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Abstract: JEM-EUSO, the Extreme Universe Space Observatory (EUSO) on-board the Japanese Experiment Module (JEM) at the International Space Station, is a space-based observatory for Ultra High Energy Cosmic Rays (UHECR) which uses the atmosphere as a huge calorimeter. Therefore, an accurate monitoring of the atmosphere in cloudy conditions is important to properly reconstruct the UHECR events observed by the JEM-EUSO telescope. In this work we study the impact of the presence of clouds on the UV signal received by JEM-EUSO from which UHECR events to be reconstructed and investigate the JEM-EUSO trigger efficiency in cloudy conditions as well.

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Observation of extensive air showers in cloudy conditions by the JEM-EUSO Space Mission.

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Abstract

JEM-EUSO, the Extreme Universe Space Observatory (EUSO) on-board the Japanese Experiment Module (JEM) at the International Space Station, is a space-based observatory for Ultra High Energy Cosmic Rays (UHECR) which uses the atmosphere as a huge calorimeter. Therefore, an accurate monitoring of the atmosphere in cloudy conditions is important to properly reconstruct the UHECR events observed by the JEM-EUSO telescope. In this work we study the impact of the presence of clouds on the UV signal received by JEM-EUSO from which UHECR events to be reconstructed and investigate the JEM-EUSO trigger efficiency in cloudy conditions as well.

Keywords: Ultra-high energy cosmic rays, JEM-EUSO, Extensive air showers, Atmosphere

1. Introduction

The origin of Ultra High Energy Cosmic Rays (UHECRs) with energies around and above 10^{20} eV is a long-standing mystery Letessier-Selvon (2011). Although they are affected by galactic and extragalactic magnetic fields, tracing back toward the arrival directions of the observed UHECRs may point back to their still unidentified and powerful sources. At such extreme energies, the Greisen-Zatsepin-Kuzmin effect Greisen (2011); Zatsepin (1966) limits the distances of UHECR sources and a suppression in the observed fluxes has to be taken into account. The former constrains potential source candidates among nearby astrophysical objects. The latter, on the other hand, requires a large-scale observatory to search for sources by the statistical approach.

JEM-EUSO (Extreme Universe Space Observatory on-board the Japanese Experiment Module) JEM-EUSO Collaboration (2008); M.Casolino (2011); T.Ebisuzaki (2012); Takahashi et al. (2009) is a novel space-based observatory that is planned to be launched by 2017. The observation of UHECRs is based on indirect detection of Extensive Air Showers (EASs) as a consequence of a cascade induced by primary cosmic rays by a fluorescence telescope utilizing the nighttime atmosphere as a calorimeter. From the ISS altitude of ∼ 400 km, the JEM-EUSO telescope with a Field Of View (FoV) of ∼ 60° overlooks an observation area of $\sim 1.4 \times 10^5$ km^2 when it points to the nadir.

To estimate the energy and arrival direction of the primary particle as well as its composition, the UV light profile from EAS is needed to be measured. From space, fluorescence light that is produced after the excitation of nitrogen molecules by EAS electrons is the dominant source of signals. A part of Cherenkov light beamed along EAS electron trajectories contributes to the light by scattering in the atmosphere. Moreover, Cherenkov photons reaching land, water or cloud are reflected and result in a characteristic signal in arrival time at the detector that may indicates the location of the impact point.

The observed profile depends on atmospheric conditions such as presence of clouds. Unlike stationary observatories on the ground, the JEM-EUSO space telescope orbiting with ISS traverses above various atmospheric situations within its large observation area. To characterize the properties of the atmosphere, the JEM-EUSO space mission counts on an Atmospheric Monitoring (AM) system Sáez-Cano (2012); Rodríguez Frías (2012) that consists of an InfraRed (IR) camera Morales de los Ríos (2011); Rodriguez Frias (2013) and a LIDAR (LIght Detection And Ranging) system Neronov (2011); Rodriguez Frias (2012b). The IR camera gives the cloud coverage in the FoV of the main telescope Morales de los Rios (2013). It provides the clouds altitude thanks to the difference in the brightness temperature in the IR bands, although a radiative model is needed to include the influence of the Earth's atmosphere. The LIDAR measure the optical depth profiles of the atmosphere in selected directions. The laser back-scatter signal allows to detect cloud and aerosol layers Sáez-Cano (2012); Neronov (2011). The LIDAR also

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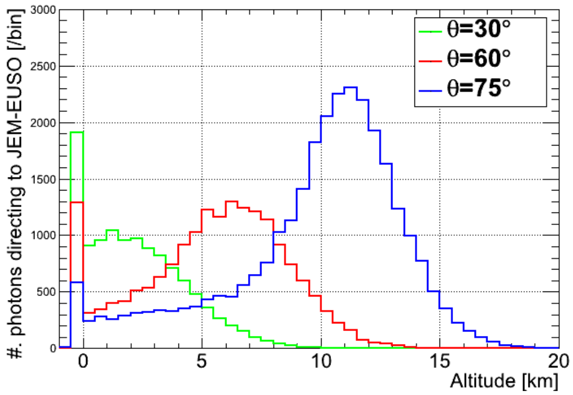

Figure 1: Number of photons produced in the direction of the JEM-EUSO telescope as a function of emission or scattering altitude for different arrival directions ($\theta = 30°$, $60°$ and $75°$) for a 10^{20}eV induced EAS.

provides a complementary measurement for the cloud-top altitude obtained by the cloud temperature measured by the IR camera data. The main JEM-EUSO telescope may also give information of clouds presence by different intensities observed in UV band.

In this work, we discuss the observation scheme of EAS in the JEM-EUSO mission in cloudy conditions. The influence of clouds to individual EAS and to the trigger aperture are analyzed. Preliminary results were reported in Sáez-Cano (2011). Here we report on the updated results of the latter analysis.

2. Cloud impact on space-based observation of EAS

Unlike ground-based observatories, the space-based observatories may efficiently measure EAS development above its maximum. Figure 1 represents the number of photons emitted toward the JEM-EUSO telescope from the typical EAS landing near the center of FoV. Three different examples of arrival directions from zenith angles $\theta = 30°$, $60°$ and $75°$ are demonstrated.

For more inclined EAS, their developments take place in higher atmosphere where air density is the lower. Moreover, more photons are produced along longer apparent tracks JEM-EUSO collaboration (2013).

For UV photons propagation in the atmosphere, Rayleigh scattering and absorption by ozone must be taken into account for the range of wavelengths where the JEM-EUSO telescope is sensitive (300–430 nm). In presence of clouds, Mie scattering must also be considered. The number of photons reaching the JEM-EUSO telescope N_{ph} is approximated by the following relation:

$$N_{\mathrm{ph}} \simeq \int_{\mathrm{surface}}^{\mathrm{ISS}} n_0(H) \times e^{-\tau(H)} dH, \qquad (1)$$

where $n_0(H)$ represents the number of photons emitted in the direction of the telescope from the altitudes between H and $H + dH$ as demonstrated in Figure 1, and $\tau(H)$ is the overall optical depth of the atmosphere above the altitude H. The optical depth $\tau(H)$ is a sum of that of atmospheric molecules $\tau_{\mathrm{atm}}(H)$ above the given altitude H and that of cloud τ_{C} there. The former is well modeled as such in LOWTRAN code Kneizys (1988). In this work, the latter is characterized by the meteorological satellite database with cloud-top altitudes and optical depths.

For the simulation studies performed in this work, we employ the software ESAF (Euso Simulation and Analysis Framework) Berat (2010) that accommodates the software packages to reproduce the assumed test cloud, namely uniform layer with a cloud-top altitude, an optical depth and a physical thickness. It should be pointed out that the intensity of the signal is most affected by the attenuation inside the clouds. Since in this work we focus on the impact on the trigger, the physical thickness of the cloud is assumed as 1 km. Moreover, in order to evaluate the impact of the clouds, we assume the single layer approximation (see JEM-EUSO collaboration (2013) for details) using the occurrence of cloudy conditions from TOVS satellite measurement TOVS (2008).

Figure 2 shows the typical time profile of observed EAS signal from $\theta = 60°$ Sáez-Cano (2011). The horizontal axis is the absolute time of photons reaching the JEM-EUSO telescope in Gate Time Units (GTUs; 2.5 μs), time resolution of detector. The vertical axis is the number of photons of detected by the telescope by different species: direct fluorescence light (red line), scattered Cherenkov light (light blue area), reflected Cherenkov light from the surface (magenta area) and reflected Cherenkov light on the top of the cloud (gray area). The top and bottom panels indicate the low-altitude optically thick cloud (2.5 km and $\tau_{\mathrm{C}} = 5$) and high-altitude optically thin cloud (10 km and $\tau_{\mathrm{C}} = 0.5$), respectively. In each panel, the case of the clear atmosphere is shown for comparison with a dashed blue line.

If the cloud is optically thick, like in the upper panel of Figure 2, photons emitted below the cloud are largely attenuated and therefore, a truncation of the observable light profile of the EAS takes place. However, if the cloud is located sufficiently low or the EAS is very inclined, most part of the EAS track including its maximum is observed as similar as in the case of clear atmosphere. Moreover, the Cherenkov light reflected from the cloud-top is much more pronounced.

If the cloud is optically thin, as presented in the bottom panel of Figure 2, photons from EAS suffer moderate attenuation Sáez-Cano (2011). This leads to a reduced amount of the photons reaching the JEM-EUSO telescope. In this case, the Cherenkov light reflected from the cloud top is little and a certain fraction of the light reaches the surface of Earth where it is reflected.

Optically thin clouds that more impact on the EAS signal are the highest ones (cirrus-like clouds), because they may be located near either the shower maximum or near the beginning of the shower development, so more pho-

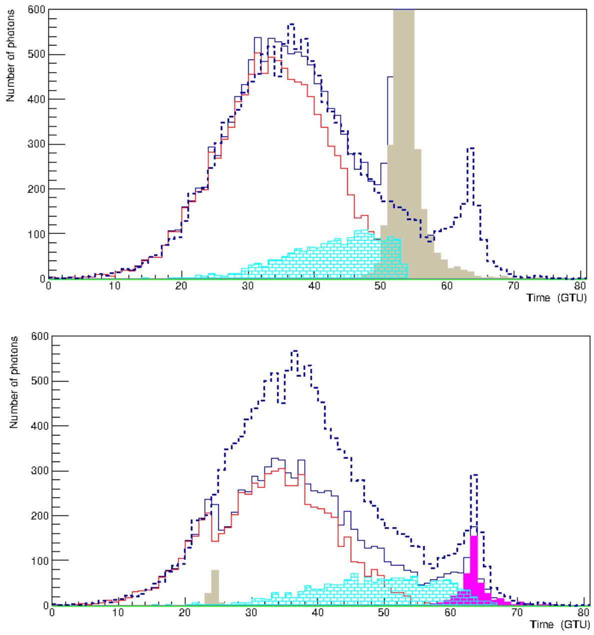

Figure 2: Arrival time distribution of UV photons at the JEM-EUSO telescope pupil produced by a 10^{20}eV and $\theta = 60°$ UHECR induced EAS. The vertical axis is the number of photons of directed fluorescence light (red line), scattered Cherenkov light (light blue area), reflected Cherenkov light on Earth's surface (magenta area) and reflected Cherenkov light on the top of the cloud (gray area) detected by the telescope. The horizontal axis is in GTU units (2.5 μs). Upper panel: a low, optically thick cloud condition is shown (H_C=2.5 km, $\tau_C = 5$). We can distinguish a very high reflected Cherenkov light peak on the surface of the cloud. Bottom panel: a high, optically thin cloud is plotted (H_C=10 km, τ_C=0.5). In this scenario the main Cherenkov contribution is the one reflected on Earth's surface. The EAS signal is attenuated due to the absorption of the cloud. For both cases the dashed blue line represents the number of photons directly emitted that reach the JEM-EUSO pupil in the clear atmosphere.

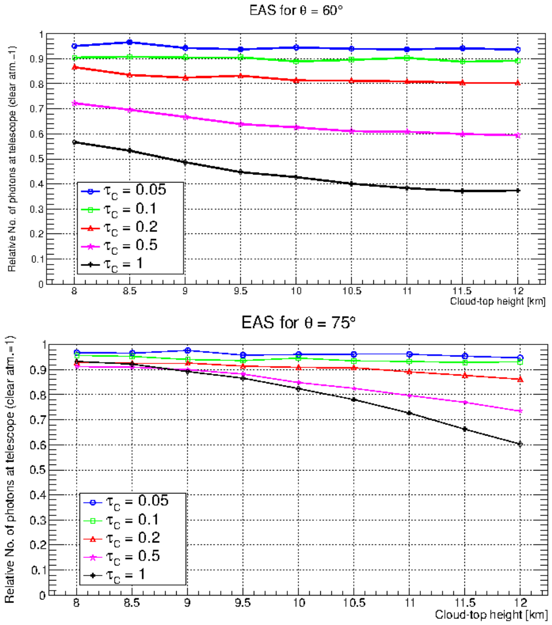

Figure 3: Attenuation of photons in cirrus-like clouds compared with clear atmosphere as a function of cloud-top alitude H_C along different optical depths denoted by different symbols. Top and bottom panels indicate the cases of $\theta = 60°$ and $\theta = 75°$, respectively.

tons are affected by absorption due to the cloud. Figure 3 represents the relative ratio of photons reaching the telescope from along the EAS in case of presences cirrus-like cloud as a function of cloud-top altitude to that of clear atmosphere. Top and bottom panels denote for $\theta = 60°$ and 70°. Different optical depths are denoted by different symbols. The top and bottom panels shows the case of $\theta = 60°$. For these showers, their maximum develops at altitudes of $\sim 7-8$ km. Thus, these clouds are located near or above the shower maximum, and therefore, its influence is significant. The bottom one shows the property for more inclined EAS ($\theta = 75°$) whose shower maxima take place at an $\sim$ 11 km altitude. This is the reason why for the bottom panel the attenuation is more as we increase the altitude of the cloud. For altitudes such as 8-10 km, the shower maximum is above the cloud, so the attenuation is produced in the end of the shower development and cloud impact is less significant than that for less inclined showers.

In reconstructing each triggered EAS event, the arrival direction determination is based on the apparent motion of signals from EAS traveling at speed of light observed at almost constant distance $\sim$ 400 km Bertaina (2013). Once arrival direction is known, the time difference of observed signals between the peak with respect to those from the reference altitude helps to estimate the EAS depth of maximum development, ie. $X_{\max}$. In clear atmosphere, the reflection of Cherenkov light from Earth's surface may give the reference, while in presence of optically thick clouds, it may be chosen the cloud-top height which is well determined by the IR camera Morales de los Rios (2013). The primary energy is technically inferred from the integration of estimated energy deposited in the atmosphere by ordinary shower profile fit. In presence of optically thin clouds between EAS and the JEM-EUSO telescope, this approach leads to an underestimation of the primary energy. Nevertheless, information on the arrival direction and $X_{\max}$ estimation is little affected.

In Figure 4 we can observe the image on the Focal Surface (FS) for three different scenarios: clear atmosphere, nimbostratus-like cloud (middle; top panel; $H_C = 7.5$ km and $\tau_C = 5$) and cirrus-like cloud (bottom; $H_C = 10$ km and $\tau_C = 0.5$) for a shower with $E = 10^{20}$ eV and $\theta = 60°$. We can observe that in the second case the cloud is optically thick enough to shorten apparent shower track. However, for the last case, although in presence of a cirrus-like cloud the EAS signal suffer attenuation, is well defined and, thus, arrival direction may be inferred with a similar uncertainty of that of a clear atmosphere. In addition, such atmospheric conditions may be recognized by the measurement of the LIDAR and the IR camera to classify the observed events into different quality category in order to fully and properly reconstruct the UHECR events.

To investigate clouds impacts in the overall observation efficiency by the JEM-EUSO Space Mission, we define 'cloud efficiency' $\zeta(E)$ as follows:

$$\zeta(E) = \frac{A(E, H_\mathrm{C}, \tau_\mathrm{C})}{A(E; \text{clear atm.})} \tag{2}$$

where $A(E)$ is the geometrical trigger aperture as a function of energy E. The numerator and denominator are those of cloudy and clear atmosphere conditions, respectively.

Table 1 summarizes the cloud efficiency for EAS induced by UHECR with $E > 6.3 \times 10^{19}$ eV in case of different cloudy conditions. Four clouds altitudes (2.5, 5, 7.5 and 10 km) and four optical depths (0.05, 0.5, 1.5 and 5) are considered.

Optically thin clouds attenuate the signal below the cloud in terms of $e^{-\tau_C}$. Therefore, they do not have a strong impact in the trigger efficiency. Optically thick clouds, on the other hand, significantly absorbs the signal originated below the cloud. This means that the number of photons emitted in the direction of the JEM-EUSO telescope above the cloud need to activate the trigger. Therefore, the trigger efficiency for thick clouds depends on the altitude of the cloud and the zenith angle of the EAS. High clouds may affect all EAS, lowering JEM-EUSO trigger efficiency, while clouds at intermediate altitudes only affect less inclined showers. If the optically thick cloud is low enough, trigger efficiency is not affected. In this case, most part of the EAS develops above the top cloud altitude.

To properly infer the UHECR physical parameters, the EAS maximum development has to be inferred Abu-Zayyad (2004). Therefore, we require a priori selection for this condition as optically thin clouds, clear atmosphere or clouds whose cloud-top height is lower than the altitude of the EAS depth of maximum development, H_max.

Figure 5 shows the cloud efficiency as function of the UHECR primary energy for all triggered event by circles and for the above selection for EAS depth of maximum development visibility, (ie. τ_C <1 or $H_\mathrm{max} > H_\mathrm{C}$) by triangles. To deduce the average effect, we weigh the different cloud scenarios assuming the cloud occurrence by the previously mentioned TOVS database. The error bar shown on the left of the plot represent the expected uncertainty of the result due to the different statistical and systematic uncertainties in the procedure.

For cloudy scenarios where the EAS depth of maximum development is observable, we can see that above $\sim 3{\times}10^{19}$ eV the value is almost constant and it accounts as $\sim 72\%$ JEM-EUSO collaboration (2013); Shinozaki (2011). This is an important value to estimate the JEM-EUSO exposure for EAS events that potentially allows reconstruction with their maxima observable. It is already included in the current estimation of JEM-EUSO exposure in nadir mode Bertaina (2013).

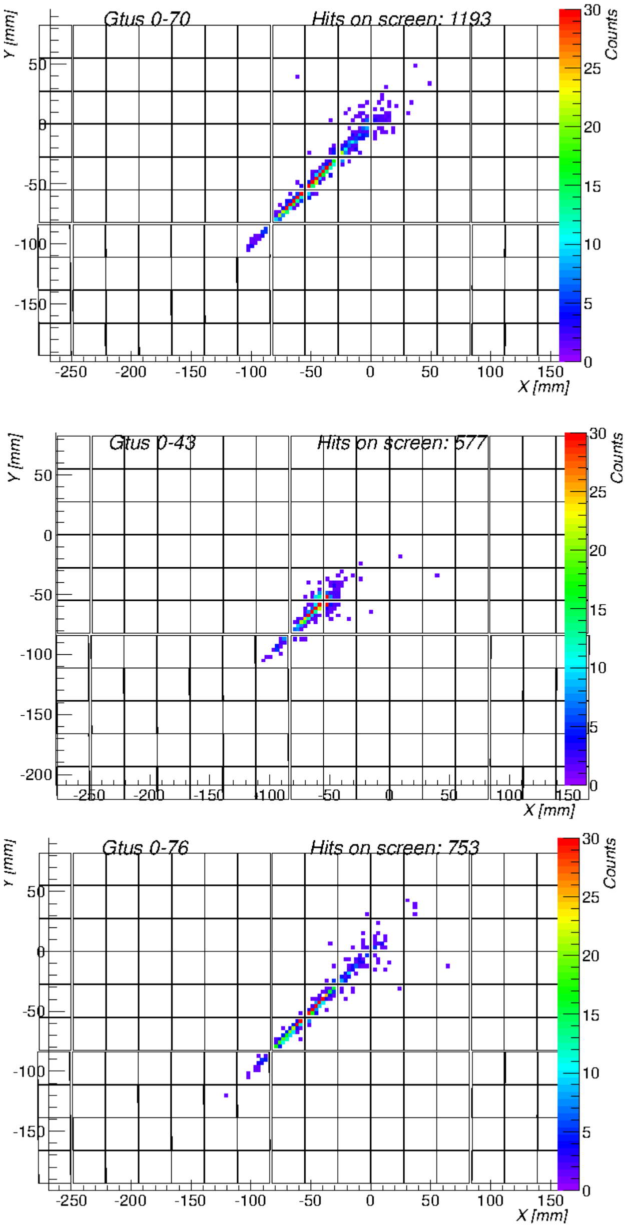

Figure 4: Shower image on the FS of a standard shower with different cloudy condtions (top; $E = 10^{20}$eV and $\theta = 60°$) for clear atmosphere, for thick cloud case (middle; $H = 7.5$ km, $\tau_\mathrm{C} = 5$), and for optically thin cloud (bottom; $H = 10$ km, $\tau_\mathrm{C} = 0.5$). For a thick cloud, the shower track is shortened by the presence of the cloud. On the other hand, for an optically thin cloud, although the EAS signal suffers attenuation, the shower track is well defined and, thus, arrival direction may be inferred with a similar uncertainty of that of clear atmosphere.

3. Discussion

Unlike UHECR ground-based detectors, the space-based detectors like JEM-EUSO are less affected by low-altitude clouds. To increase the statistics of the detected EAS, the JEM-EUSO may use events observed in cloudy scenarios

Table 1: Average cloud impact for different types of clouds for UHECR primary energy above 6.3×10^{19} eV.

	H_{C}			
	2.5 km	5 km	7.5 km	10 km
$\tau = 5$	90%	70%	26%	18%
$\tau = 1.5$	89%	74%	43%	37%
$\tau = 0.5$	89%	82%	69%	66%
$\tau = 0.05$	90%	88%	89%	88%

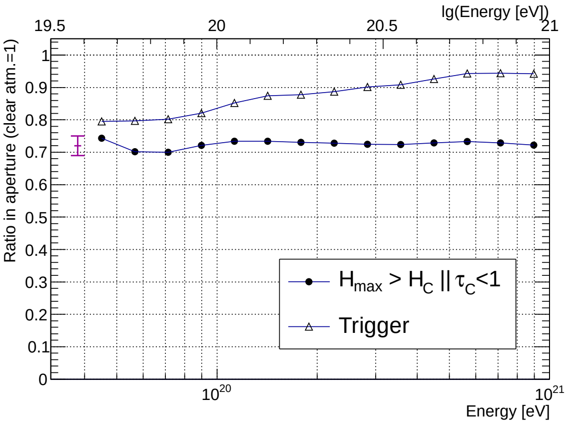

Figure 5: Cloud efficiency as a function of UHECR primary energy for all cloudy scenarios are represented by triangles. Those cloudy scenarios where the EAS depth of maximum development is observable (τ_{C} <1 or $H_{\mathrm{max}} > H_{\mathrm{C}}$) are represented by circles. The error bar shown on the left of the plot represent the expected uncertainty of the result due to the different statistical and systematic uncertainties in the procedure.

where the EAS depth of maximum development is observables such as criteria of τ_{C} <1 or $H_{\mathrm{max}} > H_{\mathrm{C}}$. Therefore, to estimate the overall JEM-EUSO exposure it is mandatory to study its trigger efficiency also in such cloudy scenarios. Taking into account the cloud coverage, and the cosmic ray energy spectrum, for UHECR primary energies above 3×10^{19} eV, the averaged trigger aperture in cloudy conditions is almost constant and accounts 72% to that of clear atmosphere.

UHECR data obtained in cloudy conditions may be of use for some analysis where very high accuracy is not needed. Optically thick clouds, as long as the maximum development of EAS is located above the cloud, may even have a positive effect as it ensures us a bright Cherenkov reflected light from the top of such a cloud. With a reasonable accuracy, this gives the location of a point of the shower track that helps to reconstruct geometrical and physical parameters of the EAS. Optically thin clouds, on the other hand, attenuate the UV signal as a factor of $e^{-\tau_{\mathrm{C}}}$. This attenuation has a more important effect for higher clouds, since most part of the EAS takes place below such cloud. However, if we detect that there is a optically thin cloud in the JEM-EUSO FoV, we may at least mark such event to reject or give a lower limit energy estimation of the UHECR event. Moreover, the apparent EAS track is not affected by the clouds and therefore the angular reconstruction is still possible for these cloudy scenarios.

For optically intermediate clouds, we may identify two main Cherenkov contributions. One is the Cherenkov light reflected on the top of the cloud. The other, since these clouds are not optically thick enough to truncate the signal below the cloud, is the Cherenkov component reflected on Earth's surface.

4. Summary

The main scientific aims of the JEM-EUSO mission is to identify the UHECR origin. Therefore the determination of and arrival direction as well as the energy of each observed EAS event are one of the mandatory tasks. The JEM-EUSO mission is intended to detect UHECR with unprecedentedly huge statistics, enough to understand how the extremely high energy range of the UHECR spectrum behaves. Moreover, considering that UHECR at such huge energies are negligibly affected by galactic and extragalactic magnetic fields, following UHECRs trajectories we may be able to identify UHECR sources.

Since the observation area of JEM-EUSO is extremely large $\sim 1.4 \times 10^5$ km^2, we can find very different atmospheric conditions in its field of view at the same time. The impact of clouds scenarios in UHECRs detection by the JEM-EUSO telescope using ESAF are investigated.

In this paper, we evaluate the effect of different cloud scenarios on the EAS observation by the JEM-EUSO space telescope. Moreover, we define the 'cloudy efficiency', which can be defined as the trigger efficiency in cloudy conditions for energies higher than 3 $\times 10^{19}$ eV.

In presence of optically thin clouds, the UV light from EAS is attenuated by $e^{-\tau_c}$ in terms of the optical depth of the cloud. Optically thin clouds with higher altitudes have a more important impact on EAS detection, since the attenuation affects more fraction of the shower. Thus, this kind of clouds are very important to be detected. For optically thick clouds, UV light from EAS that is produced or scattered below the cloud is significantly absorbed as it crosses away such cloud. However, for inclined showers and for low-altitude cloud, a relevant part of the EAS is observable which allows to estimate the EAS profile development. To quantify how the presence of these clouds affect the JEM-EUSO trigger aperture, we compare the aperture in different cloudy scenarios with that of clear atmosphere to find out that this 'cloud efficiency' is constant for UHECRs of energies above $\sim 3 \times 10^{19}$ eV.

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