope performance.

The triggering efficiency is 86% at the energy of 10^{20} eV and the threshold energy is estimated as 5×10^{19} eV in the nadir mode observation. In addition, the JEM-EUSO acceptances of 5.7×10^5 and 2.9×10^6 $km^2 \cdot sr$ for the nadir mode and the tilted mode observation, respectively, will realize a cumulative exposure of 1.1×10^6 $km^2 \cdot sr \cdot year$ with five years' observation. The expected numbers of events will be 1950 and 400 events for EASs with energies of $> 7 \times 10^{19}$ eV and $> 10^{20}$ eV, respectively.

The resolutions of arrival direction, X_{max} and energy have been estimated and their results are fulfilling the required accuracies from the scientific demands of the JEM-EUSO. Furthermore, we note that their resolutions

for EASs hitting within a radius of 100 km from the center of FoV, become better to be 0.5°2.0°, 40100 g/cm^2 and 1020%, respectively, and it will ensure the studies of EHECRs with the lower energy region of $> 3 \times 10^{19}$ eV.

REFERENCES

[1] T. Ebisuzaki et al., *Nuclear Physics B (Proc. Suppl.),* 175-176, (2008) 237.
[2] U.S. Standard Atmosphere, 1976, U.S. Government Printing Office, Washington, D.C., (1976)
[3] F. Kakimoto, E.C.Loh, M. Nagano, H. Okuno, M. Teshima and S. Ueno, *Nucl. Instrum. Meth. Phys. Res.,* A372, (1996) 527.
[4] M. Nagano, K. Kobayakawa and N. Sakaki, *Proc. of 27th Int. Cosmic Ray Conf.,* (2001) 675.
[5] Y.Kawasaki et al., *Nucl. instrum. Meth. Phys. Res.,* A564 (2006) 378.
[6] M.Bertaina et al., *Proc. of 30th Int. Cosmic Ray Conf. (Merida),* HE Vo1.5, (2007) 1049.