PROCEEDINGS OF SCIENCE

Flat-field calibration procedure of the ASTRI Mini-Array Cherenkov cameras using night sky background observations

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The ASTRI Mini-Array is an international project led by the Italian National Institute for Astrophysics (INAF) to build and operate an array consisting of nine Imaging Atmospheric Cherenkov Telescopes, currently under deployment at the Teide Observatory in Tenerife. They will study astronomical gamma-ray sources at energy above 1 TeV with unprecedented sensitivity among IACTs at E > 10 TeV. The ASTRI Mini-Array telescopes are equipped with a Cherenkov camera based on Silicon Photo-Multiplier detectors with an interferential filter as front window. They are an improvement of the ASTRI-Horn telescope prototype, operating at the M.G. Fracastoro INAF observing station in Sicily. As part of the ASTRI-Horn observational campaign, a fundamental calibration procedure was developed to determine flat-field correction coefficients. An experimental set-up was built with a stand-alone Cherenkov camera looking at the night sky pointing to the zenith without any optical system. By acquiring data with such device during particularly clear, moonless nights, pixel by pixel flat-field correction coefficients were determined to correct for differences in the filter transmission and Photo Detection Efficiency among the camera pixels. Flat-field correction can be applied to the variance data, that are related to the statistical analysis of the variability of the signals detected by the camera electronics, leading to a clearer vision of star fields with a consequent improvement of the pointing calibration procedure and of the monitoring of the telescope point spread function. The same procedure will be applied to the ASTRI Mini-Array to improve its pointing accuracy.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

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PoS(ICRC2023)739

1. Introduction

The ASTRI Mini-Array [1] is an international project with the leading of the Italian National Institute for Astrophysics (INAF); it aims to build and operate an array of nine Imaging Atmospheric Cherenkov Telescopes (IACTs), that are currently under construction and deployment at the Teide Observatory in Tenerife (Spain). It will study astronomical gamma-ray sources at energy range of 1 TeV and 200 TeV, with unprecedented sensitivity among IACTs. The ASTRI Mini-Array telescopes are small-sized (diameter of ∼ 4 m), with a large Field of View (∼ 10°) and with a dual-mirror Schwarzschild-Couder optical design. They are equipped with Cherenkov cameras composed by an array of Silicon Photo-Multiplier (SiPM) detectors [2], protected by a front window which also acts as an interferential filter. The focal plane of the camera is populated by 37 Photon Detection Modules (PDMs), each which is an assembly of a SiPM tile, a Front End Electronics (FEE) and a Field Programmable Gate Array board. The FEE consists of a board with two 32-channels CITIROC ASICs [3], [4], each of them offering two electronic acquisition chains (High Gain and Low-Gain) and trigger. Each SiPM tile is a matrix of 8×8 pixels of 7mm x 7mm, so the total amount of pixels for each camera is 2368. The telescopes and the cameras are an improvement of the ASTRI-Horn telescope prototype [5], operating at the M.G. Fracastoro INAF observing station in Sicily (Italy) and of the ASTRI-Horn camera [6], with which it is equipped.

Every instrument, including the ASTRI Mini-Array telescopes, needs calibration procedures to operate in the correct way. The calibrations are necessary to operate the instrument with the correct parameters, to perform the Cherenkov data analysis and to improve some auxiliary functions that simplify the observations. Among these calibration procedures, one of the fundamental ones is the measure of Flat-Field (FF) correction coefficients, that allows to equalize the Cherenkov camera response and, thus, to provide a clearer view of star fields during the observations as well as the improvement of the Point Spread Function (PSF) and the telescope pointing monitoring. Furthermore, the application of the FF coefficients to the variance quick-look window of the camera's Graphical User Interface (GUI) [7] can facilitate the operator in the interpretation of any camera malfunctions during operations. In this proceeding, we will describe the experimental set-up and the procedure adopted to find these parameters and how they improve telescope performance when applied to camera pixels. This procedure will then be used in the ASTRI Mini-Array cameras.

2. The flat-field calibration procedure

The FF calibration procedure is one of several more procedures needed by the ASTRI Cherenkov cameras for the correct data acquisition and subsequent data analysis. Among them, we mention the temperature compensation, the breakdown voltage determination, the trigger channels alignment and the relative gain calibration from pulse-height distributions (PHD) [8].

The procedure to measure the FF correction coefficients from the variance data and their application to them, were performed for the first time with the ASTRI-Horn camera. The variance is related to the statistical analysis of the variability of the signals detected by the camera pixels, which is linearly dependent on the photon detection rate and the level of the night sky background (NSB) flux [9]. The FEE continuously samples the SiPM output signal and the variance[1] is estimated

[1]computed in ADC^2 counts as: $\frac{\Sigma\, ADC^2}{N} - (\frac{\Sigma\, ADC}{N})^2$, where N is the number of data samples

in real time by an algorithm implemented in the ASTRI FPGA FEE, which accumulates the sum and the squared sum in ADC counts of the output signal of each camera pixel. After 65536 ADC samples (equivalent to the acquisition of approximately 1.2 seconds of data), the variance data are inserted as output in the camera telemetry, along with the scientific data acquired at each Cherenkov event trigger. Thanks to the variance acquisition mode (contemporary to the acquisition of the scientific data) and the possibility to have a quick-look window on the camera's GUI, it is possible to monitor the presence of stars, clouds and other slow varying background sources in the field of view of the telescope, the optical PSF and to calibrate the telescope pointing direction [10].

The gain equalization of the pixels, obtained for example through the pixel output PHD, does not represent a true camera FF. Infact, even after the calibration of the electronic chain, the channels present small response differences to a uniform illumination, due to the optic components of the interferential filter, to the Photo Detection Efficiency (PDE) and the cross-talk of the SiPMs. The FF calibration procedure gives the FF correction coefficients, that are used to correct these differences. These coefficients, applied to the variance data, lead to a clearer vision of star fields with an improvement of the calibration procedures that rely on them, like the pointing direction and the PSF monitoring. This occurs because the FF parameters are provided to the software that deals with the pointing procedure and to the PSF quality software that compares the variance image with the image acquired from the pointing monitor camera. Ultimately, the FF calibration procedure is important to keep the system stable, to monitor its health status and to help the observations too.

2.1 Experimental set-up and data acquisition

The ASTRI-Horn prototype is fully operative and it is a perfect laboratory to also tests the calibration procedures foreseen for the Mini-Array, including the FF procedure. The determination of the FF coefficients was made with the ASTRI-Horn camera dismounted from the telescope and placed on a table inside one of the rooms with dome of the ASTRI Counting Room (Figure 1).

Figure 1: The ASTRI-Horn telescope and the ASTRI Counting Room.

The camera was placed in such a way to look at the night sky pointing to the zenith without any optical system (Figure 2, left). A collimator of about 40 cm in diameter and 60 cm in height was placed, with the camera lids opened, on top of the filtering entrance window that covers the focal plane, thus to limit the angle of open sky visible from the camera to about 0.012 *sr* (Figure 2, right). Then the camera was connected to the acquisition system, and dedicated variance data runs were acquired with this set-up and dome opened during some very suitable nights (particularly clear and moonless) between May 2022 and July 2022, excluding the nights when the conditions on the site were not perfect (clouds, ash plumes from volcano) during the new moon phases.

Figure 2: The image on the left is a photograph of the set-up used; the image on the right is the set-up model reconstruction, with Ω as the angle of open sky visible from the camera, equal to about 0.012 *sr*.

2.2 Data analysis

By acquiring variance data with the set-up described above, we were able to measure the pixel-by-pixel FF correction coefficients and to correct for local non-uniformities of the filter transmittance window and different PDE among camera pixels.

For the variance run chosen for the analysis (about 100 frames), the FF image, $I_{i,j}$ (where i and j are the indexes of the pixels of the camera) was calculated as the mean variance of each camera pixel (excluding the unusable pixels, like the noisy and dead ones), choosing an adequate number of frames in which the variance data were particularly stable.

The FF correction coefficients $f_{i,j}$ were defined as the ratio of $\langle I_{i,j} \rangle$ to $I_{i,j}$, where $\langle I_{i,j} \rangle$ is the average value of $I_{i,j}$. In this way it was possible to equalize the value of each pixel respect to the average of all the pixels. Figure 3 shows the FF image and the FF correction coefficients obtained for the sample of variance data analysed, while Figure 4 shows the effect of the FF on the pixels of the camera.

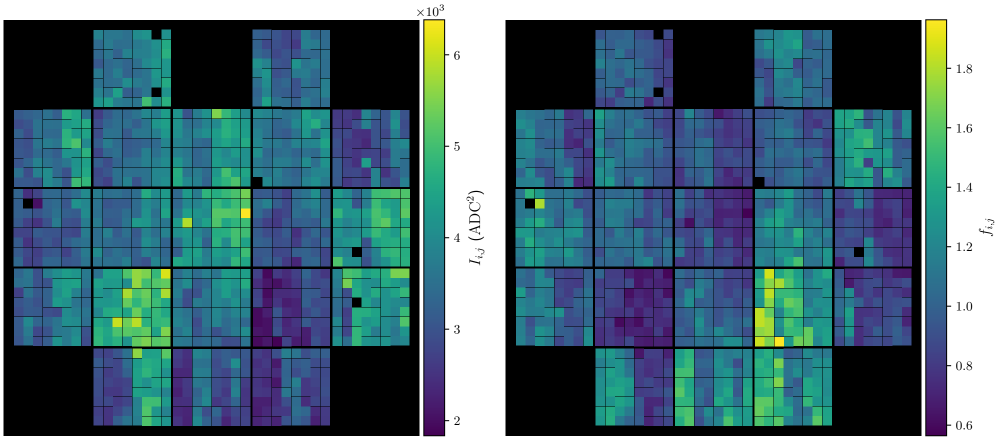

Figure 3: The FF image $I_{i,j}$ (on the left) and the FF correction coefficients $f_{i,j}$ (on the right) obtained analysing a sample of variance data acquired during the tests of the FF calibration procedure with the experimental set-up shown in Figure 2. The black dots in the FF images correspond to dead pixels. One camera PDM was not working during the tests.

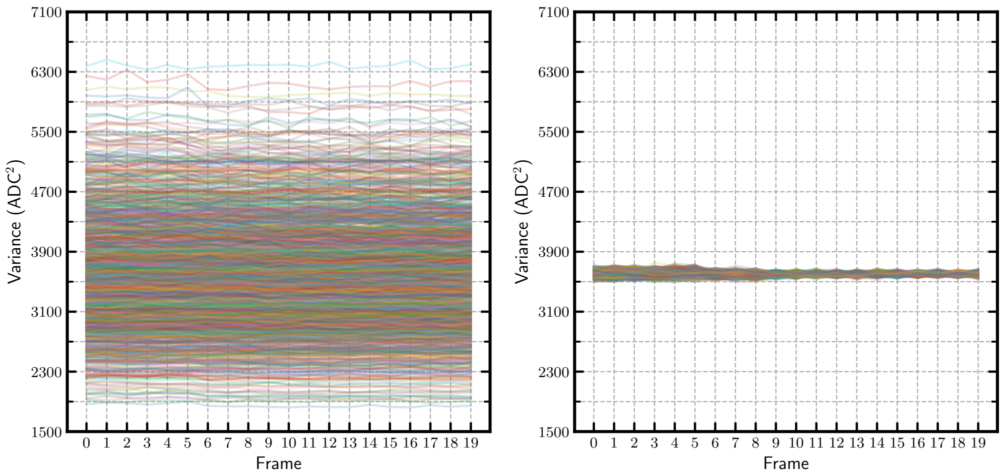

Figure 4: On the left, the plot of the 20 chosen frames of the selected run's variance data, without the FF parameters applied; on the right, the same data with the FF correction.

2.3 Application of flat-field parameters

Figures 5, 6 and 7 show, respectively, the variance images acquired with the ASTRI-Horn Telescope pointed to the Orion's Belt, to the Etna volcano mountain profile and to a bright star, before and after the application of the FF correction coefficients estimated with the procedure described above. We chose these images, among the others, for the recognizability of the Orion's Belt star field, of the profile of the South-East crater of the volcano mountain and because, with a bright star, it was possible to reveal the presence of *ghosts*, caused by mirror misalignment.

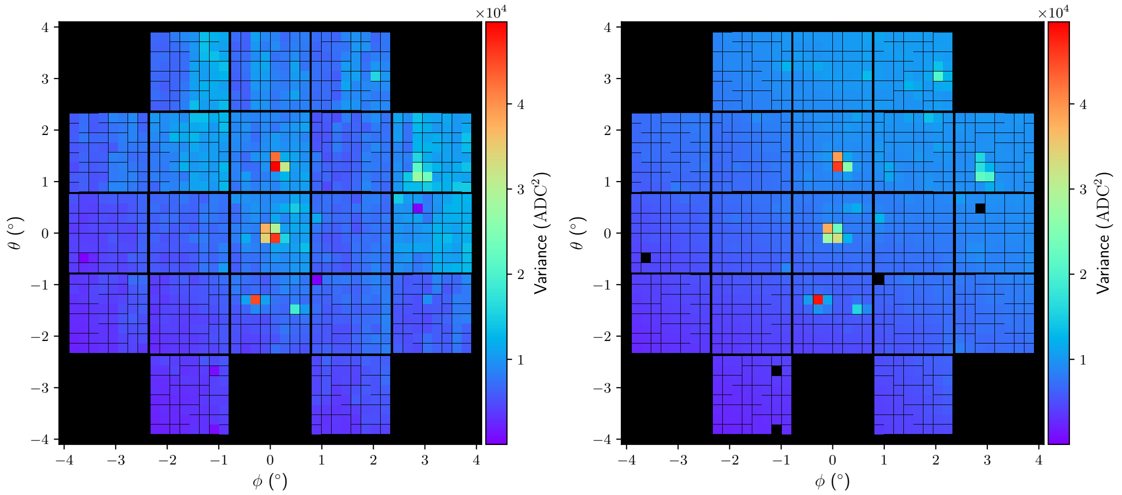

Figure 5: Effect of the FF correction to the variance data with the telescope pointed to the Orion's Belt. The black dots are dead pixels, while one of the PDMs was not working.

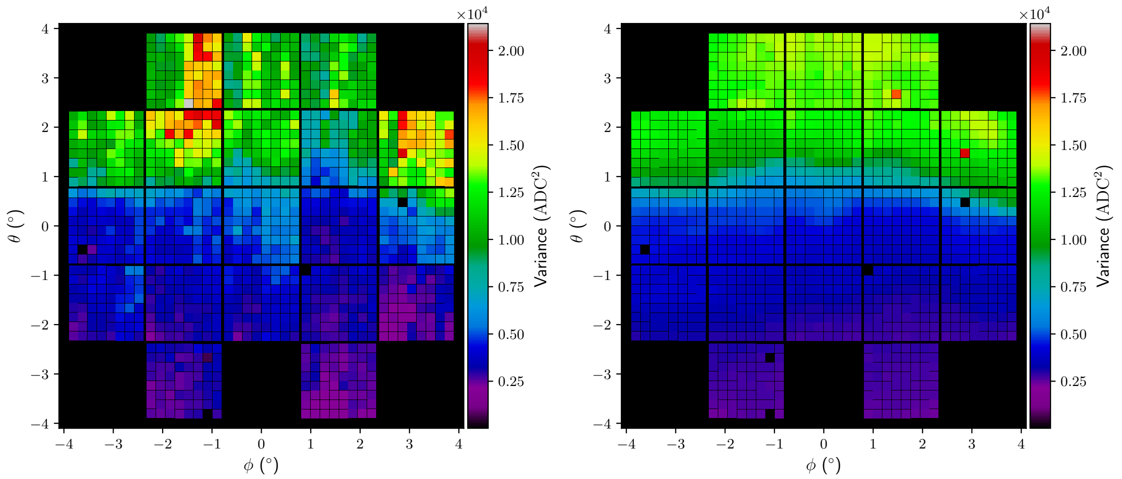

Figure 6: Effect of the FF correction to the variance data with the telescope pointed to the South-East crater of the Etna volcano mountain. The black dots are dead pixels, while one of the PDMs was not working.

Once the procedure was controlled and approved, the calculated FF correction coefficients were implemented as a multiplicative matrix of coefficients directly to the variance quick-look window of the ASTRI-Horn camera's engineering GUI. To understand how the FF procedure facilitates the operator tasks in the interpretation of any camera malfunctions and how it improves the acquisition shifts, we point out that, after the application of FF correction, it is possible to locate stars of up to

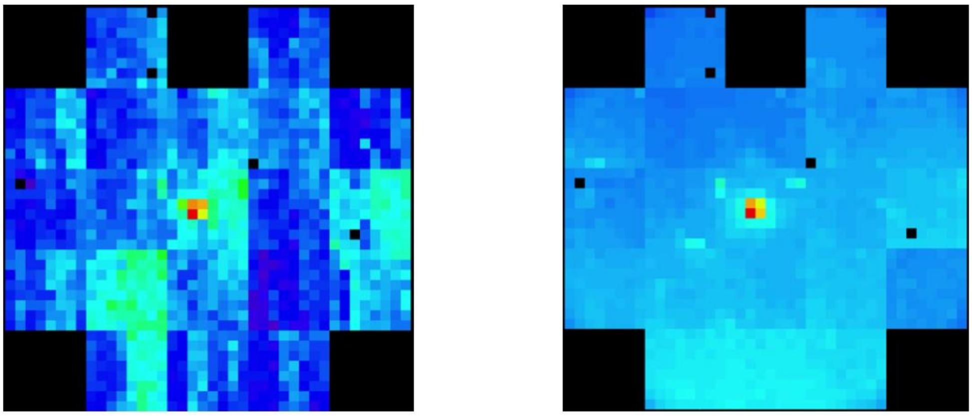

Figure 7: Effect of the FF correction to the variance data with the telescope pointed to a bright star. Thanks to the application of the FF parameters, it is possible to see that there are 3 bright spots that do not match any stars in the field of view: these are the so-called *ghosts*, caused by mirror misalignment. The black dots are dead pixels, while one of the PDMs was not working.

about 7.2 magnitude during the acquisition run (this threshold was determined by comparing the FF corrected variance images with the stellar fields shown by suitable softwares). The same procedure and application will be implemented in the ASTRI Mini-Array cameras.

3. Conclusions

In this proceeding we described the first time in which the procedure to find the FF correction parameters was applied to the ASTRI-Horn telescope prototype, acquiring dedicated data during particularly clear and moonless nights. Applying these parameters to the variance data, an improvement of the pointing calibration procedure and of the telescope PSF monitoring is achieved. Moreover, applying them to the variance quick-look window of the GUI, it leads to a clearer vision of star fields during the acquisitions. It is now possible to use the same procedure with the ASTRI Mini-Array telescopes, together with the other calibration procedures, to improve the instruments pointing accuracy.

Acknowledgments

This work was conducted in the context of the ASTRI Project. We gratefully acknowledge support from the people, agencies, and organisations listed here: http://www.astri.inaf.it/en/library/. This paper went through the internal ASTRI review process.

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