PROCEEDINGS OF SCIENCE

EUSO-TA, a ground telescope at the Telescope Array to test JEM-EUSO detector performance

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EUSO-TA is a complete prototype of the JEM-EUSO space telescope located at the Telescope Array (TA) site in Black Rock Mesa, Utah, USA. The telescope can perform observations of ultraviolet light generated by cosmic-ray showers as well as from artificial sources. The aim of the project is to test the EUSO technology and study the detector response in conjuction with the TA fluorescence detector. The detector consists of two, 1 m^2 square Fresnel lenses with a field of view of $11^\circ \times 11^\circ$. Light is focused on the Photo Detector Module (PDM), identical to the ones that will be employed in the JEM-EUSO and K-EUSO focal surfaces. The PDM is composed of 36 Hamamatsu multi-anode photomultipliers (64 channels per tube), for a total of 2304 channels. Front-End readout is performed by 36 ASICS, with trigger and readout tasks performed by two acquisition boards that send the data to a CPU and storage system. The telescope is housed in a shed located in front of one of the fluorescence detectors of the Telescope Array experiment, pointing in the direction of the ELS (Electron Light Source) and CLF (Central Laser Facility). The performance of the detector has been very good, with little (one photoelectron) electronic noise and a Point Spread Function of stars according to expectations. Measurements of the UV background in different darkness conditions and moon phases and positions have been completed. In the spring 2015 campaign, observations of various stars of different magnitude and color index have been performed. Furthermore, cosmic ray events - triggered by TA - have also been observed. Subsequent work for 2015 and following years is to increase the statistics of cosmic-ray events and implement a self-trigger adapting the EUSO trigger (optimized for space observation at a distance of 400 km) to the geometry of EUSO-TA.

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1. Introduction

EUSO-TA is a fully functional prototype of the JEM-EUSO (*Extreme Universe Space Observatory on-board the Japanese experiment module*)[1] space telescope. It is located at Black Rock Mesa, Utah, at the site of one of the fluorescence light detectors of the Telescope Array (TA) experiment [2]. From there it observes – simultaneously with TA – artificial light and cosmic ray events, allowing for tests of the technology, calibration of the detector and reduction of the systematic uncertainties of the measurements.

EUSO-TA consists of a refractive optical system with two 1 m^2 squared Fresnel lenses, focusing the light in a $11^\circ \times 11^\circ$ field of view on one Photo-Detector Module (PDM). A wider FOV can be achieved by adding more PDMs in the Focal Surface. The electronics can trigger asynchronously, or using an external trigger. The external trigger can be provided by the TA Fluorescence Detector (TAFD) allowing for simultaneous observations of $E \geq 10^{18}$ eV cosmic ray showers.

2. EUSO-TA telescope

The EUSO-TA lenses are fabricated from UV transmitting polymethyl-methacrylate (PMMA). The baseline design of the optics is shown in fig. 1 with simulated spot diagrams for incident angles of $0^\circ, 2^\circ, 4^\circ$ and 6°.

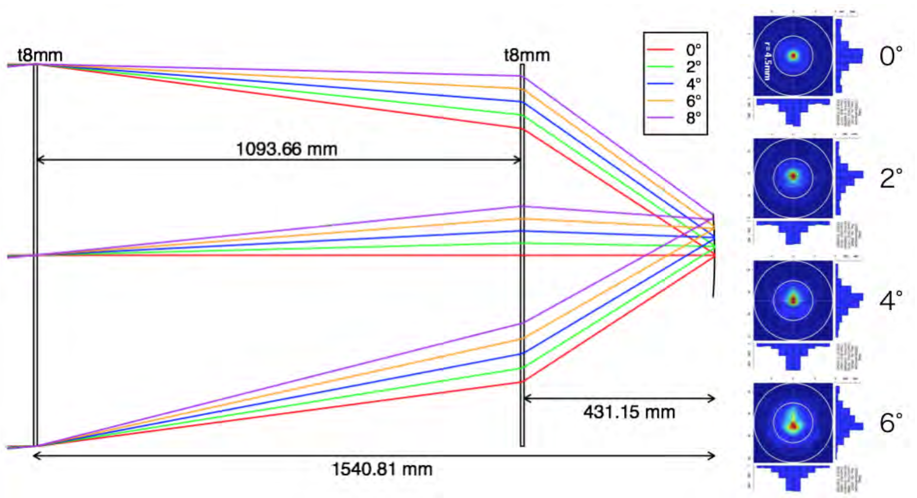

Figure 1: The design of the EUSO-TA optics. The left and right panels show the ray trace and spot diagrams for different incident angles of $0^\circ, 2^\circ, 4^\circ$ and 6°, respectively.

The 17 cm × 17 cm PDM, located in the focal plane, is composed of 36 Multi-Anode Photomultiplier Tubes (MAPMTs) [3] each containing 64 anodes, for a total of 2304 pixels. The PDM contains 36 front-end ASICs for the readout of the tubes [4], a 1st-level trigger FPGA board, High Voltage (HV) and HV switches (fig.2). The PDM is controlled by the Data Processing (DP) unit, consisting of a 2nd-level trigger board [5], CPU board, Clock board, GPS board, house keeping board and low voltage power supply [6].

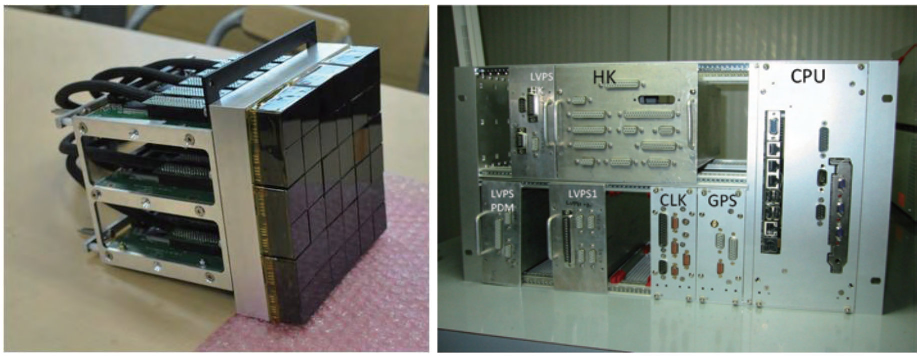

Figure 2: The PMT array and the front-end ASIC boards mounted on the PDM frame (left) and the DP box (right). The DP box houses the 2nd-level trigger board, CPU board, Clock board, GPS board, house keeping board and low voltage power supply.

Figure 3: EUSO-TA (front) and TAFD station (back).

3. Calibration and observation

An initial calibration of the EUSO-TA PDM has been performed in laboratory in RIKEN and ICRR [7].

An on-site calibration can also be performed measuring reference stars, which provide a photon flux that is stable with a known UV spectrum at different elevation angles, which allows correcting for atmospheric attenuation.

In this configuration it is feasible to compare the night sky background measurements performed with EUSO-TA to the corresponding flux values obtained from the analysis of TAFD data.

Using a technique similar to that used at the Pierre Auger Observatory [8], we superimposed views of the same sky region as observed by the EUSO-TA PDM and the TAFD telescope. The absolute night sky background flux observed by the two instruments looking toward the same sky direction (normalized to equal solid angle) provides a valuable tool for cross-calibration. Indeed, an overlap of light curves from the diffuse component measured by two independent telescopes demonstrates the accuracy of the pixel-to-pixel variation correction.

EUSO-TA acquires data while running simultaneously with TA but without causing any interference with TAFD operations. This offers the possibility to monitor the gain of individual camera pixels in realistic working condition, in which background flux can induce gain shifts. This monitoring can take place during the whole acquisition period, thus allowing detection of any eventual gain drift as well as verification of the linearity of pixel response in the range of variation of the night sky background.

4. Stars and Point Spread Function

Preliminary analysis shows that EUSO-TA can observe stars up to $M_B \simeq 6.5$ on sums of 1280 frames (about 3.2 ms observation time). While very bright stars can be seen on single frames, such stacking allows us to get a good signal to noise ratio, with negligible star movement on the sky compared to the angular size of our pixel. An example of 1280 stacked frames with a few stars clearly visible is shown in fig. 4. The Hipparcos catalogue [9] is superimposed on the image for the 4 brightest stars, allowing us to recognize Algol and stars with $M_B \geq 5.5$.

The stars can be used as point sources to analyze the point spread function (PSF) of our detector. The very-wide field of view and the optics used result in a PSF to be asymmetrical in regions of the frame far from the optical axis, most likely due to influence of aberrations such as coma or astigmatism. Therefore, the proper analysis should be based on fitting the parameters of a PSF model derived from the theory and ray-tracing simulations to the images of the stars in different positions on the frame, which is a demanding and difficult task even in detectors with much finer angular resolution [10]. Initial analysis performed with a fit of standard gaussian profile gives a PSF with average FWHM of 2.35 pixels, well within the requirements for UHECR showers.

5. Laser

To study the EUSO-TA response to a known light source we have used the light coming from the TA Central Laser Facility (CLF), distant from EUSO-TA by about 21 km. The CLF shoots vertically laser pulses of 355 nm in front of the detectors [11]. In the future we plan to use also the Electron Light Source (ELS). The ELS is a compact electron linear accelerator with a typical output of 10^9 electrons per pulse at 40 MeV, fired vertically in front of the detectors. It excites the atmosphere in a similar way to EAS, causing an emission with the same spectrum, thus fitting calibration purposes [12].

During standard observation nights the CLF shoots every half an hour for 30 s with 10 Hz shooting frequency. The scattered light of the ~ 3 mJ beam was clearly visible traversing through the EUSO-TA field of view. The shot was visible on 6 to 8 frames, depending on the shot and acquisition time synchronization, and had a length of 6-8 pixels depending on the position on the frame (fig. 5, left), which is consistent with expectations. The registered light intensity is dependent

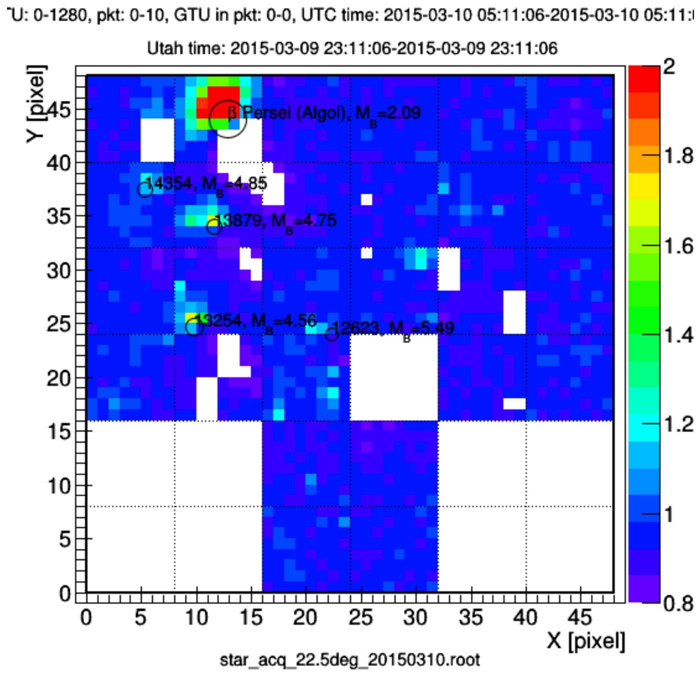

Figure 4: Sum of 1280 frames acquired with EUSO-TA with Hipparcos catalogue brightest stars' positions superimposed. The label close to the star marker is the catalogue number or the star name in case of Algol, followed by the star's magnitude in Hipparcos B filter for objects of $M_B \geq 5.5$. The color scale denotes the brightness of each pixel in arbitrary units (lower left, lower right and center right PMTs were not functioning at the time of the measurement).

on the atmospheric conditions – obstruction of the light path due to clouds – compatible with the fluctuations of the emitted light, showing the good reconstruction capabilities of EUSO-TA.

In addition to the CLF we have also performed measurements of a mobile UV laser of Colorado School of Mines. The laser could be shot with energies in the range of about 1-86 mJ, with pointing adjustable in two dimensions. The mechanics featured automatic changing of the pointing, allowing for easy "swipes" through the field of view (fig. 5, right). EUSO-TA was able to detect a few shots of 1 mJ energy shot vertically from 34 km distance. This corresponds to a UHECR with $E \simeq 10^{19} eV$, suggesting that the sensitivity is better than expected. However, the detection efficiency of the shots with such small energy depends on the data analysis algorithm. Calculations for the exact detection rate and sensitivity limit of the detector is pending. The laser was shot at growing distances (34, 40, 60, 100 km) with preliminary analysis showing detection for a 85mJ shot at distance of 100 km (see fig. 6, left). This is very promising for space detection of UEHCR (ISS is at 400 km), considering the non-optimal atmospheric conditions, the high optical thickness (since the observation was almost horizontal) and the smaller (by a factor 4) lens area.

Furthermore, the EUSO trigger has been successfully tested off-line using the same algorithm to be implemented in space on the raw data files. A precise estimation of its performances will be reported in a subsequent paper.

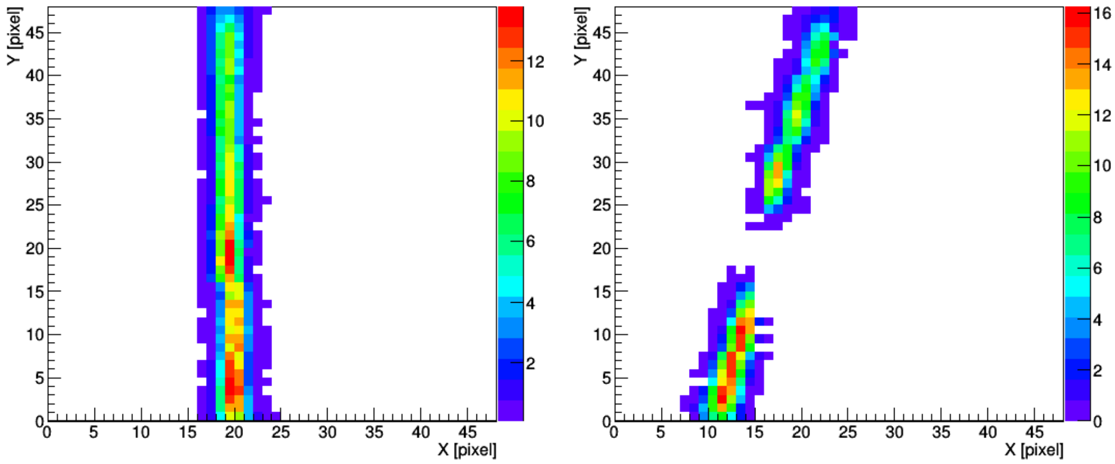

Figure 5: Left: an average of ~ 250 shots of CLF laser; right: an average of ~ 150 inclined shots of the Colorado School of Mines laser, located at 40 km from EUSO-TA ($\simeq 62mJ$), the missing part due to a non-functioning MAPMT in the center of the focal surface. The color scale on both pictures denotes the uncalibrated detector counts.

6. Cosmic Ray events

The weather conditions during the May 2015 EUSO-TA campaign made it very difficult to detect UHECR, due to the nearly constant presence of low cloud cover. However, the still ongoing analysis has detected so far an event, seen in coincidence with TAFD. The proximity of the event – around 2.5 km – makes it appear as a $E \sim 10^{18}$ eV track going through the whole FOV on a single GTU (one frame of 2.5 μs), as shown in fig. 6. Therefore, its parameters have to be derived from TAFD which, thanks to larger FOV and higher time-resolution, could see the shower movement.

In future we hope to see also more energetic events further away from the detector, moving on several consecutive GTUs through the field of view. However, such events are more sporadic, requiring significantly longer observation time.

7. Next steps

In the near future we will start the final procedure of cross-calibration with the TAFD telescope. This requires assembly of the whole focal surface consisting of 36 MAPMTs, initial tests of the detector response, and final tests under working conditions. Before the cross-calibration, we will need to perform an auto-calibration and fine-tuning of the detector to ensure the consistency in photoelectron counts between different parts of the focal surface. The next step will be to perform measurements of the night sky background and star light in different parts of the field of view and check consistency with models and calculated expectations. After completion of these tasks we shall be able to acquire data simultaneously with the TA experiment and perform a meaningful comparison.

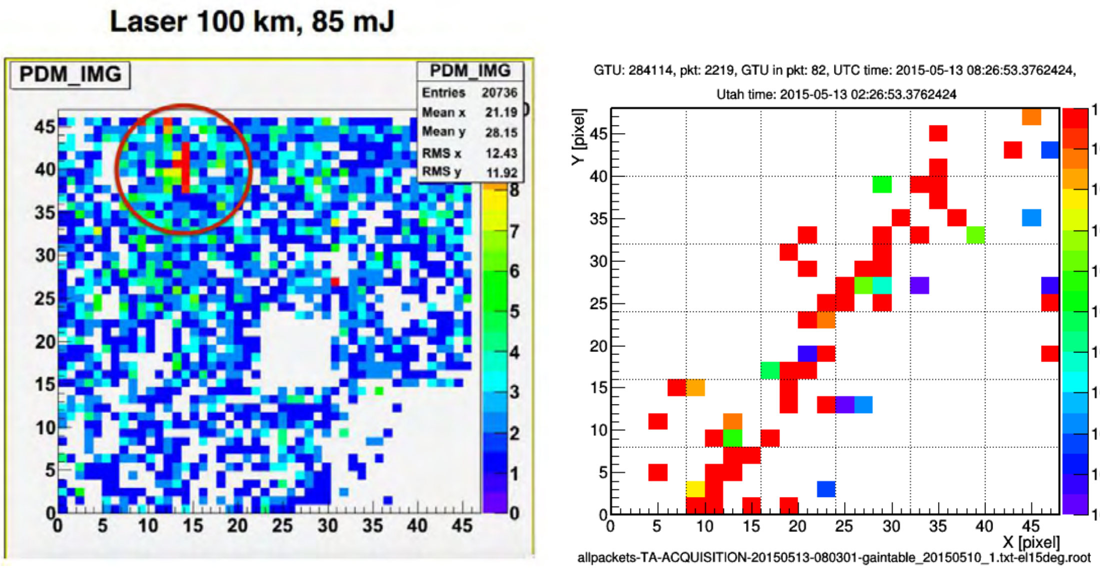

Figure 6: Left: the signal from one GTU for a laser shot at 100 km distance (85mJ). Right: An UHECR event of low ($\sim 10^{18}$ eV) energy traversing at ~ 2.5 km distance from EUSO-TA and therefore visible as a track on a single GTU, in this case going from top-right to bottom-left (distance and energy are estimated by TA). The color scale denotes uncalibrated counts of the detector. The bottom right PMTs and the center bottom right PMT were not working at the time of the measurement.

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