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A single photo-electron calibration of NectarCAM

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The medium-sized telescopes (MSTs) of the Cherenkov Telescope Array Observatory (CTAO), observing gamma-rays in the energy range from about 100 GeV to 10 TeV, will have a large field of view of 8 degrees. NectarCAM will be installed at the MSTs in the Northern sites of CTAO. NectarCAM consists of 1855 photo-multiplier tubes (PMTs) grouped into modules of 7. The full NectarCAM camera is currently in an advanced phase of integration at Irfu, CEA Paris-Saclay, France. One of the crucial sub-systems of NectarCAM is the single photo-electron (SPE) calibration system. It allows the accurate measurement of the gain of each pixel of the camera, which reduces the systematic uncertainty in the energy reconstruction of primaries of extensive air showers. The SPE calibration system of NectarCAM, developed at IJCLab, Orsay, France, mainly consists of a 10 mm thick screen (placed at a 15 mm distance from the focal plane) with a fishtail light guide, a light box having 12 LEDs emitting light at 390 nm, and XY motors to allow the movement of the screen across the camera. This work presents the preliminary analysis results of the SPE calibration data taken with NectarCAM.

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1. Introduction

The imaging atmospheric Cherenkov technique (IACT) is the primary method to observe very high energy (VHE, >100 GeV) γ-rays. In this technique, γ-rays are detected indirectly via the Cherenkov light emitted in an extensive air shower when charged particles travel faster than the speed of light in the upper atmosphere. A large dish of segmented mirrors is used to reflect this Cherenkov light to a pixellated camera situated at the focal plane of the telescope. Images of the shower observed by one or several telescopes are analyzed for background rejection and to reconstruct primary γ-ray parameters, such as energy and direction. This reconstruction is based on the raw photodetector (PMT or SiPM, hereafter PMT) data, hence it is essential to calibrate accurately photodetectors used in the VHE γ-ray telescopes.

The gain calibration system used in VHE γ-ray telescopes, mainly consists of a light source and diffuser for homogeneously spreading light over an entire camera. A LED-based flasher system placed at the center of the mirror dish is used in VERITAS. It measures the gain using the photo-statistics method (sec. 2.2.1) and single photoelectron spectrum fitting method [9] (sec. 2.2.2). H.E.S.S. employs a system comprising a pulsating LED and a diffuser, resulting in approximately 50% light intensity homogeneity across the camera. This system is placed at 2 m away from the camera [1]. It also adopts the SPE spectrum fitting method for gain measurement. MAGIC uses a system having ultra-fast powerful LED pulser (emitting in green, blue, and UV), placed at 17 m away from the camera in the mirror dish [5, 6, 10]. The gain of the PMTs is determined through the photo-statistics method.

The Cherenkov Telescope Array (CTA, [4]) is a next generation IACT telescope. It will consist of three different sizes of telescopes – Large-Sized Telescopes (LSTs), Medium-Sized Telescopes (MSTs), and Small-Sized Telescopes (SSTs). NectarCAM [7] is one of the two cameras designed for MSTs, having a field of view of 8° and covering the energy range between 100 GeV and 30 TeV. The NecarCAM has a total of 1855 PMTs. In this work, section 2 discusses the calibration system and methods adopted to calibrate these PMTs. We developed an SPE calibration system that enables the gain measurement of NectarCAM with a statistical uncertainty lower than 1% [2]. The data analysis and results are shown in section 3, followed by the conclusion in section 4.

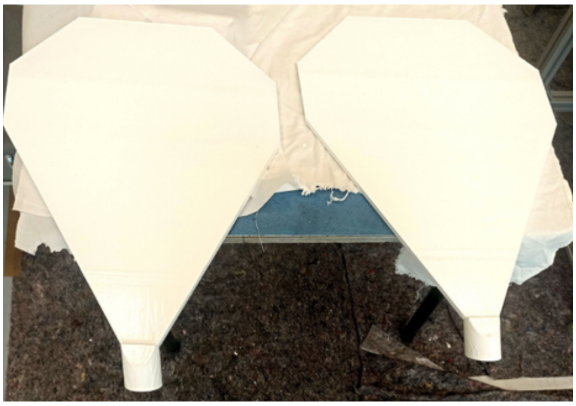
2. NectarCAM calibration system and methods

In this section, we discuss the SPE calibration system and the related calibration methods adopted for NectarCAM. The implementation of different calibration methods in the `nectarchain`[1] software, which is the data analysis tool for NectatCAM data, is also discussed.

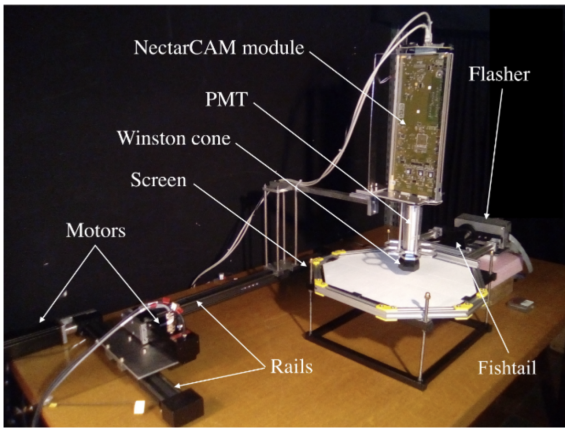
2.1 SPE calibration system

The main components of the NectarCAM SPE calibration system are a reflective target providing low light intensity down to single photo-electron level, a lightbox, and XY motorization. The details of these components are given below.

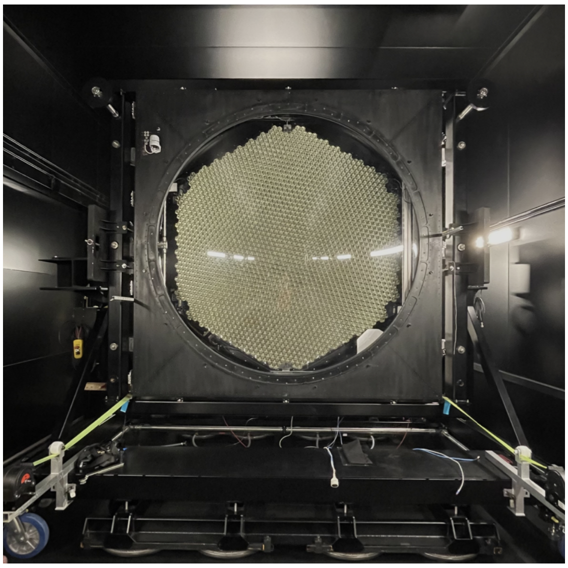
[1] `https://github.com/cta-observatory/nectarchain`



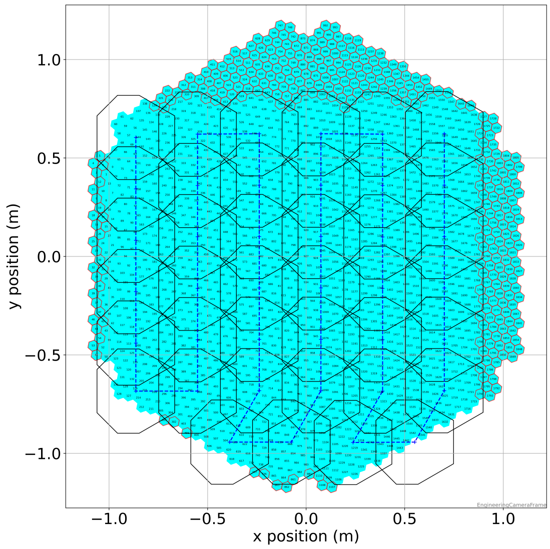
(a) Reflective white target



(b) IJCLab test bench



(c) The first NectarCAM in the CEA dark room



(d) SPE scan positions

Figure 1: Overview of the NectarCAM single photo-electron calibration system

- Reflective target: It is a 10 mm thick block of Polymethyl methacrylate (PMMA), which is painted with a white diffuse reflective Eljen paint (hence, also called as white target) with 18 % dilution. 51 PMTs are covered at once by the surface of the white target. A fishtail light guide is attached to it for injecting light into the screen. This target, having octagonal shape, is developed at Laboratoire de Physique des 2 infinis Irène Joliot-Curie (IJCLab) and shown in Figure 1(a).

- Light box: It consists of 12 flashing LEDs emitting at 390 nm and 1 LED emitting at 660 nm that simulates NSB background, and is attached to a fishtail light guide. The boards for this box are developed by Laboratoire Univers et Particules de Montpellier (LUPM).

- XY motorization: The reflective target is moved across the camera with the help of a XY motorization developed at IJCLab.

Several screens have been produced and painted with various dilutions. Each screen undergoes a test for light-intensity homogeneity at various temperatures in the IJCLab test bench, shown in Figure 1(b). The details of these tests and results are discussed in previous works [2, 11]. One of these tested screens is currently used for SPE calibration runs at the CEA test bench, where NectarCAM is in an advanced stage of integration (shown in Figure 1(c)). The current configuration of the XY motorization scans the NectarCAM at 40 positions, covering ~80% of the PMTs. These scan positions are shown in Figure 1(d). An upgrade of the XY motorization mechanics which will be able to scan the 100% of the camera is under development. The part of the reflective target facing mirror-dish is homogenously painted with three layers and can be used for mirror alignment and point spread function measurement.

2.2 Calibration methods

This section briefly explains the methods used to measure the gain of the NectarCAM PMTs. In order to measure and correct for the relative inhomogeneities (due to different quantum efficiency of PMT, reflectivity of cones, etc.), NectarCAM will also use a Flat-Field unit that delivers uniform illumination across the camera.

2.2.1 Photo-statistics

The photo-statistics method is one of the gain calibration procedures that is only based on statistics and uses the variability of charge at high luminosity. This method exploits the flat-field flasher at the center of the telescope dish, as developed by the IJCLab and LUPM, and the method is simpler than the SPE spectrum fitting (section 2.2.2). The gain in a pixel can be derived from equation 1

$$g = \frac{\sigma_x^2 - \sigma_{ped}^2 - B_f^2 \langle x \rangle^2}{\langle x \rangle (1 + \beta^2)} \tag{1}$$

where x is the charge computed in the pixels, σ represents the standard deviation, the term $B_f^2 \langle x \rangle^2$ is the standard variation due to the flasher variability and β is the SPE resolution. The brackets represent the average over the run. Therefore, the photo-statistic method needs Flat-Fielding (FF) events taken at high intensity (> 20 pe) and pedestal events. Moreover, this method is very fast (runs within a few seconds) and can be easily used as an online calibration method. However, the SPE resolution has to be computed previously with a dedicated analysis done with the SPE spectrum fit method. Although this limitation, the SPE resolution does not vary much in time, therefore we can compute the SPE resolution quite fairly to make it possible to not re-compute its value each time the photo-statistic method is used. This alternative method is much different from the SPE spectrum fit and is not applied to the same data, thus it brings a perfect method to cross-check the gain computed from the SPE spectrum fit method.

2.2.2 SPE spectrum fit

The SPE spectrum fit method adopted in this work approximates the single photo-electron response of a PMT by a double Gaussian model. This method is used in this work for gain estimation [3]. The details of the implementation of this gain-independent model can be found in the dedicated proceeding on `nectarchain` [8]. The SPE runs are taken in the CEA dark room using the white target (SPE-WT run) discussed in section 2, and also with the LED-based calibration box placed at ~12 m from the camera (hereafter, SPE Standard run). We test the SPE spectrum fitting module of `nectarchain` with both types of runs (independent of each other) and compare the analysis with the photo-statistics method.

In the dark room, the delivered intensity of the Flat-Field unit can be lowered down to deliver a single photo-electron illumination which allows us to cross-check the results with the SPE-WT runs. Note that while the SPE spectrum fits based on low-intensity FF runs can be taken in the dark room, such a method cannot be employed on-site as the night-sky background would pollute the low-intensity signals.

3. Data Analysis, Results, and Discussion

The SPE calibration runs with a white target are taken at different configurations of LED flasher providing different light intensities. In this work, we show the analysis of SPE-WT run 4283 taken with the configurations of the flasher, as shown in Table 1. The results are also compared with the photo-statistics method.

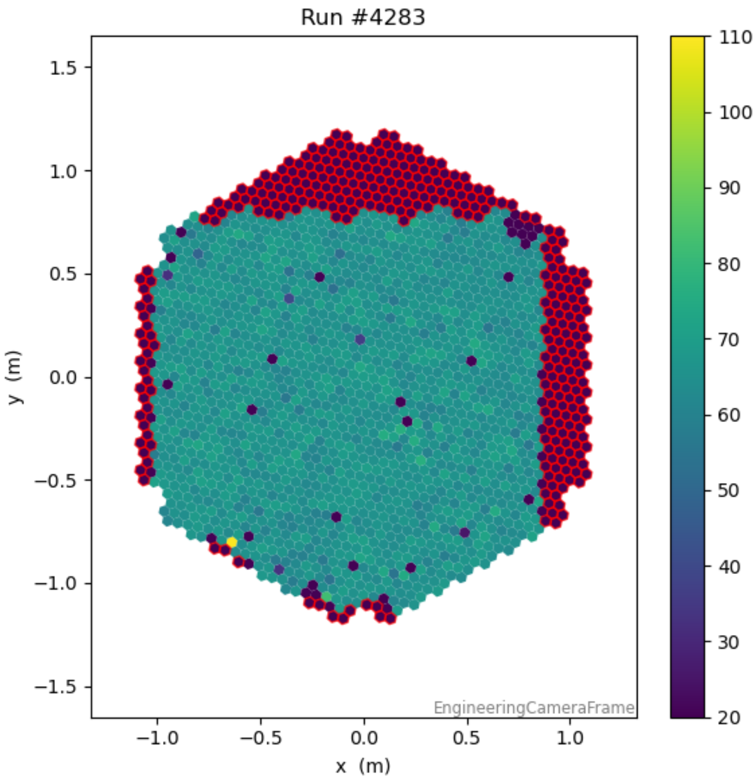


Figure 2: A map of SPE gain for run 4283. The pixels in the red border are not included in the analysis

Table 1: The details of the runs. All these runs are taken at a trigger rate of 1 kHz.

Run number	Run type	Flasher intensity
4283	SPE-WT	4 LEDs at 10 V
3942	SPE Standard	1 LED, 8.5 V
3936	SPE Standard	1 LED, 8.5 V
3937	Flat-Field	13 LEDs, 10 V
3938	Pedestal	-

These runs are analyzed with `nectarchain-v0.1.3`[2]. This tool implements the modules, as discussed in sections 2.2.2, to analyse the SPE runs with photo-statistics and SPE spectrum fit methods, and FF runs. First the peak of the averaged waveform is found for each position of the white target, and then the time window of -5, +11 ns around this peak position is used for the charge extraction in this work. The pixels having partial or no coverage of the white target are excluded from the analysis, and shown with red-border pixels in Figure 2.

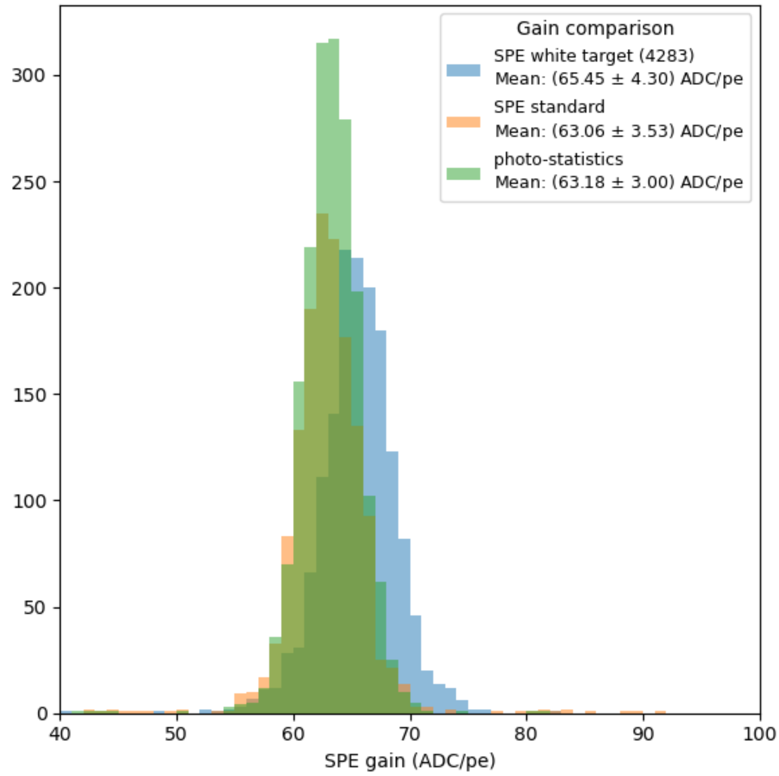


Figure 3: The comparison of SPE gain

The map of SPE gain with the SPE spectrum fit method is shown in Figure 2 for run 4283. The gain distribution of this SPE run taken with the white target is compared with the standard SPE run. The SPE spectrum fit method is also compared with the photo-statistics method. This comparison

[2] https://github.com/cta-observatory/nectarchain

is shown in Figure 3. The mean for this method is found to be (65.45 ± 4.30) ADC/pe (Analog to digital converter count / photo-electron), which is (63.18 ± 3.00) ADC/pe for photo-statistics. For the SPE-WT run, a few pixels show very low gain values due to low statistics in the SPE peak. This will be solved in the near future by increasing the exposure of SPE-WT runs.

The SPE gains measured with the SPE spectrum fit method for the SPE Standard run and SPE-WT run, and that measured with the photo-statistics method are compared in Figure 3. The means of all three SPE gain distributions are comparable. The differences observed in these distributions could be due to different conditions in which the runs were taken.

4. Conclusions

The analysis of the SPE calibration data taken with the white target and the analysis with the SPE spectrum fit method is presented in this study. The results are also compared with the standard SPE runs. The analysis has been performed for the ~80% pixels covered by white target with the current mechanical system. The comparable results have been found for the SPE gain estimation between the SPE standard runs and those with the white target. The difference found between these estimations could be due to different run conditions. More precise comparisons will be done in the future. The analysis of SPE runs with different light illuminations and optimization of the scan positions for the SPE white target runs are underway.

Acknowledgements

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