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Atmospheric Monitoring system of the JEM-EUSO telescope

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Abstract: The JEM-EUSO fluorescence telescope will observe UV emission from Ultra High Energy Cosmic Ray (UHECR) induced Extensive Air Showers (EAS) from space. Observation with a space-based telescope has an advantage compared to the ground-based observations, because the EAS signal from the upper atmosphere above 10 km altitude (above the top of the Troposphere) is never obscured by optically thick clouds for such a telescope. Nevertheless, proper interpretation of the UV signal from the lower parts of some 60-70% EAS detected by JEM-EUSO, including the reconstruction of the energy, direction and identity of the UHECR particle, requires a detailed knowledge of the influence of clouds and aerosols on the detected UV signal. The Atmospheric Monitoring system of JEM-EUSO will use the LIDAR, operating in the UV band, an infrared camera, the UV images of the night sky obtained by the JEM-EUSO telescope itself, as well as real time global meteorological data and models to deduce the distribution and properties of clouds and aerosol layers in the atmospheric volumes around the location of each triggered EAS event. In this contribution we describe the set-up of JEM-EUSO Atmospheric Monitoring System and characterise its performance. In addition, we show that the reconstruction of UHECR events will be possible also for events occurring in cloudy sky conditions if the data of the Atmospheric Monitoring are taken into account.

Keywords: Ultra High Energy Cosmic Rays, Atmospheric Monitoring, IR Camera, LIDAR

1 Introduction

JEM-EUSO (the Extreme Universe Space Observatory onboard the Japanese Experiment Module) on the International Space Station (ISS) is a new space mission which aims to discover the origin of the Ultra High Energy Cosmic Rays (UHECRs) with energy above 10^{19} eV [1, 2]. It is a refractive telescope with the aperture $\simeq 2.5$ m which it will detect fluorescence UV emission from Extensive Air Showers (EAS) produced by UHECRs penetrating in the atmosphere. The properties of the primary UHECR particles (energy, type, arrival direction) will be derived from the imaging and timing properties of the UV emission from the EAS track in the atmosphere. The amount of both fluorescence and Cherenkov signals reaching JEM-EUSO depends on the extinction and scattering properties of the atmosphere. A correct reconstruction of the UHECR energy and of the type of the primary cosmic ray particle requires, therefore, information about absorption and scattering of the UV light.
Also, the presence of clouds and aerosols layers will alter the physical properties of the atmosphere. Uncertainties on the knowledge of extinction and scattering coefficients related to the variable meteorological conditions introduce distortions of the UV signal from the EAS leading to systematic errors in the determination of the properties of UHECR from the UV light profiles [3].
In particular, presence of optically thin cloud layers between the EAS and JEM-EUSO telescope reduces the overall intensity of UV light leading to an under-estimate of the UHECR energy. EAS penetration into an optically thick cloud produces strong enhancement of the scattered Cherenkov light emission from the shower, which can be misinterpreted as Cherenkov light reflection from the ground/sea. This again leads to a wrong estimate of the depth of the EAS maximum in the atmosphere.
Since the ISS is moving with an orbital velocity of ~ 7 km/sec, JEM-EUSO will experience all possible weather conditions. The AM system will continuously monitor the variable atmospheric conditions in JEM-EUSO Field of View (FoV) during the entire UHECRs data taking period, providing information on cloud cover and optical properties of cloud/aerosol layers at the time and location of the EAS. In this contribution we describe the set up of the AM system of JEM-EUSO and its expected performance.

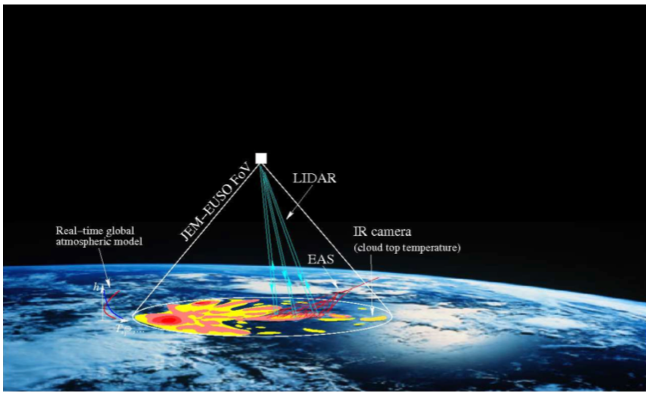

Figure 1: Sketch of the concept of Atmospheric Monitoring in JEM-EUSO.

2 Atmospheric Monitoring system

The goal of the AM system is to obtain information on the distribution and optical properties of clouds and aerosol layers inside the JEM-EUSO FoV [5].
The basic requirements on the precision of the measurements of the clouds and aerosol layers characteristics are obtained from the general requirements on the precision of measurements of the UHECRs properties: *(A1)* measurement of UHECR energy with precision better than 30%; *(A2)* measurement of the depth of the shower maximum with precision better than 120 g/ cm^2.
Since the energy of the UHECR is proportional to the overall intensity of the UV fluorescence emission from the EAS, the uncertainty of the energy measurement (A1) will depend on the uncertainty in the determination of the extinction properties in the atmosphere. Adopting a maximum 15% uncertainty as a reference value (so that the error introduced by this uncertainty is sub-dominant), one can conclude that the measurement of the optical depth profile of the atmosphere around the EAS location has to be $\Delta\tau \geq 0.15$.
In addition, the depth of the shower maximum will be affected by the uncertainty in the determination of the location and physical properties of clouds and aerosol layers, in such a way that uncertainties in the determination of both extinction and scattering properties of these features will directly affect the precision of X_{max} measurement (A2). Imposing a maximum of 60 g/cm2 as a possible contribution to the uncertainty of X_{max} measurement, lead to the conclusion that a measurement of the cloud top with an accuracy $\Delta H \leq 500$ m is required.

The AM system will include [4]:

1. an Infrared (IR) camera;
2. a LIght Detection And Ranging (LIDAR) device;
3. global atmospheric models generated from the analysis of all available meteorological data by global weather services such as the National Centers for Environmental Predictions (NCEP), the Global Modeling and Assimilation Office (GMAO) and the European Centre for Medium-Range Weather Forecasts (ECMWF).

The principle of the AM system in JEM-EUSO is illustrated in Fig 1. The JEM-EUSO telescope will observe the EAS development only during nighttime. The IR camera will monitor the entire FoV to detect the presence of clouds and to obtain the cloud cover and cloud top altitude during the observation period of the JEM-EUSO main instrument. The LIDAR will be shot in several directions around the location of each triggered EAS event and it will measure the optical depth profiles of the atmosphere in these selected direction, with the ranging accuracy of $375/cos(\theta_z)$ m, where θ_z is the angle between the direction of the laser beam and the nadir. The power of the laser will be adjusted in such a way that cloud/aerosol layers with optical depth $\tau \geq 0.15$ at 355 nm wavelength will be detectable.
The LIDAR measurements are complementary to the measurements taken by the infrared camera. From one hand the IR camera will provide an overall picture of the optically thick cloud coverage in the JEM-EUSO FoV, which is not possible to measure with the LIDAR, since this device can retrieve the optical properties of the atmosphere only for a certain direction. On the other hand the LIDAR will provide information (altitude and optical depth) of optically thin clouds and aerosol layers, which cannot be identified by the IR camera.
Finally real-time atmospheric profiles from global models will be used as an input for the off-line analysis of the LIDAR data, calibration of the IR camera and modelling of the EAS development in the atmosphere and its reconstruction.

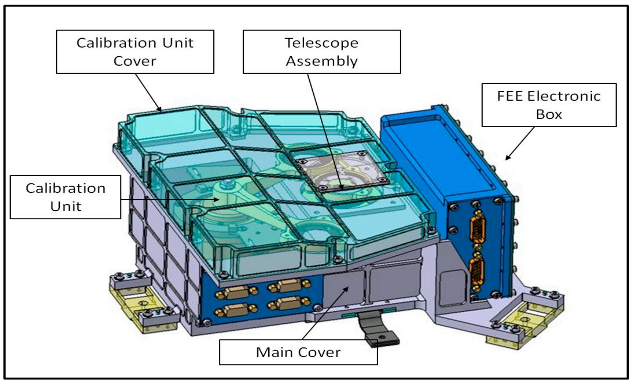

Figure 2: Illustrative picture of the IR Camera design

3 Infrared Camera

The IR camera of JEM-EUSO is an infrared imaging system aimed to detect the presence of clouds in the FoV of the JEM-EUSO main telescope and to obtain the cloud cover and cloud top altitude during the observation period of the JEM-EUSO main instrument. It will consist of a refractive optics made of germanium and an uncooled μbolometer array detector [6]. Interferometer filters will limit the wavelength band to 10-12.5 μm. In the current configuration, two $\delta\lambda = 1$ μm wide filters (centred at 10.8 μm and 12 μm) will be used to increase the precision of the radiative temperature measurement. The FoV of the IR-Camera will totally match the FoV of the main JEM-EUSO telescope. The angular resolution, which corresponds to one pixel, is about 0.1°. A temperature-controlled shutter in the camera and mirrors are used to calibrate background noise and gains of the detector to achieve an absolute temperature accuracy of 3 K.
To accomplish the mission and scientific requirements for the Infrared camera, a System Preliminary Design (SPD) of a prototype of the IR camera is under development by the Spanish consortium involved in JEM-EUSO [7]. A schematic illustration of the camera hardware can be seen in Fig. 2.

4 LIDAR

The LIDAR is composed of a transmission and receiving system. The transmission system comprises a Nd:YAG laser and a pointing mechanism to steer the laser beam in the direction of triggered EAS events.
The specifications of the laser unit of the LIDAR transmission system are similar to the laser ranging devices on board of several satellites for atmospheric sounding purposes such as the NASA's satellite CALIPSO [8]. The main difference from the previous space-based lasers is that the operational

wavelength (λ = 355 nm) will be the third harmonic of the Nd:YAG laser, rather than the first, at 1064 nm, or the second, at 532 nm, harmonics, as in existing systems. LIDAR measurements should probe the atmosphere at the location of each triggered EAS event. To get this information, the LIDAR will have a re-pointing capability. The laser beam will be repointed in the direction of EAS candidate events following each EAS trigger of the JEM-EUSO telescope. Re-pointing of the laser beam will be done with the help of a steering mirror with two angular degrees of freedom and maximal tilting angle $\pm15°$, needed to point the laser beam anywhere within the JEM-EUSO FoV. The laser backscattered signal will be received by the main JEM-EUSO telescope which is well suited for detection of the 355 nm wavelength. Any Multi-Anode Photo-Multiplier Tube (MAPMT) in the focal surface of JEM-EUSO telescope could temporarily serve as the LIDAR signal detector; a special LIDAR trigger is foreseen in the Focal surface electronics of JEM-EUSO detector.

A summary of the specifications needed for the entire system is reported in table 1.

Parameter	Specification
Wavelength	355 nm
Repetition Rate	1 Hz
Pulse width	15 ns
Pulse energy	20 mJ/pulse
Beam divergence	0.2 mrad
Receiver	JEM-EUSO telescope
Detector	MAPMT (JEM-EUSO)
Range resolution (nadir)	375 m
Steering of output beam	$\pm30°$ from vertical
Mass	14 kg
Dimension	$450 \times 350 \times 250$ mm
Power	< 20 W

Table 1: Specification for the JEM-EUSO LIDAR.

Measurements of the laser backscattered signal with time resolution of 2.5 μs (representing the duration of the time unit, named Gate Time Unit or GTU, of the pixel-level digital trigger) will provide a range resolution of 375 m in nadir direction. The energy of the laser pulse will be adjusted in such a way that the backscattered signal will have enough statistics for the detection and measurement of the optical depth of optically thin clouds with $\tau \leq$0.15 at large off- axis angles.

In order to study the capability of the system in retrieving the physical properties of atmospheric features such as cloud and aerosol layers a simulation of the LIDAR has been implemented inside the ESAF Simulation Framework used for the JEM-EUSO mission [9]. This simulation chain has been used to study the features of the LIDAR backscattered signal and to reproduce a real-case observation in which the EAS profile shows observable deviations from the "clear sky case" and needs to be corrected.

In fact, once an EAS is detected, LIDAR is used to monitor whether the shower developed in clear sky or not. If the presence of a cloud is detected the backscattered signal from the laser is used to measure the cloud optical depth. Examples of the simulated laser backscattered signal as it would appear in the JEM-EUSO detector are shown in Fig. 3. The top panel shows the comparison of signal in

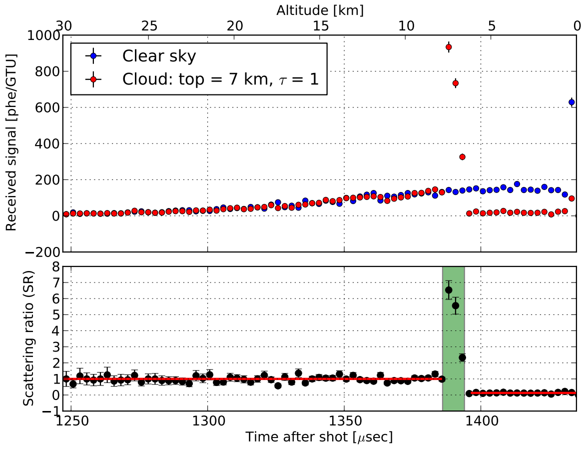

Figure 3: *Top*: LIDAR backscattered signal in clear sky (blue) and in the presence of a cloud (red) as a function of time. *Bottom* Scattering ratio (SR) for the case of LIDAR shooting an optically thick ($\tau = 1$) cloud located at an altitude of 7 km. The cloud mark region is highlighted with a green box. A fit of the SR is shown as a red line. The cloud optical depth is retrieved by this fit procedure.

case of clear sky (blue points) and in presence of the cloud (red points) as a function of the time after shooting the laser and the altitude. The presence of a cloud at $\sim$7 km is clearly detected by the LIDAR as an increasing of backscattered signal coming from that region. The bottom panel shows the so-called LIDAR Scattering Ratio (SR), the ratio between the backscattered signal detected in the real condition and a reference profile represented by the backscattered signal in clear sky. Fitting the SR in the region below the cloud allows to measure the optical depth (τ) of the cloud, simply using the formula: $SR = -log(2\tau)$.

Once the cloud is detected and its optical depth measured the EAS profile can be corrected. The result of this correction is reported in Fig 4. The profile of the detected photoelectron signal is shown as a function of GTU for a shower generated by a UHE proton with E = 10^{20} eV and $\theta = 60°$. The blue points represent the shower time profile in clear sky conditions and it is characterized by the presence of a feature at $\sim$ 60 GTU, the "ground mark", due to Cherenkov photons hitting the ground and reflected back to the JEM-EUSO focal surface. The second profile, in red, represents the shower crossing an optically thick cloud ($\tau = 1$) located at an altitude of 7 km. The cloud mark (green band), generated by photons reflected by the cloud top layers, is visible this time, while the Cherenkov mark from the ground is strongly suppressed. The reconstructed profile is shown by the black point. Statistical errors are calculated propagating the error on the optical depth measurement. Lack of information on the optical depth profile inside the cloud does not allow for a correct reconstruction of the shower profile in that region. It is worth to notice that the ground mark is almost entirely recovered by this analysis procedure.

5 Global Atmospheric Models

Analysis of both the IR camera and LIDAR data can be improved if initial values of the physical parameters of the atmosphere (temperature and pressure profiles, humid-

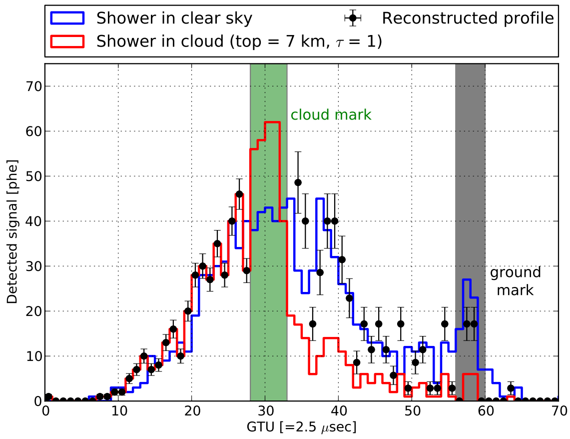

Figure 4: Reconstructed time profile (black points) of 10^{20} eV EAS together with the clear sky (blue) and cloud affected (red) profiles for an EAS of E = 10^{20} eV and $\theta = 60°$. Error bars are statistical only. The loss of information inside the cloud does not allow for a good reconstruction of the profile in that region. The ground mark (gray band) is almost entirely recovered by this procedure.

ity, wind speed, etc) in the monitored region are known [10]. Weather forecasting services across the world, such as ECWMF [11] in Europe or GMAO [12] and NCEP [13] in US systematically collect all the available meteorological data (from weather stations, meteorological balloons, satellite and aircraft measurements) to use them as input data for the Global Atmospheric Models (GAM), which are computer generated models of atmospheric conditions at the entire Earth. The product of the model is an estimation of the state of the atmosphere, or state variables at any given point on a latitude-longitude grid and at different times. This calculation takes into account the real-time conditions of the atmosphere as boundary condition for the global model. As result, data products, e.g. temperature, pressure and humidity profiles, are available.
Currently some efforts have been made by the collaboration to investigate the possibility of using data from the Global Data Assimilation System (GDAS) of NCEP [14]. GDAS data have been successfully incorporated in JEM-EUSO simulation of the air showers, and the final goal is to incorporate them in the EAS reconstruction analysis and in the analysis of the data of the LIDAR and IR camera in JEM-EUSO.

6 Conclusions

JEM-EUSO is a next-generation fluorescence telescope which will detect UHECRs induced EAS from space. To correctly reconstruct the EAS profile, knowledge of the atmospheric condition at the location of the shower is needed. The AM system of JEM-EUSO, which includes the IR camera, the LIDAR and global atmospheric model data, will provide sufficient information on the state of the atmosphere around the location of EAS events. This information will be used to correct the profiles of cloud-affected EAS events for the effect of clouds and aerosol layers, so that most of them could be retained for the UHECR data analysis.

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