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The atmospheric science of JEM-EUSO

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An Atmospheric Monitoring System (AMS) is critical suite of instruments for JEM-EUSO whose aim is to detect Ultra-High Energy Cosmic Rays (UHECR) and (EHECR) from Space. The AMS comprises an advanced space qualified infrared camera and a LIDAR with cross checks provided by a ground-based and airborne Global Light System Stations. Moreover the Slow Data Mode of JEM-EUSO has been proven crucial for the UV background analysis by comparing the UV and IR images. It will also contribute to the investigation of atmospheric effects seen in the data from the GLS or even to our understanding of Space Weather.

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1. Introduction

The Extreme Universe Space Observatory, EUSO, is a novel space-based instrument designed to observe EAS produced by Ultra-High Energy Cosmic Rays (UHECRs) and Extremely High Energy Cosmic Rays (EHECRs). Because the instrument will look down from Space with a wide Field of View (FoV), a large exposure can be achieved. And this is required, due to the small UHECRs flux [1]. The arrival direction map will provide information about the origin of the UHECRs, perhaps allowing us to identify the nearest UHECR sources with known astronomical objects. Moreover, EUSO observations will allow us to understand their acceleration mechanisms and to clarify the acceleration and emission mechanisms. The telescope will use the atmosphere as a calorimeter.

Information about properties of the Earth's atmosphere and presence of clouds is critical. The telescope includes an Atmospheric Monitoring system (AMS) which provides information on the clouds and aerosol distribution, as well as their optical properties within the telescope's Field of View (FoV). The AMS will consist of an infrared camera (IR), and a LIght Detection And Ranging device (LIDAR). Moreover, it will include Global Light System (GLS) stations which are under development.

2. The AMS of the EUSO Space Mission

To fully monitor the atmosphere and to retrieve the cloud coverage and cloud top height in the EUSO FoV, an Atmospheric Monitoring System (AMS) will be part of the instrument [2, 3]. The AMS is also needed to estimate the effective UHECR & EHECR exposure of the telescope and for the reconstruction of main parameters of the UHECR & EHECR events under cloudy conditions. The AMS of EUSO will include [4]:

- a bi-spectral Infrared (IR) camera.
- a LIght Detection And Ranging (LIDAR) device.

The AMS will be supported by the following:

- The Ground Light System (GLS) consisting of a network of ground-based and airborne steerable UV lasers and UV LED flashers [5]. The GLS has many functions to support JEM-EUSO. One of these functions is to cross check absolute photometric calibration which includes the atmosphere.
- The 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 Slow Mode Data (SMD) of EUSO, the monitoring of the pixel signal rate every 3.5 s for the observation of Transient Luminous Events (TLEs), which will give additional information on cloud distribution and the intensity of the night sky airglow.

The EUSO telescope will measures Extensive Air Shower (EASs) during night time. The IR camera will view the entire FoV of the telescope to detect the presence of clouds and to retrieve the cloud cover and the cloud top height parameters. The LIDAR will probe in some pre-defined directions around the location of triggered EAS events. The LIDAR will be used to measure the clouds altitude and optical depth as well as the vertical profile of the atmosphere along these directions with a range accuracy of 375 m (in nadir direction). The IR camera and the LIDAR have been designed to work in a complementary way.

2.1 IR camera

The IR Camera onboard EUSO [6, 7] will use refractive optics made of Germanium and an uncooled μbolometer array detector. The FoV of the IR Camera is 48°, totally matching the FoV of the main EUSO telescope [8], with an angular resolution, which corresponds to one pixel, is about 0.1° [9]. In the System Preliminary Design (SPD) of the IR camera (Figure 1), a bi-spectral approach is foreseen with two filters in the cold spot of the optics that allow a multispectral snapshot camera without a dedicated filter wheel mechanism.

In the System Preliminary Design (SPD) of the IR camera a bi-spectral approach with two filters in the cold spot of the optics that allows a multispectral snapshot camera without a dedicated filter wheel mechanism is foreseen. This solution leads to a reliable baseline and eliminates the needs for a complicated filter wheel mechanism in a space-based application. The only drawback of this solution is that, in order to overcome the use of half of the available area of the detector for each spectral band, the IR-Camera images acquisition time has to be shorter to avoid gaps during the ISS orbit. This solution has an impact on the restricted data budget allocated for an ISS mission.

To test the technologies and methods used in the forthcoming main mission, the EUSO-Balloon pathfinder was flown in August 24-25, 2014 with a first prototype of the infrared camera as a stand-alone payload of EUSO-Balloon gondola. The IR camera of the EUSO-Balloon [11] has the same filters as the ones chosen for the main mission, and the same μbolometer detector. The changing IR background can be measured from 40 km with an equivalent technology to that planned for EUSO, as well as the algorithms that will be used to retrieve the atmospheric physical information [11, 13, 12, 19]. Reference [20] shows a validation of the simulated temperature profiles in EUSO-Balloon comparing them to real radiosoundings close to the balloon's path recorded

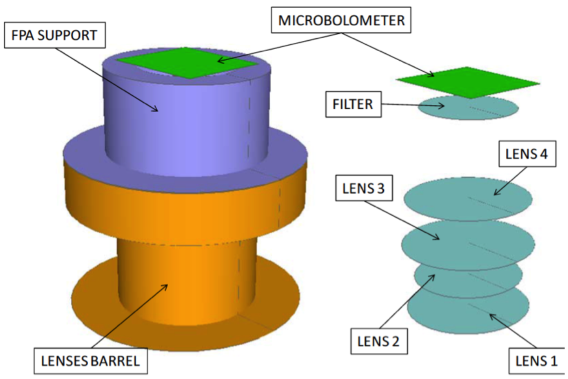

Figure 1: Preliminary Design Scheme of the Optical Unit Assembly of the Infrared Camera.

during the flight, while in reference [19] the Weather Research and Forecasting (WRF) model has been validated not only in the EUSO-Balloon trajectory but in other parts of the globe following the ISS trajectory. Moreover, [20] compares the CTH evaluated using WRF temperature profiles with the Moderate Resolution Imaging Spectroradiometer (MODIS), while in reference [19] a one-step CTH retrieval algorithm has been fully developed and successfully applied to the real infrared images obtained with the infrared camera of EUSO-Balloon during the CNES flight of August 24, 2014 and moreover these CTH have been validated with the very accurate Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) onboard the CALIPSO satellite. This is the first attempt made in order to validate the one-step CTH retrieval combined algorithm that will use the infrared camera and the LIDAR of JEM-EUSO.

2.2 LIDAR

The task of the LIDAR is to localize optically thin clouds and aerosol layers and to provide measurements of the scattering and abortion properties of the atmosphere in the region of the Extensive Air Shower (EAS) development and between the EAS and the EUSO telescope.

The LIDAR is composed of a transmission and a receiving system. The transmission system comprises a Nd:YAG laser and a pointing mechanism (PM) to steer the laser beam in the direction of the triggered EAS events. As the laser backscattered signal will be received by the EUSO telescope (working as the LIDAR receiver), the laser operational wavelength was chosen to be the third harmonic of the Nd:YAG laser, at λ = 355 nm [**?**]. The laser is being developed at RIKEN (Japan) and will be part of the JAXA (Japanese Space Agency) contribution to the Mission. The PM is under development at the University of Geneva, in close collaboration with CSEM (Switzerland). In the current EUSO design, the light of the pumping diodes is guided to the laser head through an optical fiber. The PM is conceived to have a steering mirror with two angular degrees of freedom and a maximal tilting angle of $\pm$ 15°, needed to move the laser beam anywhere within the EUSO FoV. The LIDAR is expected to receive on average a new trigger from a candidate EAS events roughly every 10 s. In the time between two consecutive triggers, the PM decodes the information on the location of the last triggered event within the telescope FoV, points the laser beam in this direction, and shoots 5 laser shots to cover a sufficiently wide region around the EAS position. The effective time available to the pointing system to steer the laser beam is thus typically of few tenths of seconds, thus requiring a lightweight mirror with limited inertia to optimize the operations of

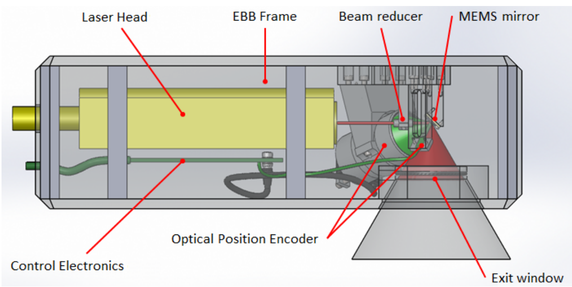

Figure 2: The housing of the commercial version of the laser it will be used for the Elegant Bread- Board (EBB), the optical system supporting the positional sensor, the Micro-Electro-Mechanical Systems (MEMS) mirror, and the electronic board. All components are represented in scale.

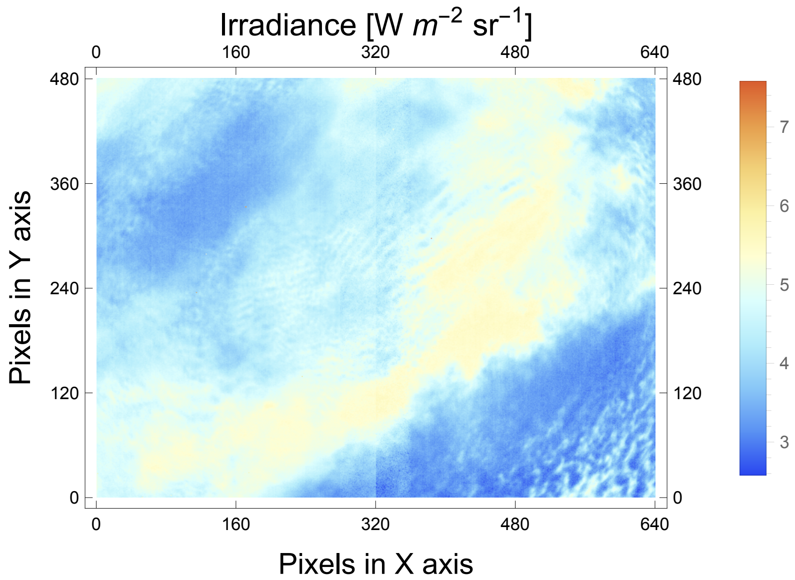

Figure 3: The Infrared radiance obtained by the IR camera in one of its images during the August 24, 2014 EUSO-Balloon flight

the PM. For this reason, innovative Micro-Electro-Mechanical Systems (MEMS) technology has been selected for the development of the tilting mirror (Figure 2).

3. The Ground Light System of JEM-EUSO

The GLS will serve many functions for JEM-EUSO by providing calibrated LED flasher point sources and calibrated UV laser test beams that will be measured by the same instrument that also measures tracks from extensive air showers. Measurements of these calibrated optical signatures by JEM-EUSO will provide an independent test of the calibration of JEM-EUSO [14]. The GLS will also support the AMS in that the flasher point sources, and laser test beams can be used to check the atmospheric models and measurements derived from the AMS measurements.

4. Space weather studies with the EUSO Space Mission

With the Slow Mode Data (SMD) of EUSO, the Transient Luminous Events (TLEs) can be monitored. TLEs are generally associated with interactions between low atmosphere, ionosphere and magnetosphere as well as with strong thunderstorm activity. Thus, EUSO is relevant for some space weather studies related to effects in magnetosphere/ionosphere/low atmosphere coupling. This can contribute to better understanding of electromagnetic responses to lightning on the Earth and of selected processes at high altitudes in the atmosphere [15]. EUSO is unique in that its temporal and spatial resolutions allow the time evolution of the subtle structures (filamentation) in TLE's [16]. In the EUSO collaboration, these data will be analyzed by the CBK Warsaw and IEP Kosice groups who have a long history of experience with measurements of waves and particles for magnetospheric/ionospheric research as well as with physical analysis/interpretation of the data [17].

5. IR-UV Background

Precise characterization of the Earth's night side UV background [18] using, for instance, the signal measured by the PDM of the EUSO-Balloon [13], is essential for observation of the UHECR and EECR induced EAS from the space. The comparison of the UV and IR images reveals a strong dependence of the upward UV radiance on the atmospheric conditions, so the possibility to use the UV albedo effect for characterization of the clouds is considered. There was found a clear anti-correlation between IR and UV radiance. With increasing IR radiance when atmosphere is more transparent for IR radiation from the ground, the reflected upward going UV intensity is decreasing, due to the fact that albedo of ground layer is smaller than albedo of clouds. This implies that using of both spectral ranges in UV and IR background analysis is mandatory [13]. Based on this analysis, an area in the FoV can be specified in which high quality data of EAS can be expected. A more complex understanding of clouds by observations in different wavelength ranges is offered.

6. The Cloud Top Height retrieval algorithms developed with the AMS of the EUSO space mission

After the detailed System Preliminary Design of the infrared camera for the ISS [10], a two step CTH retrieval algorithm does not fulfill the technical requirements of the infrared camera, because the intermediate step to retrieve cloud temperature, increases the Noise Equivalent Temperature Difference (NETD) parameter, a critical driver parameter in the infrared camera design, over the budget allowed for the ISS. Cloud height, not cloud temperature, is the critical measurement required by EUSO for UHECR measurements. Consequently a detailed and dedicated *one-step CTH retrieval algorithm* that fulfill the scientific and technical requirements of the infrared camera is currently under development [19]. This algorithm retrieves the CTH parameter directly from the Brightness Temperature (BT) of the infrared camera image without any intermediate step relying on the CTT. In a first approach this *one step CTH retrieval algorithm* has been successfully applied to the real images of the infrared camera of EUSO-BALLOON during the flight of August 24, 2014 [19].

Another one-step approach to retrieve the CTH is the Stereoscopic Algorithm [21]. The mandatory technical requirement coming from the design of the infrared camera as of [10] is an image overlapping of 17 s for a Stereoscopic Algorithm that can properly obtain the CTH from the images of the infrared camera as of [10]. It is worth mentioning that this Stereoscopic Algorithm retrieves directly the height, in a one-step approach as [19], without any intermediate step relying on the temperature of the cloud. A decision is pending on whether this one-step Stereoscopic CTH Retrieval algorithm will fulfill the new updated technical requirements of the infrared camera.

For retrieving CTH using remote sensors such as the IR camera, it must be recalled that thermal emission (Figure 3) of the cloud comes from its uppermost layer. Thus, the retrieved CTH is not the physical cloud boundary but the radiative effective one. A method has been developed to extract CTH using vertical profiles predicted by the WRF together with the BT of the IR-Camera. As a result, in each cloud pixel from the IR Camera, the brightness temperatures were transformed to

CTH by using the closest vertical temperature and humidity profile obtained by the WRF model and the radiance given by the IR camera [19].

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