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Requirements and Expected Performances of the JEM-EUSO mission

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Abstract: In this paper we describe the requirements and the expected performances of the Extreme Universe Space Observatory (EUSO) onboard the Japanese Experiment Module (JEM) of the International Space Station. Designed as the first mission to explore the Ultra High Energy (UHE) Universe from space, JEM-EUSO will monitor, night-time, the earth's atmosphere to record the UV (300-400 nm) tracks generated by the Extensive Air Showers produced by UHE 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 on 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.

Keywords: JEM-EUSO, Ultra High Energy Cosmic Rays, Space Instrumentation.

1 Introduction

JEM-EUSO [1, 2] is an innovative space-based mission with the aim of detecting Ultra High Energy Cosmic Rays (UHECR) from the International Space Station (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 $\sim$90 minutes, JEM-EUSO is designed to detect, from an altitude of 350-400 km, the moving track of the UV (300-400 nm) fluorescence photons produced during the development of Extensive Air Showers (EAS) in the atmosphere. The telescope, which contains a wide Field-of-View ($\pm 30°$, FOV) optics composed by Fresnel lenses [3], records the EAS-induced tracks with a time resolution of 2.5μs and a spatial resolution of about 0.5 km ($\sim 0.07°$) in nadir mode by using a highly pixellised focal surface ($\sim 3\times 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 $\sim$ 7 km/s, the variability of the FOV observed by JEM-EUSO is much higher than that observed by ground-based experiments. 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 strongly affect any comparison between different observatories exploring, from ground, different hemispheres.
The other great advantage of JEM-EUSO, in comparison to any existing or studied ground-based observatory, is the significant increase of aperture (see Section 4). There are however other relevant advantages 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 minimize uncertainties due to scattering by aerosols limited to altitudes below the atmo-

spheric boundary layer. Finally, as the EAS maximum develops, for most zenith angles, at altitudes higher than 3-5 km from ground, space measurements are also possible in cloudy sky 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 [3] (with ∼1.5 better throughput and ∼1.5 better focusing capability), to the photo-detector [9] (∼1.6 higher detection efficiency), to the better geometrical layout of the focal surface that maximizes the filling factor [10], and to the improved performance of the electronics [11, 12], which allows to exploit more complex trigger algorithms [13].

The key element to estimate the science 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 terms 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. [14] 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 anthropic lights (e.g. city lights) have been included. Results indicate that for a zenith angle position of the sun higher than 108° (120°), the fraction of time in which the night-glow background is less than 1500 ph/m^2/ns/sr is 22% (18%). 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. This is a conservative estimate for the highest energies where measurement could be performed even in a higher background condition. 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 [15]. We therefore assume a value of 20% as the most probable value for the observational duty-cycle of the mission.

3 The cloud impact

Space based UHE observatories can observe EAS induced tracks also in cloudy conditions: this is typically not the case for ground-based observatories. In fact if the maximum of the shower is above the cloud top layer the reconstruction of the shower's parameters is still possible. It is clear that the same cloud top layer will affect in different ways showers of various inclination or originating from different type of primary particles (e.g. neutrino will develop much deeper in the atmosphere compared to protons). Thin clouds (τ <1, typical of cirrus) might affect the measurement of the energy but arrival direction will still be nicely measurable. Thick clouds (τ >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 [16]. Table 1 reports the results of the occurrence of each cloud typology for oceans during daytime using visible and IR information.

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	Cloud-top altitude			
	<3km	3-7km	7-10km	>10km
>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

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 of Table 1 can be understood as it follows. Clear sky corresponds to $\tau < 0.1$ and this accounts for ∼30% of the observation time. 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 ∼30%, which gives a total of ∼60% of the time when the measurement is possible with no major correction. Thick optically depth ($\tau > 1$) high clouds (h>7km) will prevent the possibility of any measurements, and they account for $\sim$19%. For the remaining $\sim$21% angular and energy measurements will be possible 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 possible 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 in cloudy conditions compared to clear sky, for all events and for those events which have 'good quality' characteristics (clouds with $\tau < 1$, and shower maximum well above the cloud top height). More details can be found in [17]. From these results we

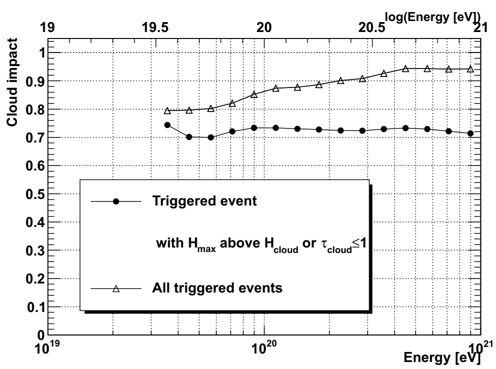

Figure 1: Ratio in the trigger efficiency for clear-sky and cloudy conditions.

conclude that 70% is a conservative estimate of the fraction of observing time in which the measurement will not be hampered by atmospheric factors. This number convoluted with the 20% duty-cycle, provides a final 14% factor to be applied to the aperture to determine the exposure Fig. 2.

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 ph/m^2/ns/sr.

Fig. 2 shows the full aperture, and 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.

Fig.2 shows that 80-90% of the full aperture is already reached at energies $\sim$2-3$\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 [18]). The 80-90% is reached at $\sim 5\times 10^{19}$ eV if showers distributed in the entire FOV are considered.

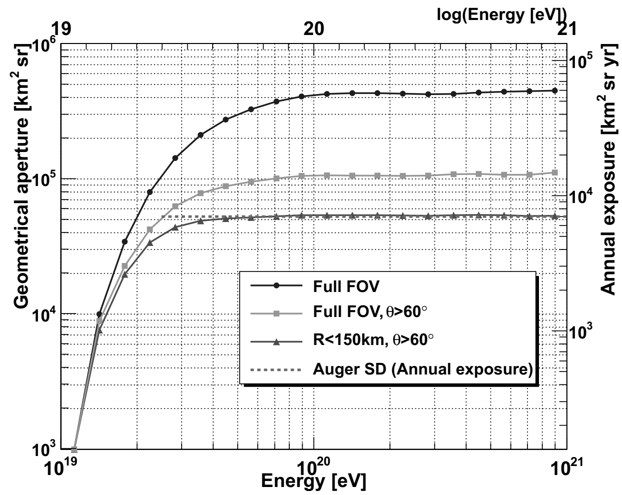

Figure 2: Aperture and annual exposure of JEM-EUSO for different quality cuts.

The convolution of the trigger aperture with the observational duty cycle and the cloud impact gives the annual exposure. In the most stringent conditions JEM-EUSO has an annual exposure equivalent to Auger ($\sim 7 \times 10^3$ km^2 sr y) while it reaches $\sim 60 \times 10^3$ 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 2-3$\times 10^{19}$ eV) with ground-based experiments to cross-check systematics and performances. At higher energies JEM-EUSO will be able to accumulate statistics at a pace per year at about one order or magnitude higher than currently existing ground based detectors. JEM-EUSO will also be operates in tilt mode to further increase the exposure at the highest energies ($E > 3 - 5 \times 10^{20}$ 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 [19], 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 [20]. The technique to reconstruct the different

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

Observatory	Aperture (km^2sr)	Status	Start	Lifetime	Duty Cycle × Cloud Impact	Annual Exposure (km^2 sr yr)	Relative Exposure Auger = 1
Auger	7000	Operations	2006	4(16)	1	7000	1
TA	1200	Operations	2008	2(14)	1	1200	0.2
TUS	30000	Developed	2012	5	0.14	4200	0.6
JEM-EUSO (E∼ 10^{20}eV)	430000	Design	2017	5	0.14	60000	9
JEM-EUSO (highest E) tilt mode °	1500000	Design	2017	5	0.14	200000	28

shower parameters is extensively discussed in [21]. 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 still possible confirming the possibility of overlapping with ground based experiments over a sufficient wide energy range. Regarding the arrival direction analysis, our current results ([21]) indicate that showers of energy $E \sim 7 \times 10^{19}$ eV 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} uncertainties the $\sigma_{X_{max}}$ are better than 70 g/cm^2 for $E \sim 10^{20}$ eV

6 Meeting the Scientific Requirements

The scientific requirements of the mission are described in detail in [2]. They can be summarized as: Observation area greater than 1.3×10^5km^2; Arrival direction determination accuracy better than 2.5° for 60° inclined showers at E $>1\times10^{20}$ eV (standard showers); Energy determination accuracy better than 30% for standard showers; $\sigma_{X_{max}} <$ 120 g/cm^2.

Results of simulations shown in the previous section confirm that the requirements can be already achieved with the current configuration.

The number of events that JEM-EUSO will observe depends of course on the UHE flux, which is uncertain especially at the highest energies. The apertures shown in fig. 2 can be however converted into number of events, assuming fluxes reported in literature by the Pierre Auger and the HiRes observatories [22, 23], and a conversion factor 0.14 between aperture and exposure (cloud impact included). We obtain more than 500 events with energy E $>5.5\times10^{19}$ eV for the flux measured by Auger and more than 1200 in the case of the HiRes spectrum.

A synthetic comparison between the JEM-EUSO aperture and exposure and the ones of other observatories is reported in Table 2.

7 Conclusions

The expected performance of the JEM-EUSO mission has been reviewed. Simulations show that JEM-EUSO can reach almost full efficiency already at energies around 2.5-3$\times10^{19}$ for a restricted subset of events, and full aperture at energies E$>$ 5.5×10^{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 has been assessed. Results indicate that the assumptions of 20% operational time and 70% cloud impact are matched by the present analysis. The angular, energy and X$_{max}$ resolutions satisfy the requirements. The total number of events expected at energies E$>$ 5.5×10^{19} in 5 years of operations ranges between 500 and 1200 events.

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