Atmospheric Monitoring System of JEM-EUSO


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Abstract: JEM-EUSO telescope on International Space Station will detect UV fluorescence emission from Ultra High Energy Cosmic Rays (UHECR) induced Extensive Air Showers (EAS) penetrating in the atmosphere. The accuracy of reconstruction of the properties of the primary UHECR particles from the measurements of UV light depends on the extinction and scattering properties of the atmosphere at the location of the EAS and between the EAS and JEM-EUSO. The Atmospheric Monitoring system of JEM-EUSO will use the LIDAR, operating in the UV band, and an infrared camera to detect cloud and aerosol layer features across the entire 60° Field of View (FoV). At the altitude of the ISS $H \approx 400$ km the area over which the EAS events will be detected is $\approx (400 \text{ km})^2$. The ISS orbits the Earth with the period $P \approx 90$ min along an inclined orbit extending between $\pm 52^\circ$ from Equator.

The properties of the primary EECR particles (energy, type, arrival direction) will be derived from the imaging and timing properties of the UV emission from the EAS trace in the atmosphere. The Earth atmosphere absorbs and scatters UV light. The amount of absorption and scattering depends on the air column density between the emission and detection point and also on the type of absorbing and scattering centers. Scattering and absorption properties of the atmosphere are strongly affected by the presence of clouds and aerosol layers [3]. Cloud- and aerosol-induced variations of the scattering and absorption properties at the locations of EAS events distort the UV signal from EAS detected by JEM-EUSO. In the absence of detailed information on the presence and physical properties of the cloud and aerosol layers in JEM-EUSO FoV, distortions of the UV signal from EAS lead to systematic errors in determination of the properties of EECR from the UV light profiles.

Keywords: Ultra-High-Energy Cosmic Rays; Fluorescence Telescope; International Space Station; LIDAR; Infrared Camera.

1 Introduction

JEM-EUSO is a next-generation fluorescence telescope for detection of Extreme Energy Cosmic Rays (EECR, cosmic rays with energies $\sim 10^{20}$ eV and higher) which will be installed at International Space Station (ISS) in 2016 [1, 2]. It is a refractive telescope with the aperture $\approx 2.5$ m which will detect fluorescence UV emission from Extensive Air Showers (EAS) produced by EECR penetrating in the atmosphere within the 60° Field of View (FoV). At the altitude of the ISS $H \approx 400$ km the area over which the EAS events will be detected is $\approx (400 \text{ km})^2$. The ISS orbits the Earth with the period $P \approx 90$ min along an inclined orbit extending between $\pm 52^\circ$ from Equator.
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 EECR energy. EAS penetration into an optically thick cloud produces strong enhancement of the scattered Cherenkov light emission from EAS, which can be misinterpreted as Cherenkov light reflection from the ground/sea. This again leads to a wrong estimate of the depth of EAS maximum in the atmosphere. Statistics of the Earth cloud coverage known from the satellite measurement [4, 5] indicates that as much as 70% of EAS profiles might be affected by the presence of the clouds.

Cloud and aerosol layer induced distortions of the EAS profiles could be corrected if the detailed information on distribution and optical properties of the cloud/aerosol layers in JEM-EUSO FoV is known. This information will be provided by the Atmospheric Monitoring (AM) system of JEM-EUSO. The ISS orbital speed is \(\approx 7\) km/s so that the atmospheric volume monitored by JEM-EUSO changes every \(400\) km/\(\approx 60\) s. This means that the distribution of clouds and aerosol layers in JEM-EUSO FoV is continuously changing. The AM system will continuously monitor the variable atmospheric conditions in JEM-EUSO FoV during all EECR data taking periods.

In this contribution we describe the set up of the AM system of JEM-EUSO and its expected performance.

2 Atmospheric Monitoring system

The goal of the AM system of JEM-EUSO is to provide information on the distribution and optical properties of the cloud and aerosol layers within the telescope FoV. The basic requirements on the precision of measurements of the cloud and aerosol layer characteristics are determined by the requirements on the precision of measurement of EAS parameters [7]: (A1) measurement of EECR energy with precision 30%; (A2) measurement of the depth of the shower maximum with precision 120 g/cm².

Precision of the measurement of the energy of EECR is affected by the absorption of UV light cloud and aerosol layers. Precision of the measurement of the depth of shower maximum is additionally affected by the uncertainties of location of clouds and aerosols in the atmosphere. Imposing the requirements on the performance of the AM system: (B1) measurement of the optical depth of atmospheric features with precision down to \(\Delta \tau \leq 0.15\); (B2) measurement of the altitude of the boundaries of atmospheric features with precision \(\Delta H \leq 500\) m, assures that the systematic error of the measurement of the energy and the depth of the EAS maximum introduced by the uncertainty of atmospheric conditions is significantly below that of requirements A1, A2.

The required precision of measurement of the altitude and optical depth of the cloud and aerosol layers will be achieved with the following dedicated AM system which will consist of (Fig. 1):

1. Light Detection And Ranging (LIDAR) device,
2. Infrared (IR) camera and
3. global atmospheric models from the post-analysis of all available meteorological data by global weather prediction services like ECMWF [8] and GMAO [9].

JEM-EUSO will take the cosmic ray data during the ISS nighttime. To reveal the overall picture of cloud distribution in the FoV an IR camera will be used. The IR camera is an infrared imaging system used to detect the presence of clouds and to obtain the cloud coverage and cloud top altitude during the observation period of the JEM-EUSO main instrument. Measurement of the temperature of the clouds will be used to estimate the altitude of the cloud top layers. Such an estimate is possible in the troposphere in the altitude range \(0 - 10\) km where the atmosphere is characterized by a steady temperature gradient of \(dT/dH \approx 6^\circ/\text{km}\). To achieve the precision of measurement of the cloud top altitude \(\Delta H \approx 0.5\) km the precision

Figure 1: The principle of Atmospheric Monitoring in JEM-EUSO
of the temperature measurements by the IR camera will be \( \Delta T = (dT/dH) \Delta H = 3 \text{ K} \).

The AM system will additionally use a LIDAR device. The LIDAR will measure the optical depth profiles of the atmosphere in selected directions, with the ranging accuracy of \( 375/\cos(\theta_m) \text{ m} \). The energy of the laser will be adjusted in such a way that the backscatter signal will have enough information to correct for the cloud/aerosol layers with optical depth \( \tau \geq 0.15 \) at 355 nm wavelength will be detectable.

The IR camera and LIDAR measurements will provide complementary information with the amount of details sufficient to

- select the EAS events appearing in the clear sky conditions;
- provide information on the optical properties of the clouds needed for correction of the cloud affected EAS profiles which could be retained for further analysis;
- reject EAS events occurring in the complicated atmospheric conditions (multi-layer cloud/aerosol structures).

3 IR camera

The IR camera on board of JEM-EUSO will consist of a refractive optics made of germanium and zinc selenide and an uncooled microbolometer array detector [11]. Interferometer filters will limit the wavelength band to 10-12 \( \mu \text{m} \). In the current configuration, two \( \delta \lambda = 1 \mu \text{m} \) wide filters will be used centered at the wavelengths 10.8 \( \mu \text{m} \) and 12 \( \mu \text{m} \), two increase the precision of the radiative temperature measurements. The FoV of the IR camera is 60\( ^\circ \), totally matching the FoV of the main JEM-EUSO telescope. The angular resolution, which corresponds to one pixel, is about 0.1\( ^\circ \). 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. Though the IR camera takes images continuously at a video frame rate (equal to 1/30 s), the transfer of the images takes place every 30 s, in which the ISS moves half of the FoV of the JEM-EUSO telescope.

Fig. 2 shows the precision of the measurement of the cloud temperature for different cloud altitudes, reachable with the current IR camera design. The precision is within the required 3 K limit almost everywhere down to the altitude of \( \sim 1 \text{ km} \). Three different columns show the error derived from the measurements in the shorter (B1) and longer (B2) wavelength bands as well as in the combined \( B_{\text{TIR}} \) measurement (see [6] for more details).

![Figure 2: Error in the determination of temperature of clouds with the IR camera as a function of the cloud altitude.](image)

4 LIDAR

The most relevant information about the absorption and scattering properties of clouds and aerosols is at the locations around the EAS events. To get this information, the LIDAR will have a re-pointing capability. The laser beam will be re-pointed in the direction of EAS candidate events following each EAS trigger of JEM-EUSO telescope. The average trigger rate of JEM-EUSO will be \( \sim 0.1 \text{ Hz} \). During the time interval between subsequent triggers, the LIDAR will

- re-point to the direction in which the EAS trigger occurred and
- take the measurements of laser backscattering signal in several directions around the supposed EAS maximum.

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 \( \pm 15^\circ \). The laser backscatter 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 [10]. Measurements of the laser backscatter signal with time resolution of 2.5 \( \mu \text{s} \) (time unit of the focal surface detector) will provide ranging resolution of 375 m in nadir direction. The energy of the laser pulse will be adjusted in such a way that the backscatter 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. Examples of the simulated laser backscatter signal as it would appear in the JEM-EUSO detector are shown in Fig. 3. The upper panel shows the signal in the presence of an optically thin cloud with \( \tau = 0.06 \pm 0.04 \).
Figure 3: Simulated LIDAR backscatter signal in the presence of an optically thin (top) and optically thick (bottom) clouds.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>355 nm</td>
</tr>
<tr>
<td>Pulse repetition rate</td>
<td>&gt; 1 Hz</td>
</tr>
<tr>
<td>Pulse width</td>
<td>15 ns</td>
</tr>
<tr>
<td>Pulse energy</td>
<td>20 mJ/pulse</td>
</tr>
<tr>
<td>Steering of output beam</td>
<td>±30°</td>
</tr>
<tr>
<td>Receiver</td>
<td>JEM-EUSO telescope</td>
</tr>
<tr>
<td>Detector</td>
<td>MAPMT (JEM-EUSO)</td>
</tr>
<tr>
<td>Range resolution</td>
<td>375 m</td>
</tr>
<tr>
<td>Mass</td>
<td>17 kg</td>
</tr>
<tr>
<td>Power</td>
<td>&lt; 70 W</td>
</tr>
</tbody>
</table>

Table 1: Characteristics of JEM-EUSO LIDAR

$(\tau = 0.05$ was assumed in the simulation) at the altitude of 10 km. Laser pulse energy $E = 20$ mJ is assumed. Bottom panel shows an example of optically thick low altitude cloud. Assuming the same laser pulse energy $\tau = 0.8 \pm 0.2$ is derived from the simulated data, while $\tau = 0.9$ was assumed in the simulation.

Parameters of the LIDAR system of JEM-EUSO are summarized in Table 1.

5 Global Atmospheric Model data.

Precision of the analysis of both IR camera and LIDAR data is largely improved when the basic atmospheric parameters of the atmosphere (temperature and pressure profiles, humidity etc) in the monitored region are known. Such parameters will be systematically retrieved from the global atmospheric model resulting from the post-analysis of weather models, calculated on regular basis by global meteorological service organizations (GMAO, ECMWF). These models also provide information on the presence and altitude distribution of cloud and aerosol layers, information which is directly relevant for JEM-EUSO data analysis. This justifies the incorporation of real time global atmospheric models in the AM data of JEM-EUSO.

6 Conclusions.

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 effects of clouds and aerosol layers, so that most of the cloud-affected events could be retained for the in the EECR data analysis.

References

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