Performances of JEM-EUSO

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Abstract. In this paper we describe the requirements and the expected performances of JEM-EUSO. Designed as the first mission to explore the Ultra High Energy Universe from space, JEM-EUSO will monitor the earth's atmosphere at night to record the UV (300–400 nm) tracks generated by the Extensive Air Showers produced by Ultra High Energy primaries propagating in the atmosphere. After briefing summarizing the main aspects of the JEM-EUSO Instrument and mission baseline, we will present, in details, our studies of the expected trigger rate, the estimated exposure, as well as on the expected angular, energy, and X_{max} resolution. Eventually, the obtained results will be discussed in the context of the scientific requirements of the mission.

1. INTRODUCTION

The Extreme Universe Space Observatory (EUSO) onboard the Japanese Experiment Module (JEM) of the International Space Station (ISS), JEM-EUSO, [1, 2] is an innovative space-based mission with the aim of detecting Ultra High Energy Cosmic Rays (UHECR) from the ISS, by using the earth's atmosphere as a fluorescence detector. JEM-EUSO consists of an UV telescope and of an atmosphere monitoring system. Orbiting the earth every ∼90 minutes, from an altitude of 350–400 km, JEM-EUSO is designed to detect the UV (300-400 nm) fluorescent photons produced along the track of Extensive Air Showers (EAS) in the atmosphere. The telescope, which contains a wide Field-of-View ($\pm 30°$, FOV) optics composed by Fresnel lenses [3], records the EAS-induced tracks with a time resolution of 2.5 μs and an angular resolution of ∼0.07° (corresponding to a spatial resolution of ∼0.5 km on the Earth's surface at the nadir) by using a highly pixellised focal surface (∼3×10^5 pixels) [4]. These time-segmented images allow an accurate measurement of the energy and arrival direction of the primary particles.

Since the ISS orbits the earth in the latitude range $\pm 51°$, moving at a speed of ∼7 km/s, the variability of the FOV observed by JEM-EUSO is much higher than that observed by ground-based experiments.

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In particular the atmospheric conditions, which eventually determine the acceptance, must be carefully monitored via an atmosphere monitoring system consisting of an infrared camera [5] and a LIDAR [6]. Thanks to the ISS orbit, JEM-EUSO will monitor, with a rather uniform exposure, both hemispheres minimizing the systematic uncertainties that might affect any comparison between different observatories exploring, from ground, different hemispheres.

Another peculiarity of JEM-EUSO, in comparison to any existing or studied ground-based observatory, is the significant increase in the aperture with increasing energy (see Sect. 4). There are however other interesting aspects in using space-based UHE observatories. First, the non-proximity of the detector to the EAS considerably reduces all problems associated with the determination of the solid angle and with the different attenuation suffered by the UV light in the atmosphere. Second, the near-constant fluorescence emission rate at different heights below the stratosphere simplifies all assumptions on the energy-fluorescence yield relation at the EAS maximum as well as on the dependence of the EAS time structure on the production height [7]. Third, the observation from space elimates uncertainties due to scattering by aerosols limited to altitudes below in the planetary boundary layer. Finally, as the EAS maximum occurs, for most zenith angles, at altitudes higher than 3–5 km from ground, space measurements are also possible in cloudy conditions. Compared to ground-based detectors, the duty cycle is therefore mainly limited by the moon phases, while the cloud impact is less relevant.

The JEM-EUSO observational approach mainly relies on the fact that a substantial fraction of the UV fluorescence light generated by the EAS can reach a light-collecting device of several square meters: typically a few thousand photons reach the JEM-EUSO detector for a shower produced by a 10^{20} eV particle. JEM-EUSO is designed to record not only the number of photons but also their direction and arrival time. It is the observation of the specific space-time correlation that allows to very precisely identify EAS tracks in the night glow background.

We wish also to observe that JEM-EUSO has considerably improved with respect to the original Extreme Universe Space Observatory [8] studied by the European Space Agency. Main improvements have to be ascribed to the new optics, to the photo-detector ($\sim$1.6 higher detection efficiency), to the better geometrical layout of the focal surface that maximizes the filling factor, and to the improved performance of the electronics, which allows to exploit more complex trigger algorithms.

The key element to estimate the scientific potential of JEM-EUSO is its exposure. This is determined by three main contributions: the trigger aperture, the observational duty cycle and the cloud impact. In the following sections the three contributions are discussed in details.

2. NIGHT-GLOW BACKGROUND AND ESTIMATION OF THE OBSERVATIONAL DUTY CYCLE

The UV tracks of EAS must be discriminated in the night-glow background. One key parameter is therefore the fraction of time in which EAS observations are not hampered by the brightness of the sky. We define *observational duty-cycle* the fraction of time in which the sky is dark enough to measure EAS. Pavol et al. [9] have conducted an analysis of the duty-cycle using measurements performed by the Tatiana satellite rescaling them to the ISS orbit. In this estimate all major atmospheric effects, such as lightnings, meteors and anthropogenic light (e.g. city lights) have been included. Results indicate that for a zenith angle position of the sun higher than $109°$, the fraction of time in which the night-glow background is less than $1500\,\mathrm{ph/m^2/ns/sr}$ is 20%. In fact the mean of all background levels less than 1500 ph/m^2/ns/sr, weighted according to their relative occurrence, is equivalent to an average background of 500 ph/m^2/ns/sr: the so-called standard background actually measured by different balloon experiments [10–12]. It should be noted that a somewhat higher background can be tolerated for the highest energy cosmic rays. These recent studies confirms previous estimates of 18%–22% performed in the context of the EUSO studies, based on a combined analytical and simulation approach [13]. We therefore assume a value of 20% for the observational duty-cycle of the mission.

Table 1. Relative occurrence (%) of clouds between 50°N and 50°S latitudes on TOVS database in the matrix of cloud-top altitude vs optical depth. Daytime and ocean data are used for the better accuracy of the measurements.

Optical Depth (τ)	Cloud-top altitude			
	< 3 km	3–7 km	7–10 km	> 10 km
> 2	17.2	5.2	6.4	6.1
1-2	5.9	2.9	3.5	3.1
0.1–1	6.4	2.4	3.7	6.8
< 0.1	29.2	<0.1	<0.1	1.2

Our result is slightly higher than what has been reported in [14] mainly due to the fact that OWL will fly at higher altitudes ($\sim$1000 km) does reducing the duty cycle by about 15–20% due to the shorter night time. Moreover, in our estimation we have taken into account the possibility of accepting some moonlight as far as the total diffuse light is less than 1500 ph/m^2/ns/sr. Man-made lights and lightning will further reduce the aperture by $\sim$10% [9] and this effect is taken into account in the exposure curve.

## 3. THE CLOUD IMPACT

Space based UHECR observatories can measure EASs even in cloudy conditions [1, 15]: this is typically not the case for ground-based observatories. In some case, the presence of a cloud could even be an advantage. An optically thick cloud represents a very uniform layer which enhances the Cherenkov albedo and gives a brighter end point of the track. Of course, the cloud top should be known with reasonable uncertainty (500–1000 m), and for that, an atmospheric monitoring system will be very useful. Naturally, in case of optically thin clouds or of very inclined showers, such an advantage might not be usable, as the Cherenkov mark is not as well defined as in the previous case. Therefore, it is mandatory to develop in parallel reconstruction algorithms which do not rely on the detection of the Cherenkov mark [16]. The combined or alternative use of complementary approaches on an event-by event basis will allow to avoid, or at least tag, mis-reconstructions of shower geometry. Therefore, it is reasonable to assume that when the maximum of the shower is above the cloud top layer the reconstruction of the shower's parameters is possible. It is clear that the same cloud top layer will affect showers at various inclination or originating from different types of primary particles in different ways. Thin clouds (optical depth $\tau < 1$, typical of cirrus) might affect the measurement of the energy but arrival direction will still be nicely measurable. Thick clouds ($\tau > 1$) will strongly impact the measurement only if located at high altitudes. As an example, a 60° zenith-angle inclined shower will reach the shower maximum at an altitude of 6–7 km, much higher than the typical range of stratus. In order to quantify the effective observational time, a study on the distribution of clouds as a function of altitude, optical depth and geographical location has been performed using different meteorological data sets [17] (TOVS, ISCCP and CACOLO data sets) obtaining similar results on the cloud occurrence. Therefore, we report here only the results obtained using TOVS data, which are the most conservative ones. Table 1 reports the results of the occurrence of each cloud typology for oceans during daytime using visible and IR information.

In Table 1 cloud coverage data taken during daytime are chosen since they are in general more precise. The same applies to data of clouds above the oceans, more reliable than the ones taken above land. A comparison between day and night cloud coverage has been then performed for data above land as higher variations are expected in comparison with day/night variation above the oceans. Differences however resulted to be of only a few percents. The results in Table 1 can be understood as it follows. Clear sky corresponds to $\tau < 0.1$ and this accounts for $\sim$30% of the aperture. Clouds below 3 km height do not hamper the measurements as the shower maximum will develop at higher altitudes, regardless of their τ and they account for another $\sim$30%, which gives a total of $\sim$60% of the aperture when the measurement is feasible with no major correction. Thick optically depth ($\tau >$1) high clouds (h>7km)
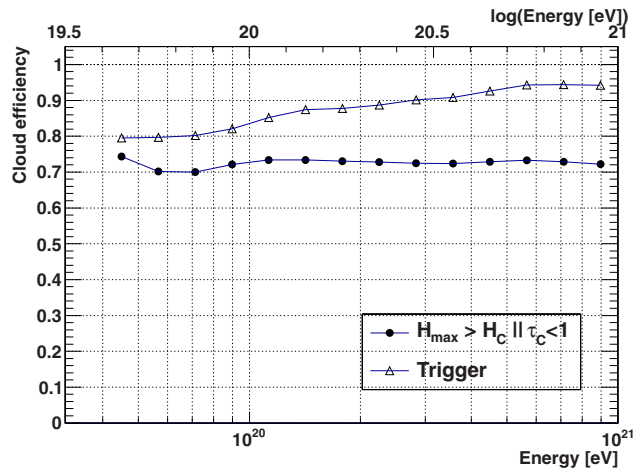
Figure 1. Relation between cloud efficiency and energy. Triangles shows the average over the cloud distribution summarized in Table 1. Closed circles represent the case applying $H_{max} > H_C$ selection for optically thick clouds.
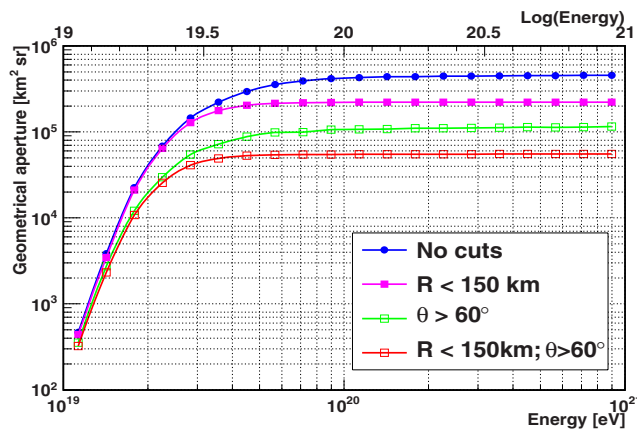
Figure 2. Annual exposure of JEM-EUSO for different quality cuts and $H_{ISS} = 400$ km.

will prevent the possibility of any measurements, and they account for ∼20%. For the remaining ∼20% angular and energy measurements will be feasible for very inclined showers (zenith angle >60°) which correspond to the best set of showers characterized by long tracks. For the non inclined showers of this last sample arrival direction analysis will still be feasible while the energy estimation will be severely hampered by the shower attenuation in the atmosphere.

More quantitative results have been obtained by simulating showers according to the conditions of Table 1, determining the trigger efficiency in the different conditions, and by convoluting it with the corresponding aperture. Fig. 1 shows the ratio between the aperture when the role of clouds is included compared to pure clear sky, for all events and for those events which have "good quality" characteristics (clouds with $\tau < 1$, or shower maximum well above the cloud top height). More details can be found in [18]. From these results we conclude that 70% is a conservative estimate of the fraction of the full aperture in which the measurement will not be hampered by atmospheric factors. Our result is comparable to a previous estimation done at the time of the EUSO experiment, even though a bit higher because of the stricter quality cuts applied in [21]. The cloud factor convoluted with the 20% duty-cycle, and the city light impact will provide a final 13% factor to be applied to determine the exposure in Fig. 2.

Our results do not support the conclusions derived in [19]. In their approach only cloud-free scenes were considered, which naturally reduce the fraction of time by a factor of three, and inside the same cloud scene, very strict conditions were applied to define them as truly cloud-free. As an example, no correlation on the altitude of the possibly cloudy pixel and location of the track was applied, which of course tend to reject very inclined events which have much longer path in atmosphere even though all the visibile part of the track is located above clouds. It is clear that the above conditions severely reduce the overall efficiency. The same authors comment that they could have underestimated by even a factor of three the cloud-free efficiency. Finally, as already previously mentioned, it was afterwards proved by simulation [1, 15] the feasibility of recostructing EAS with reasonable uncertainty in presence of clouds. It is important to stress anyhow the fact that the AM system will have an important role in monitoring the atmospheric conditions in which EAS develop, together with the information coming from satellites, ground-based observations and meteorological models.

4. TRIGGER RATE AND ESTIMATED EXPOSURE

The last parameter needed to estimate the aperture and the exposure is the trigger efficiency. Main objective of the trigger system is to reduce the rate of UHECR candidates to $\sim$0.1 Hz, limit imposed by downlink telemetry capabilities. The rejection level of the trigger algorithm determines the aperture of the instrument as a function of the energy. The rejection power depends also on the average night-glow background. In the following, the background has been assumed to be $500 \, \mathrm{ph/m^2/ns/sr}$. Figure 2 shows the annual exposure of JEM-EUSO in nadir mode for the entire FOV of the detector and for a few high quality conditions corresponding to "quality cuts". Quality cuts are defined by the better performance of the optics in the center of the FOV or for showers with inclined zenith angles ($\theta > 60°$ from nadir), which produce longer and less attenuated tracks.

Figure 2 shows that 80–90% of the full exposure is already reached at energies $\sim 3 \times 10^{19}$ eV when the foot print of the shower is located in the central part of the FOV (R $<$ 150 km from nadir) and for showers with zenith angles $\theta > 60°$ (more details in [20]).

In the most stringent conditions, which are defined only to cross-check the the understanding of the rising exposure at low energies using the full FoV, JEM-EUSO has an annual exposure equivalent to Auger ($\sim 7 \times 10^3 \, \mathrm{km^2}$ sr y) while it reaches $\sim 60 \times 10^3 \, \mathrm{km^2}$ sr y at 10^{20} eV that is 9 times Auger. JEM-EUSO will well overlap (about one order of magnitude, starting from $\sim 3 \times 10^{19}$ eV) with ground-based experiments to cross-check systematics and performances. At higher energies JEM-EUSO will be able to accumulate statistics yearly at a pace of about one order or magnitude higher than currently existing ground based detectors. JEM-EUSO will also be operated in tilt mode to further increase the exposure at the highest energies (E higher than several 10^{20} eV) by a factor of $\sim$3 compared to nadir mode. The optimization of the tilt parameters is still under evaluation.

5. RECONSTRUCTION CAPABILITIES

The JEM-EUSO reconstruction capabilities have been estimated using the ESAF code [21], a software for the simulation of space based UHECR detectors developed in the context of the EUSO ESA mission. Currently the ESAF code is being updated to the most recent JEM-EUSO configuration [16]. The technique to reconstruct the different shower parameters is extensively discussed in [22]. Regarding the energy reconstruction, at the current status of development of the instrument and of the reconstruction algorithms, proton showers with zenith angle $\theta > 60°$ are reconstructed in clear-sky conditions with a typical energy resolution $\Delta E/E$ of $\sim$25% (20%) at energies around 4×10^{19} (10^{20}) eV. The energy resolution slightly worsen for more vertical showers where it is of the order of 30% around 10^{20} eV. This result indicates that the reconstruction of events with $E < 5 \times 10^{19}$ eV is feasible confirming the possibility of overlapping with ground based experiments over a sufficient wide energy range. Regarding the arrival direction analysis, our current results [22] indicate that showers of energy $E \sim 7 \times 10^{19}$ eV

Table 2. Relative comparison of saturation exposures of current and planned UHECR observatories.

Observatory	Status	Start	Annual Exp. (km^2 sr yr)	Rel. Exp. Auger = 1
Auger	Operations	2006	7000	1
TA	Operations	2008	1200	0.2
TUS	Developed	2012	1000	0.13
JEM-EUSO nadir	Design	2017	60000	9
JEM-EUSO tilt	Design	2017	200000	28

and zenith angle $\theta > 60°$ can be reconstructed with a 68% separation angle less than 2.5°. Eventually our still preliminary results indicate that the X_{max} resolution (ΔX_{max}) is better than $70\,g/cm^2$ for $E \sim 10^{20}\,eV$.

6. CONCLUSIONS

The scientific requirements of the mission are described in detail in [2]. They can be summarized as: Observation area greater than $1.3 \times 10^5\,km^2$; Arrival direction determination accuracy better than 2.5° for 60° inclined showers at $E > 1 \times 10^{20}\,eV$ (standard showers); Energy determination accuracy better than 30% for standard showers; $\Delta X_{max} < 120\,g/cm^2$. Results of simulations shown in the previous section confirm that the requirements can be already achieved with the current configuration.

Simulations show that JEM-EUSO can reach almost full efficiency already at energies around $3 \times 10^{19}\,eV$ for a restricted subset of events, and full aperture at energies $E > 5.5 \times 10^{19}\,eV$. The expected annual exposure of JEM-EUSO at 10^{20} is equivalent to about 9 years exposure of Auger. The duty cycle and the impact of clouds have been assessed. Results indicate that the conversion factor between geometric aperture and exposure is ∼13%. The number of events that JEM-EUSO will observe depends of course on the UHECR flux, which is uncertain especially at the highest energies. The exposures shown in fig. 2 can be however converted into number of events, assuming fluxes reported in literature such as in [25]. We obtain around 130 events/year in nadir mode with energy $E > 5.5 \times 10^{19}\,eV$, which will give 650 events in 5 years operation. A synthetic comparison between the JEM-EUSO saturation exposures and the ones of other observatories is reported in Table 2.

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