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Requirements and Simulation Study of the Performance of EUSO as External Payload on board the International Space Station

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The "Extreme Universe Space Observatory – EUSO" has been conceived as the first Space mission devoted to the investigation of Ultra High Energy Cosmic Rays, using the Earth's atmosphere as a giant detector. The scientific objectives of the experiment are to observe the UHECR spectrum above the GZK energy, with an improvement of one order of magnitude in the statistics of collected events with respect to the existing experiments, in such a way to study the source distribution in a full sky survey, as well as to open the channel (set a confidence limit) on the neutrino astronomy in this energy range. Supposed to be accommodated as external payload on board the International Space Station, EUSO Phase A study has been positively completed in July 2004. Nowadays, due to funding problems of the Space Agencies involved in the project, EUSO is currently on hold. Nevertheless, as a result of an end-to-end simulation approach, we summarize here the expected scientific performance coming out from Phase A, as well as the expected improvements in the technical performance of the EUSO Instrument to be achieved during Phase B, in order to fulfil the scientific objectives posed as goal of the experiment.

1. Introduction

The observation of Ultra High Energy Cosmic Rays (UHECR) is a very challenging issue: the existence of sub-atomic particles with individual energy greater than 5×10^{19} eV (where the GZK cut-off is expected to take place) raises fundamental scientific questions in connection with their origin and propagation in the interstellar and intergalactic space populated with photons from the Cosmic Microwave Background.

The UHECR particles, interacting with the Earth's atmosphere, give rise to propagating Extensive Air Showers (EAS) reaching the Earth surface more or less at their maximum ($>10^{10}$ particles). An EAS can be seen as a thin disk of few tenths of nanoseconds accompanied by isotropic emission of UltraViolet (UV) fluorescence induced in air Nitrogen by the secondary charged particles. But the fluorescence light is a feeble flare and, moreover, the expected flux of UHECR is of the order of 1 particle/km^2/century for energies above 10^{20} eV. This means that, for looking upward from a ground installation, a huge area is needed as in the Auger project, so to have the chance to observe ($\cong$100 events/year at E=10^{20}eV).

A solution to improve statistics is provided by observing from Space the UV induced fluorescence in the Earth's atmosphere, which allows surveying a much larger area with respect to the ground-based observatories, obtaining all-sky coverage. An observational premium of such a technique is the possibility of detecting also the reflected UV light due to the impact of the Cherenkov beam, accompanying the EAS, on top of clouds, land or sea.

The "Extreme Universe Space Observatory - EUSO" [1] is the first proposed Space mission devoted to the investigation of UHECR, whose observational approach is based on the detection of the streak of fluorescence light produced when such a particle interacts with the Earth's atmosphere. EUSO will observe the fluorescence signal looking downward from Space the dark Earth's atmosphere under a 60° full field-of-view (FoV). Fluorescence light, directly reaching EUSO from its EAS source, will be imaged by a large Fresnel lens optics (~2.5 m Ø) onto a finely segmented focal surface, composed by fast detectors (Multi Anode Photo Multiplier Tube) operating in the UV band 330÷400 nm. The accompanying Cherenkov beam will be seen by EUSO too, for that fraction which, according the reflecting surface diffuses upward in the atmosphere. The highly focal surface segmentation (more than 250 000 channels) and the fast detector time resolution (10 ns) will allow reconstructing the shower arrival direction and energy with high precision. Under the hypothesis of EUSO accommodated as external payload on board of the International Space Station (ISS), the wide-angle FoV of EUSO combined with the altitude of the ISS (of the order of 400 km will allow EUSO to observe a portion of ~230 km radius of Earth surface, corresponding to a target mass of $\sim 2\times 10^{12}$ tons of atmosphere.

Proposed to the European Space Agency (ESA) as free-flyer satellite in winter 1999, EUSO was accepted for an Accommodation Study on the ISS (end 2000) and then approved in Phase A (study report and conceptual design), positively completed in summer 2004; nowadays, due to funding problems of the Space Agencies involved in the project, EUSO is currently on hold.

An overall detailed description of EUSO is given in the “EUSO RedBook – Report on the Phase A Study” [2]; specific items are also discussed in several contributions to this Conference [3]. Here we report on the EUSO performance coming out from the Phase A study. To do this, a complete end-to-end simulation chain has been identified and developed, which goes from the physical process to the event reconstruction, through the atmosphere transport equation and a detailed detector performance simulation, taking into account the distortion introduced by the variability of the atmospheric conditions as seen by EUSO on board the ISS. Moreover, we summarize the expected improvements in technical performance of the Instrument to be achieved during Phase B, in order to fulfil the scientific objectives posed as goal of the experiment.

2. Discussion

The following scientific requirements in the definition of the EUSO features descend from the scientific goals: to obtain a UHECR rate in the energy range $>10^{20}$ eV of 10^3 events/year; to have an energy threshold able to perform an absolute flux calibration with the largest ground-based experiment (AUGER), i.e. at least half a decade overlap in the energy spectrum ($E_{thr}\leq 5\times 10^{19}$ eV); to have a pointing accuracy less than 1° and an energy resolution $\Delta E/E\leq 20\%$ in the energy range greater than 10^{20} eV. It is also necessary to be able to perform a systematic surveillance of the atmosphere and to map cloud and aerosol features and distribution, which influence the EAS development and detection. In fact, the “active” target, i.e. the Earth’s atmosphere, plays a manifold major role in EUSO: it is the medium where the showers develop, it is the light emission medium (yield of fluorescence from Nitrogen, and Cherenkov light associated to the shower development), and the transmission medium where the light (fluorescence, diffused and reflected Cherenkov light) propagates and attenuates from its source location to the telescope site, and it is the source of the largest fraction of noise, the expected UV background.

As a consequence of the scientific goals and observational requirements, and taking into account the specific constraints posed by its external accommodation on board the ISS, the EUSO Instrument will have to answer specific requirements, studied during Phase A through a complete end-to-end simulation chain [see references for details] whose starting point is the observational approach, folded to the actual Instrument design and parameters.

A first important point is the EUSO trigger efficiency; it is determined by the signal attenuation due to the light transmission in the atmosphere, the smearing effect of noise and the detection efficiency of the Instrument. The main ingredients for the trigger logic are: the Gate Time Unit (GTU) for counting the number of photoelectrons N_{pe} in a pixel of the detector at the focal surface; the minimum number N_{thresh} of photoelectrons piling-up in a GTU in a pixel, necessary to define it as an hit-pixel; the persistency level N_{pers}, i.e. the minimum number of consecutive GTU, N_{cons}, in which the ORed pixels of a given portion (macrocell) of the focal surface are hit. The first level trigger occurs when the hit-pixel condition $N_{pe} \geq N_{thresh}$ is detected with persistence $N_{cons} \geq N_{pers}$ in a given macrocell. This trigger scheme takes advantage of the very special space-time correlation that qualifies an EAS. The random photon noise background (natural or man-made sources) does not exhibit any space-time correlation and will be eliminated with efficiency depending on the shower energy. A second trigger level, consisting in a rough track finding algorithm on the hits in consecutive GTUs, based on the requirement of different fired hit to be space-time adjacent within a macrocell, has been implemented during Phase A, to further reject the fake triggers due to the random noise. The setting of the trigger parameters is determined by a trade-off between the desired extension of the energy range downward, toward faint showers, and both the need of a tolerable rejection power against the fake trigger contamination and a detection of tracks bright and long enough to be reconstructed with good resolution. Particular attention was given to the energy region below 10^{20} eV, where the cross-calibration with AUGER data will be required; in this energy region a value of ~80% overall trigger efficiency is required for $E>5\times10^{19}$ eV (averaged over the zenith angle and shower position in the EUSO FoV). The actual design of the detector, the technical performance of its component, and the preliminary reconstruction algorithm allow us to respect this figure only for showers inclined more than 65°, which are longer and better reconstructed. The outcome of Phase A study shows that, to reach the necessary requirements, some technical improvements are needed, in particular the final detector design should contain a refurbishment of the overall throughput of the detection chain and mainly of the optical system, as well as a more detailed track finding algorithm that should be included as high trigger level in the event selection phase.

A second point concerns the EUSO acceptance that, folded to the trigger and reconstruction efficiency and to the flux predicted by the theoretical models, is the main ingredient to derive the EUSO sensitivity. The geometrical acceptance given by the EUSO FoV ($\sim6\times10^5$ km^2 sr) is reduced by the condition that the shower falling inside this fiducial area is visible. The acceptance were then studied for showers of different quality, i.e., when the maximum of the fluorescence peak is observed with a sufficient intensity or not, and the Cherenkov peak is large enough to emerge from the background. Showers for which the fluorescence maximum and the Cherenkov peak are observed are named *golden* EAS. The outcome of Phase A study shows that the acceptance for golden EAS of 10^{20} eV under clear-sky conditions (no clouds) is seen to be ~80% of the total acceptance (duty cycle × 6×10^5 km^2 sr). In case of cloudy sky, a hiding effect is present which produces a distortion (peaking towards inclined showers) of the acceptance curve; a fraction of 68% of the events is reconstructed in this case. The duty cycle, i.e. the fraction of time during which EAS detection is possible, is essentially determined by the amount of background photons. Limiting the duty cycle to the night time of the ISS orbit, reduces the useful time to ~34%. Apart from man-made sources, background is determined by starlight, airglow and moonlight. A lower threshold can be set limiting the observation to the fraction of moonless time (new moon/moon below the ISS horizon), combined to night time; this lower limit is of the order of 13%. Allowing however the combined effect of low moon light and of other background sources not to exceed by more than 20% the expected level of moonless night background, the observational duty cycle has been estimated to rise up to 19%.

Trigger efficiency, acceptance and duty cycle so evaluated during EUSO Phase A study enable to predict the expected event statistics, according to the incoming flux of primary cosmic rays. Table 1 shows the result in terms of number of events, computed with 19% duty cycle, assuming an overall light throughput efficiency to be improved by ~20% with respect to the performance of the baseline detector of Phase A and two different hypotheses for the energy spectrum: a GZK, and a Super-GZK spectrum (corresponding to a $E^{-2.7}$ spectrum with no GZK suppression and normalized to 3.6×10^{-33} eV^{-1} m^{-2} s^{-1} sr^{-1} for $E=10^{19}$ eV). In a 3 year lifetime, in the case of Super-GZK, the number of expected events above 10^{20} eV is of the order of 3000; for the GZK case, this number is of the order of 250. This implies that the GZK decrease can be precisely measured as well as the GZK recovery.

Table 1. EUSO UHECR event rate (in 3 years of operation)

Energy		Super-GZK	GZK
Log (E(eV))	eV×10^{19}	# of events>E	
19.7	5.0	7832	3435
19.8	6.3	5932	1647
19.9	7.9	4169	641
20.0	10	2876	227
20.1	12	1934	84
20.2	15	1294	42
20.3	20	861	26
20.4	25	568	17
20.5	31	368	11
20.6	39	233	7.0
20.7	50	155	4.3
20.8	63	85	2.5
20.9	79	45	1.3
21.0	100	16	0.5

3. Conclusions

EUSO is a pioneering experiment for studying UHECR originated EAS from Space. Soundness and sensitivity of the EUSO Instrument are a priority for Phase B. The results of the Phase A study show that an instantaneous aperture of 6×10^5 km^2 sr with a duty cycle ~20% is a technically achievable goal with up-to-date technology. In particular, the final detector design should contain an improvement of the overall throughput of the detection chain, with a major effort to be devoted to the optical system optimisation, as well as a more detailed track finding algorithm that should be included as high trigger level in the event selection phase.

References

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[3] EUSO Collaboration, several contributions to this 29th ICRC, Pune (2005).