Absolute calibration of the JEM-EUSO photodetection modules

Daniil Trofimov [1,2,3*], Alexander Belov [2], Sylvie Blin [1], Alexandre Creusot [1], Pavel Klimov [2], Etienne Parizot [1], Guillaume Prévôt [1], for the JEM-EUSO collaboration
[1] Université Paris Cité, CNRS, Astroparticule et Cosmologie, F-75013, Paris, France
[2] Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, 1(2), Leninskiye Gory, Moscow 119991, Russia
[3] Faculty of Physics, Lomonosov Moscow State University, 1(2), Leninskiye Gory, Moscow 119991, Russia
* trofimov@apc.in2p3.fr

Overview

The JEM-EUSO (Joint Experiment Missions for Extreme Universe Space Observatory) collaboration constructs a series of balloon and orbital telescopes to detect fluorescent UV emission from the Earth atmosphere, with the primary aim to study ultrahigh energy cosmic rays (UHECRs) from space.
The detectors have wide field-of-view, high temporal resolution (1-2.5 µs) and sensitivity provided by a large aperture. Currently one of these detectors is operating onboard the ISS (Mini-EUSO). The next one is planned to be launched in the spring of 2023 (EUSO-SPB2). These projects use the same photo-detection modules (PDMs) composed of 36 multi-anode photomultiplier tubes (MAPMTs), each with 64 pixels, for a total of 2304 pixels. Mini-EUSO uses one PDM, EUSO-SPB2 will use three PDMs, and the future full-scale missions will use several tens of PDMs.
In the process of developing the PDMs, a new technique was developed to characterize their performance and provide absolute calibration of the MAPMTs used in the different JEM-EUSO missions. The method provides the efficiency of each pixel (including the discovery of sub-pixel structures), as well as the actual area occupied by the different pixels on the photocathode of the MAPMT.
The method and its application to EUSO-SPB2 PDMs at different high voltages and in different modes of operation are presented.

Scientific motivation for EUSO-SPB2

With energies up to 100 EeV, Ultra High Energy Cosmic Rays (UHECRs) are the most energetic particles in the Universe. Although ground-based observatories have observed these energetic particles for decades, their source and acceleration mechanisms remain largely unknown, and their study is observationally challenging because of their extremely low flux at Earth's surface (arXiv:2205.05845).
The Extreme Universe Space Observatory on a Super Pressure Balloon 2 (EUSO-SPB2) is the third (and most advanced) balloon mission undertaken by the JEM-EUSO collaboration and will build on the experiences of previous missions. The timeline of the evolution of the JEM-EUSO missions is shown in Fig. 1.
EUSO-SPB2 has two observation instruments Fluorescence Telescope (FT) and Cherenkov Telescope (CT):
The main objective of Fluorescence Telescope is:

- Observing the first extensive air showers via the fluorescence technique from suborbital space. Expected number of EAS events: 0.12±0.01 events/hour, or ~0.6 events per night (fig. 2 J. Eser et al., 2021,arXiv:2112.08509v1, G. Filippatos et al.,arXiv:2112.07561v1)

The aims of Cherenkov Telescope are:

- Observing Cherenkov light from upwards going extensive air showers initiated by cosmic rays.
- Measuring the background conditions for the detection of neutrino induced upwards going air showers.
- Searching for neutrinos from astrophysical transient events (e.g. binary neutron star mergers)

In this poster, the structure and calibration of a fluorescent telescope are considered.

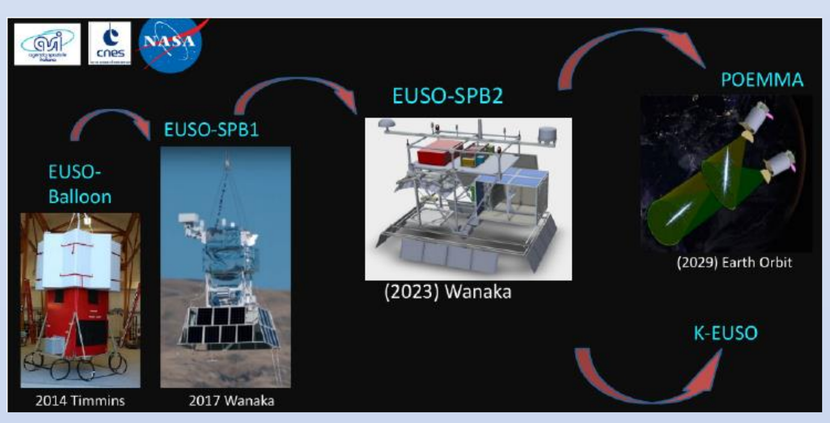

Fig. 1 Development stages of the JEM-EUSO program to study UHECRs from space, through the detection of the fluorescence light of extensive air showers (balloon, ISS & free-flyer missions).

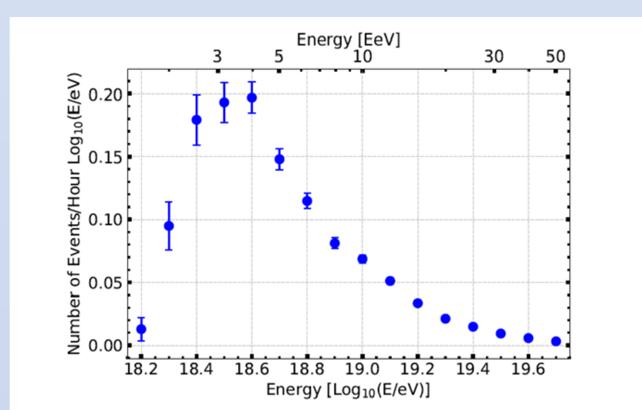

Fig. 2 Expected number of EAS events. Vertical axis – number of events per hour, horizontal axis – energy of events

Structure of the Fluorescence Telescope

The telescope is built according to the Schmidt scheme and has 6 mirror segments with a radius of curvature of 1659.8 mm and an effective focal length of 860 mm. The aperture is 1 m, field of view 37.4°×11.4°, for one pixel 0.2°x0.2°, the direction of FoV – nadir (fig. 3, V. Kungel et al., PoS (ICRC2021) 412).
The FT camera consists of 3 photodetection modules (PDMs, fig.4). Each PDM contains 9 elementary cells (EC – units, fig.5). Inside the elementary cell there is SPACIROC3, a specialized chip designed to count photoelectronic pulses for a certain time. The basis of the chip is an amplitude discriminator, which provides the selection of single-photoelectronic pulses . The main parts of each EC are 4 multi-anode photodetection tubes (MAPMTs) Hamamatsu R11265-103-M64 with 64 channels of registration. Thus each PDM has 64×4×9 = 2304 channels of registration.

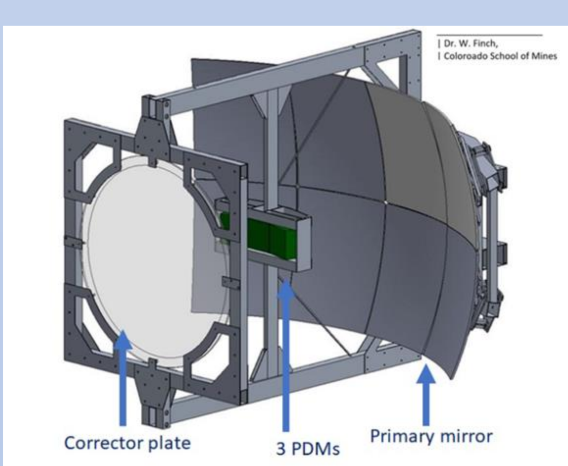

Fig. 3: General scheme of the EUSO-SPB2 Fluorescence Telescope.

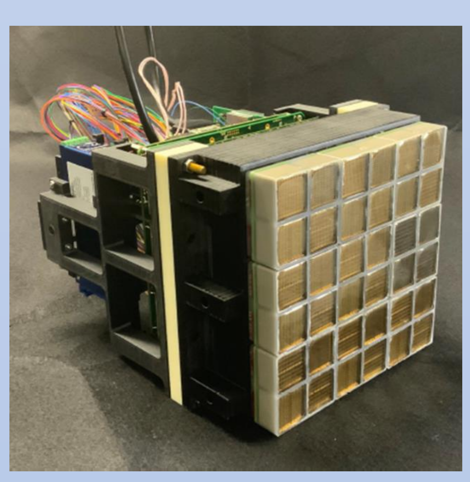

Fig. 4: Assembled photodetection module (PDM) of EUSO-SPB2's FT.

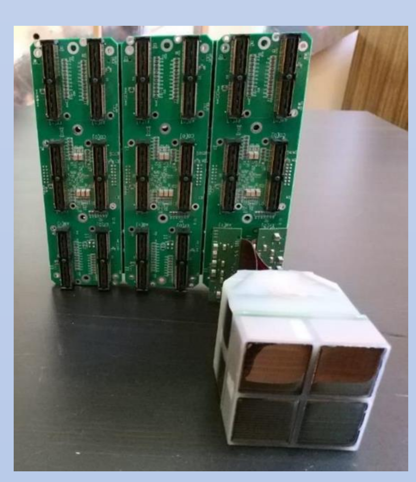

Fig. 5: Elementary cell (EC) with 64×4=256 detection channels

PDM calibration

The calibration uses a controlled light source, either in full illumination mode (all pixels at once) or in single pixel illumination mode (with a collimator). The first method provides effective pixel efficiency and allows to determine the optimal value of the electronics threshold used to record a photon count for each pixel (cf. next section), and the second is used in conjunction with a mechanical scanning procedure to determine the high-precision response of the photosensitive area to local illumination, also allowing to determine the actual borders of each pixel. The principle is shown on Fig. 6: the PDM is placed in a black box, with negligible low photon background. It is connected to the computer, which also has connections to a power-meter for precise light intensity control and to an xy-movement motor providing precise positioning of the light source in front the PDM. The light control system uses an integrating sphere with three holes: one is used to received light (input), another one to direct light to the PDM pixels (output), and the third one to measure the light intensity inside the sphere with a NIST photodiode (control). The output hole is connected to a collimator, which allows to illuminate a surface smaller than one pixel. The intensity of the output light is in a constant (purely geometric) ratio with the intensity of light on the control NIST. Thus, it can be precisely calibrated at high intensity, and then used a low intensity for detailed calibration in single photon counting mode. Also, the method uses precise positioning system, which runs and stays in front of each pixel automatically.

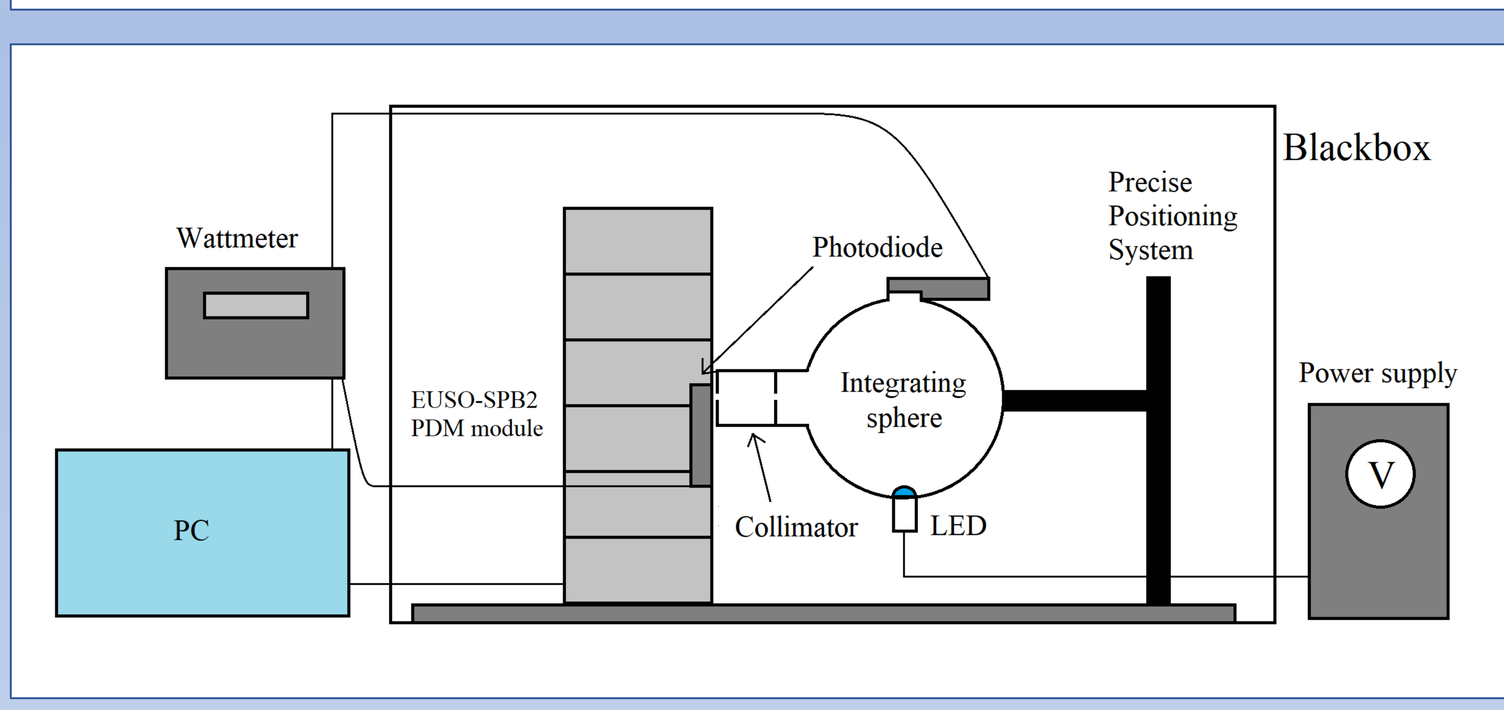

Fig. 6: Scheme of the calibration process, with a collimator attached to the integrating sphere for single pixel illumination.

S-curve measurements

When a photon hits the photocathode of the MAPMT, it generates an internal electron cascade which results in a signal on the anode. This signal is read by an ASIC which counts one count if the signal is above a given threshold, adjustable through a DAC. The so-called "s-curve" is the curve giving the number of counts as a function of that threshold (or DAC). At low threshold (high DAC), the ASIC essentially counts electronic noise (pedestal). At higher thresholds (lower DAC), it counts only real photoelectrons, with an efficiency given by the number of counts per incoming photons. If the threshold increases, the number of counts decreases (i.e. some photoelectrons are missed). The ASIC used is SPACIROC-3 (Blin et al., NIM A, 912, 363). It can adjust its threshold through a combination of DACs: a "DAC-10" (10 bits, from 0 to 1023), set at the level of the MAPMT and a "DAC-7", set at the level of individual pixels (before the pedestal). Figure 8 shows the adjustment of all 2304 pedestals thanks to proper DAC-7 choices.

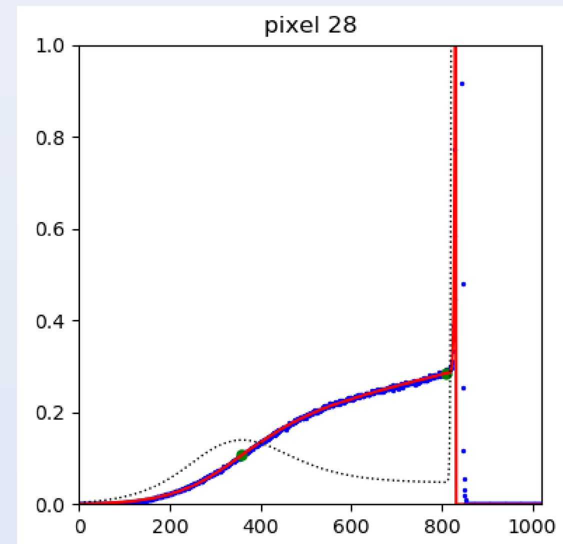

Fig. 7: S-curve for one pixel in DAC-10 mode. Vertical axis: efficiency. Horizontal axis: DAC-10 threshold. The dashed line is the s-curve derivative, i.e. the charge histogram of photoelectrons, showing the one photoelectron peak (at DAC-10 ≈370)

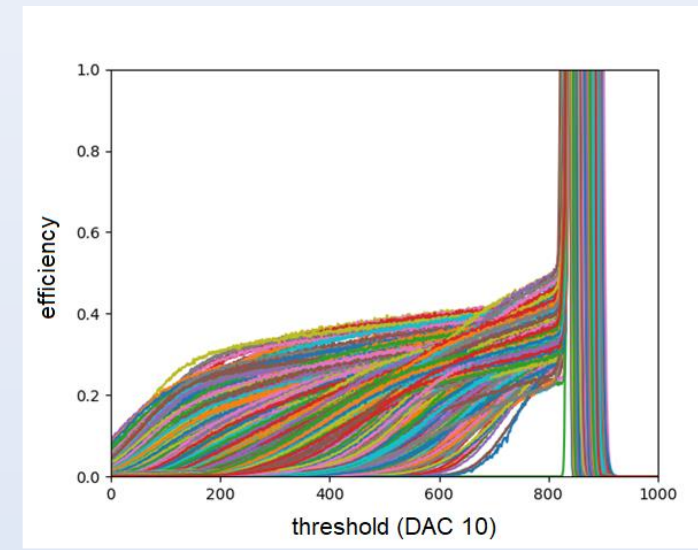

Fig. 8: S-curve plot for all (2304) pixels in DAC-10 mode with individual DAC-7 adjusted so that all pedestals appear around the same DAC-10 value, allowing the choice of a common DAC-10 threshold for all pixels.

PDM scans

After setting individual thresholds, the full scans for each PDM were obtained. Each full scan has a resolution 200×200 points, it allows to see some details in the internal structure of the pixel (Fig. 9). Full scans were made for all PDMs using 2 LED with 375nm or 405nm wavelengths, and in 2 different modes of cathode high voltage (with normal and reduced efficiencies for bright events).
The most accurate scans were obtained for some MAPMTs with a resolution of 100×100 points (Fig. 10), revealing additional details on the internal structure of the photocathode, down to sub-pixel resolution (Fig. 11).

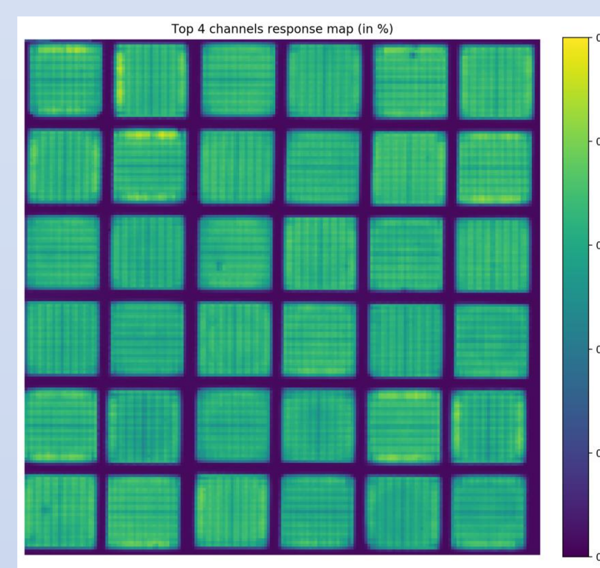

Fig. 9: Full scan of PDM 3, at a wavelength of 375 nm.

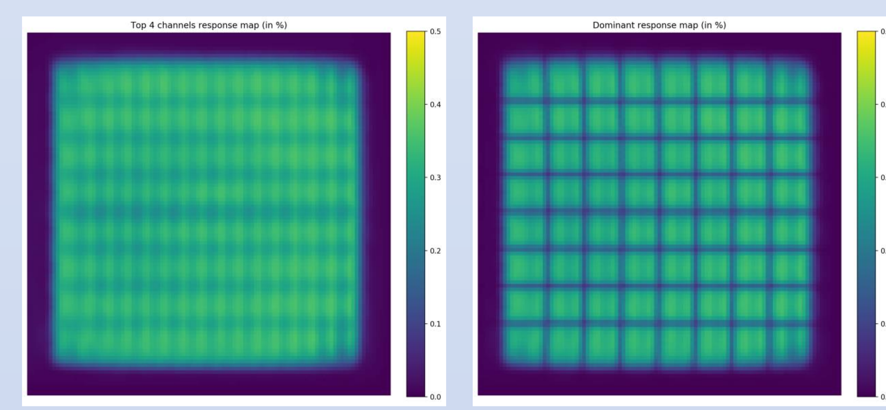

Fig. 10: Left: top-4 channel response map (for each position, we sum the photon count of the 4 brightest pixels to derive the total detection efficiency at that position). Right: dominant response map (photon count rate of the brightest pixel only). The Figure reveals that border pixels are larger than central ones – causing "border effects" in full illumination mode. [PMT22 of PDM2, λ = 405nm, 100 x 100 resolution]

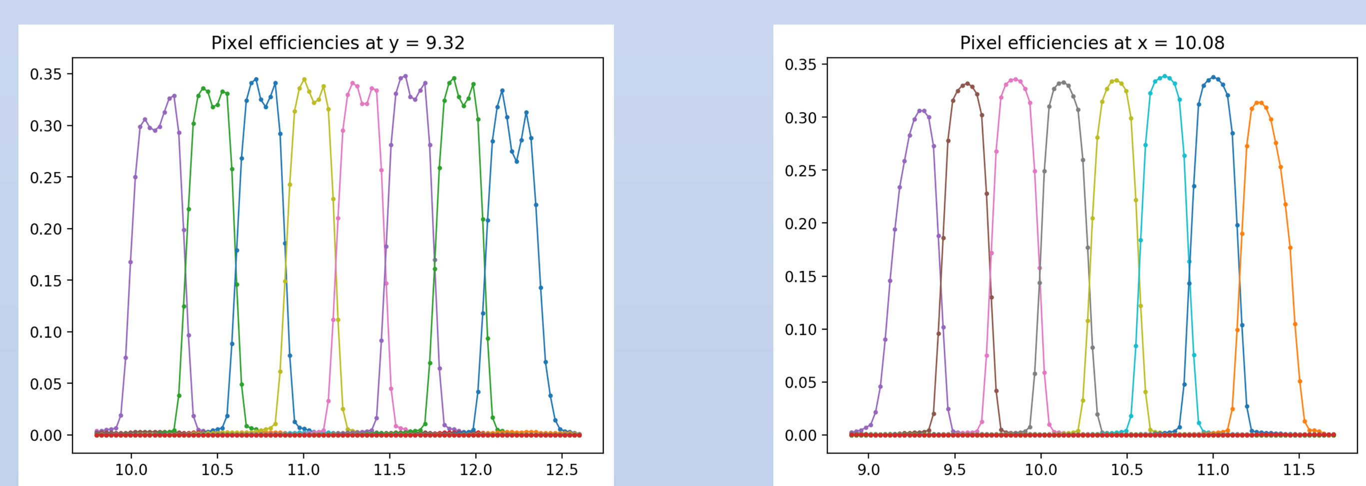

Fig. 11 The structure of the pixels depends on the direction of scanning (vertically or horizontally). In the center of the left picture the efficiency is lower! PMT22 of PDM2, wavelength λ = 405 nm.

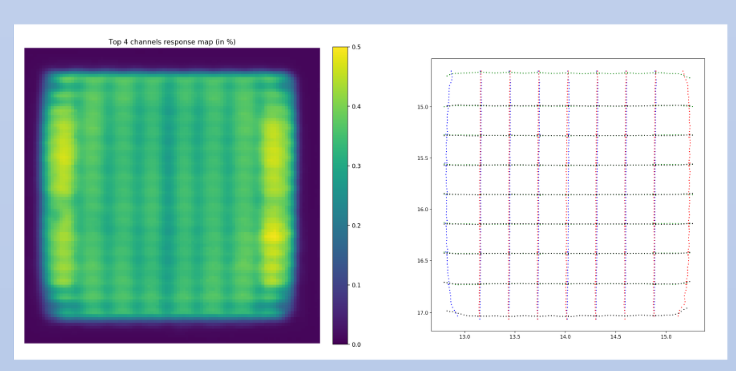

Fig. 12: Determination of the pixel size. The scanning procedure allows to determine the position of pixel borders and in turn provides a measurement of the area of each pixel individually. This allows to renormalize the efficiency obtained in full illumination mode.

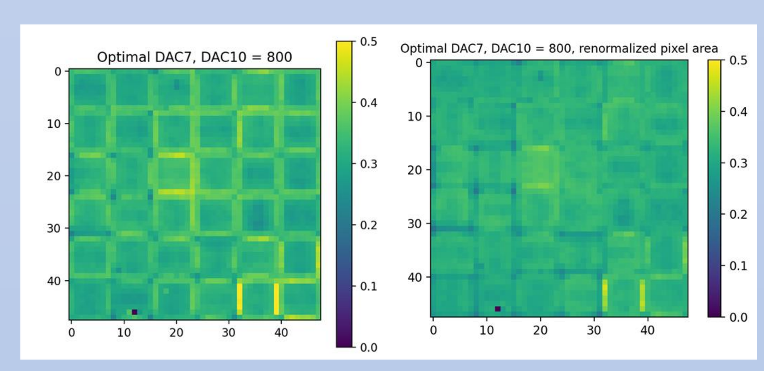

Fig. 13: Full PDM illumination. Color means detection efficiency. Left: efficiency assuming the average pixel size for all pixels (according to Hamamatsu datasheet). Right: renormalized efficiency, taking into account the individual pixel areas. The efficiency map appears more uniform.

Pile-up effect

For high light intensity, "pile-up" occurs when the time interval between consecutive photoelectrons is smaller than the time resolution of the ASIC (a few ns). The number of counts thus saturates and eventually decreases as the photon rate increases (more and more photons being missed). Figures 14 and 15 show saturation (pile-up) curves, i.e. number of counts/µs as a function of photons/µs. The expected counting rate is $\varepsilon\dot{N} \times \exp(-\varepsilon\dot{N}\delta t)$, where $\dot{N}$ is the incoming photon rate, ε is the detection efficiency and δt is the double pulse resolution (dead time).

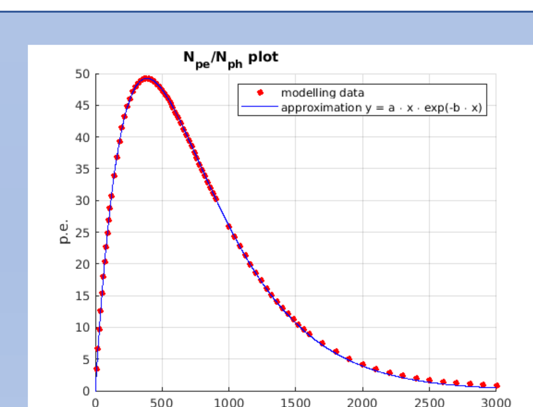

Fig. 14: Simulated pile-up curve for $\delta t = 7.5\,ns$ (assuming a poissonian source of photons).

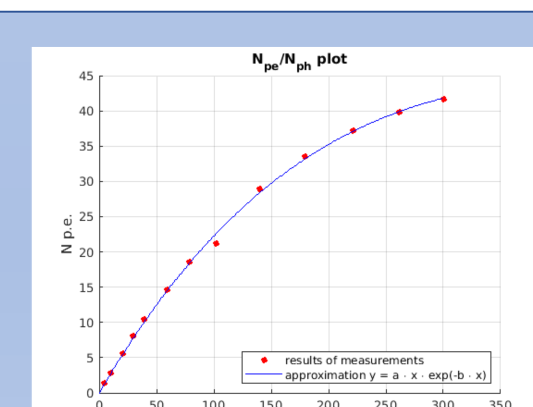

Fig. 15: Example of a pile-up curved, measured for one pixel and fitted with δt = 8.3 ns (LED wavelength 405 nm).

Summary

All three PDMs of the EUSO-SPB2 fluorescence telescope have been calibrated with high precision in different modes. Detailed information about the size and efficiency of each pixel will allow the analyses of extensive air showers and other events detected during the mission, which is expected to be launched in spring 2023 from Wanaka (NZ). The calibration methods presented here will also be useful for the future missions of the JEM-EUSO Collaboration and can be applied more generally to any instrument using MAPMTs.