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A new observing season for the ASTRI-Horn Cherenkov telescope: enhanced techniques for pointing calibration, astrometry, and PSF monitoring.

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ASTRI-Horn is the first Cherenkov telescope with a dual-mirror (Schwarzschild-Couder) optical configuration. It was developed by the ASTRI team as a prototype for the Cherenkov Telescope Array (CTA) and the ASTRI Mini-Array, a nine-telescope array currently under construction in Tenerife. ASTRI-Horn, after its validation with the detection of the Crab Nebula (2020), is currently in a new scientific campaign, also serving as a testbed for novel calibration procedures and technical improvements. Promising results have recently been obtained using the so-called *variance* channel (VAR), a statistical method implemented in front-end electronics, based on the Poissonian nature of pixel signal fluctuations. The VAR constitutes an ancillary output of the Cherenkov camera that provides images of the sky, thus offering a unique opportunity to use stars in the field of view for calibration purposes. By analyzing VAR data taken in the winter of 2022-2023, we measured for the first time the alignment of the Cherenkov camera with respect to the telescope's optical axis with an accuracy of 1 arcsec, demonstrating the effectiveness of this technique. Furthermore, an optimized version of our custom astrometry software for the Cherenkov cameras allowed us to monitor the position of the source of interest even during wobble mode observations. Finally, VAR data can also be used to assess the PSF of the telescope, allowing us to continuously monitor the quality of optics (alignment and deterioration of mirrors) during scientific observations. These techniques, which are fundamental to the accuracy of ASTRI Mini-Array, can also be applied to CTA.

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Figure 1: The prototype telescope ASTRI-Horn.

1. Introduction

ASTRI (acronym of *Astrofisica con Specchi a Tecnologia Replicante Italiana*) is an international project lead by the Italian National Institute for Astrophysics (INAF) aimed to study the cosmic radiation in the Very High-Energy (VHE) range, up to 200 TeV and beyond [1], exploiting the Imaging Atmospheric Cherenkov Technique (IACT) [2]. To this end, the ASTRI Team developed a new type of ground-based Cherenkov telescope, introducing several novelties with respect to the former and current operative instruments. The optical system implements a dual-mirror configuration (the Schwarzschild-Couder design) producing an aplanatic Field of View (FOV) of large extension (10.5°) with a reduced plate-scale (the camera diameter is ~40 cm) [3]. The curved focal surface is covered with modern Silicon Photo-Multiplier (SiPM) sensors, very small and highly performing for our purposes in comparison to Photo Multipliers Tubes (PMTs) [4]. The validation of this new telescope type was successfully carried out in 2020, when the ASTRI-Horn prototype installed at the INAF "M.C. Fracastoro" observing station in Serra La Nave on Mount Etna (in Italy, see figure 1) detected the Crab nebula with a confidence level above 5σ [5]. At that time, ASTRI-Horn was the only Cherenkov telescope of its kind, while nowadays an array of nine identical ASTRI-like telescopes, the ASTRI Mini-Array, is currently under installation in Tenerife [6]. Nevertheless, the potential of ASTRI-Horn is not depleted yet. The prototype has entered a new phase, taking new scientific data as well as serving as a test bench for all (or most) the calibration procedures developed for the ASTRI Mini-Array.

In this contribution we report preliminary results concerning three different methods developed respectively for measuring the alignment of the Cherenkov camera with the optical axis of the telescope (section 2), checking its pointing direction in the sky (section 3), and monitoring the optical point spread function (PSF) of the system (section 4). The characteristic of these methods is that they do not need any device installed on purpose, but they just work with the analysis of the images taken directly by the Cherenkov camera in the so-called *variance* mode (VAR). In fact,

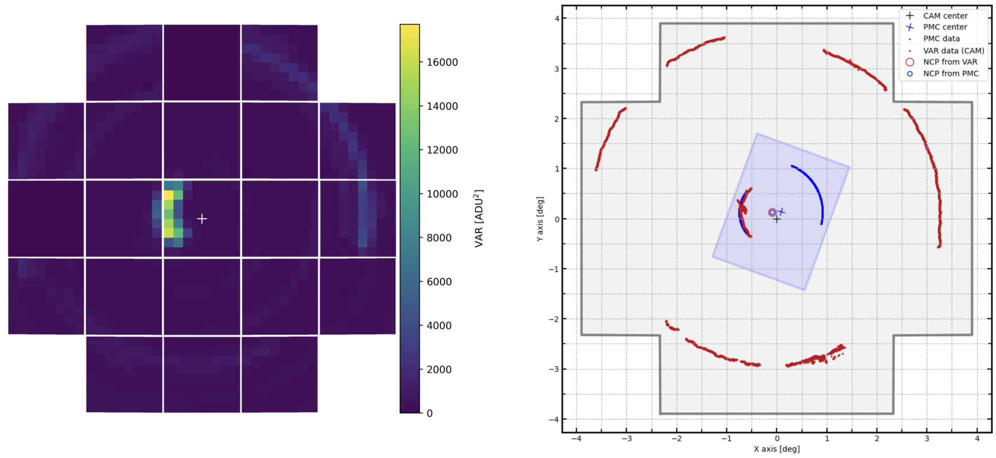

Figure 2: *Left*. FOV rotation in a long acquisition run with the telescope in staring mode pointing at the NCP. *Right*. VAR data elaboration and comparison with the PMC field (blue rectangle). It is possible to see the mis-alignment between the Cherenkov camera geometric center (black cross), the PMC center (blue cross) and the North Celestial Pole (red and blue empty dots).

while the main task of the camera is to record nanosecond atmospheric flashes produced by the incoming cosmic radiation, the VAR is dedicated to the analysis of the slowly varying night sky background conditions, producing images similar to those of optical telescopes, at a low frequency of one every ~ 3 s (figure 3). VAR images constitute a unique opportunity for pointing calibration purposes, but they are affected by an important limitation, due to the coarse angular resolution determined by the large pixel size of the Cherenkov camera ($\sim 11'$). For this reason, an ancillary optical device specifically dedicated to the measurement of the telescope pointing accuracy (the Pointing Monitoring Camera, PMC) is mounted on the back of the secondary mirror. However, as it is discussed below, the VAR analysis is still fundamental for a full characterization of the optical system and, in turn, for the pointing model of the telescope, and hence for the scientific accuracy of the whole apparatus.
The following sections report methods and preliminary results obtained during the calibration of the system before the observing session of winter 2022-2023. The ASTRI Cherenkov camera was in a reduced configuration, with 21 pixel tiles instead of the nominal 37, and only 7.5° FOV.

2. Camera alignment

For an accurate pointing performance a crucial quantity to be measured is the camera offset with respect to the *mechanical* optical-axis of the telescope, i.e. the celestial coordinate actually tracked by motors [7]. An effective method to characterize this offset, which is zero for an ideal telescope, is to use the rotation of the FOV [8] during a long observing run in tracking mode, and fit the star trajectories in VAR images (red arcs in figure 2, *right*) with ellipses [9]. However, if telescope mount is not following a perfect star-tracking pattern (e.g. due to residuals of the pointing model, wind gusts, gravity flexures, failures, and others), in general it is impossible to disentangle the contribution due to the camera offset and to the telescope motion. In this case, another strategy

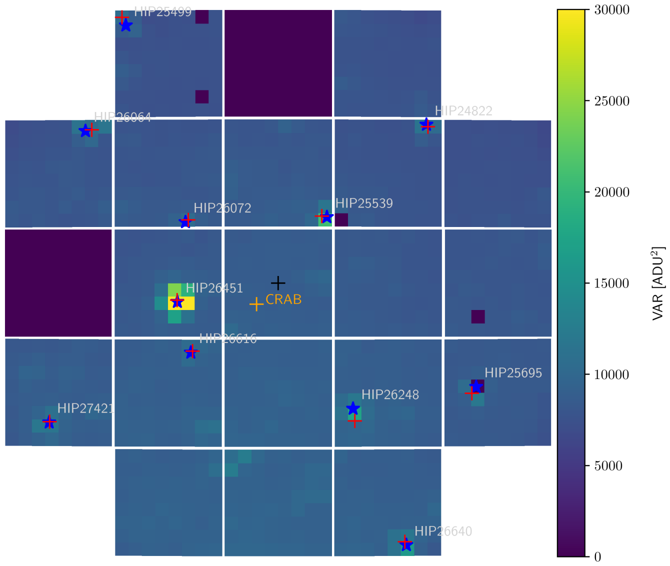

Figure 3: Output of V-STAR. Stellar spots in the VAR image are marked with red crosses, while in blue are the sources from stellar catalogs successfully matched. The target (Crab nebula) is in orange.

must be adopted and with ASTRI-Horn we tested for the first time a different solution that has already been suggested in the past [10]. We set the telescope in staring mode pointing at the North Celestial Pole (NCP) and we acquired VAR and PMC data for 6.3 h. In such condition, the FOV rotation is free by any eventual distortion due to tracking errors. Consequently, the characterization of the camera offset now has a better precision with respect to previous measurements made in tracking mode [11].

We elaborated VAR images using a stacking of all the frames (7585) and isolating bright objects in motion considering the variance of every pixel in time, see figure 2, *left*. After a suitable procedure of data cleaning, the star trajectories in the FOV were ready to be fitted with circumferences, finding the true position of the NCP with respect to the Cherenkov camera frame. The same process is applied to images from the PMC, obtaining the NCP position with respect to the PMC frame. Lastly, considering the respective plate-scale and the relative orientation[1] of the two cameras, we superimposed the two frames obtaining the plot reported in figure 2, *right*. Matching the position of the NCP and the arc of the brightest star (Polaris, HIP 11767 [12]), we characterized the relative arrangement of three crucial elements for the pointing performance of the telescope: the target coordinate (NCP), the PMC center and the Cherenkov camera center.

In the case of ASTRI-Horn the two cameras are not aligned, probably due to mechanical tolerances in the mount assembly. In particular, the distance between their centers is equal to $\Delta_{\text{CAM}} = 9.44'$, with an uncertainty lower than $1''$ thanks to the very large number of images collected. The measurement of this quantity is very important for the characterization of the system. If fact, in case of pointing errors the PMC (angular resolution $\sim 7''$) may be adopted for the pointing correction

[1]This angle is measured considering the star trajectories in a dedicated observation pointing at the local meridian with $0°$ declination.

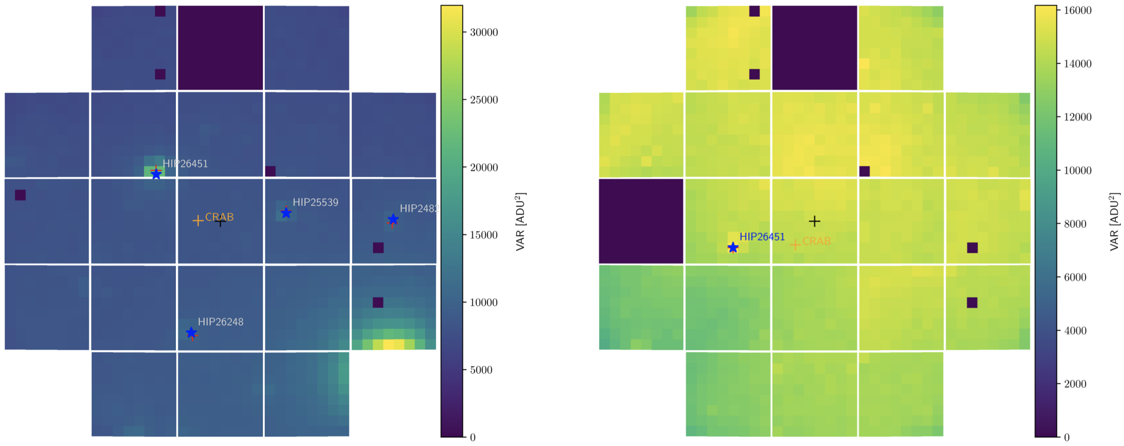

Figure 4: Output of V-STAR with Mars on the edge of the FOV (left) and clouds (right).

post-facto[2], but the precise sky position of the Cherenkov camera (angular resolution $\sim 11'$) can only[3] be computed using Δ_{CAM}.

3. Telescope Pointing

As a baseline, the pointing accuracy of the telescope is constantly monitored using both the signal from motors encoders and the images from the PMC, corrected for the offset of the Cherenkov camera described in section 2. However, a pointing analysis based on VAR data is desirable, as it directly accesses the sky portion actually framed by the Cherenkov camera, independently of any auxiliary device that may introduce systematic errors. For this reason, a custom astrometry software was developed on purpose for the ASTRI project [11]. Its name is V-STAR and it is based on the matching between isolated spots in VAR images and stars expected in the FOV, for a given pointing direction, at a given time (see figure 3).
During the last observing season with ASTRI-Horn, we improved V-STAR implementing several additional features. First, since Mars was in the FOV during a few observations, we implemented the capability to recognize and remove strong light signals due to planets, so that the astrometry can now converge despite wide halos produced by the atmosphere around bright objects (see figure 4, *left*). Second, sometimes it may happen that only a single bright[4] star is visible in the FOV, due to veiled clouds, other obstacles, or poor sky regions. For these circumstances we nevertheless implemented the possibility to calculate the target position using its position angle and the parallactic orientation of the FOV [13], as shown in figure 4, *right*. Third, for observations in wobble mode [14] we implemented the useful possibility to indicate the position of both the tracking coordinates and the target of interest.
In the last ASTRI-Horn observing campaign, V-STAR helped with the reduction and analysis of the Cherenkov data verifying both the pointing accuracy of the telescope and the actual target

[2] In the ASTRI Mini-Array the PMC will be definitely adopted as an auto-guiding camera.
[3] Another method, with lower precision, is the star field astrometry of VAR images described in section 3.
[4] The magnitude limit is 5.5 in this version of the software.

position within the camera during the observations. Specific criteria were adopted to determine if the V-STAR output is reliable in a certain VAR frame. For example, we usually consider the evolution in time of the number of matched stars and the level of the sky background, as reported in figure 5, *left*. When there are no clouds in the FOV the background level is lower and the number of stars is higher, increasing the precision of results. On average, V-STAR presents only a modest angular precision (1′) due to the large pixel size of the Cherenkov camera. However, it is sufficient to detect pointing offsets due to coarse errors. An example is reported in figure 5 right, where V-STAR detected an average pointing offset of 4.0′, with an error of 0.6′.

4. PSF monitoring

VAR images offer a unique opportunity to monitor the shape and the size of the focal spot actually recorded by SiPM sensors, in real time, even during scientific observations. In the assembly integration test and verification phase, the optical system is calibrated using a dedicated optical camera (pixel size ∼1.1″) mounted in place of the Cherenkov instrument [15]. An image of the star Polaris recorded by that camera is reported in figure 6 *left*, after the optimization of the system before the observing session in winter 2022-2023. However, during regular data taking, the star light is integrated over the large pixels of the Cherenkov camera and hence in VAR images the focal spot is very poorly sampled. This effect is visible in the image of Polaris reported in figure 6 *right*. Nevertheless, despite the coarse angular resolution VAR images still allow us to check if the current status of the PSF is compatible with requirements, using the following numerical approach.
First, a certain light distribution is guessed (e.g. a 2D Gaussian, or the real profile recorded by the optical camera) and it is integrated over the camera pixels, resulting in a particular illumination pattern. Afterwards, the distribution parameters (e.g. center and width) are optimized with a fit algorithm in order to reproduce the light spot actually recorded in VAR images. Lastly, this procedure is replicated in several frames containing the same star, and the statistical dispersion of

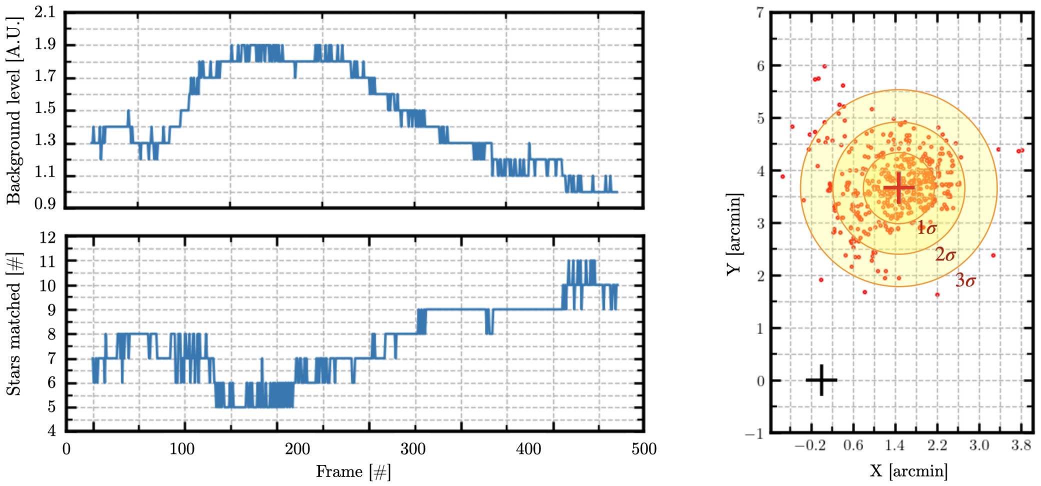

Figure 5: *Left*. When the background light in the FOV decreases the number of cross-catalog matched stars grows. *Right*. The target position in camera coordinates in every VAR frame (red dots) indicates that *on average* (red cross) it is 4′ distant from the camera center (black cross).

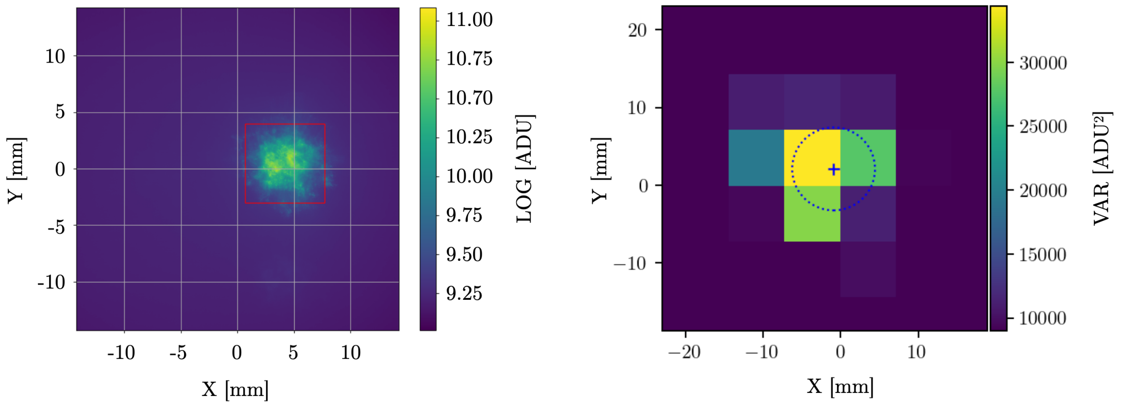

Figure 6: The light spot of Polaris recorded by the optical camera during the calibration of ASTRI-Horn (*left*) and by the VAR during regular data taking (*right*). The red square is the size of the SiPM, reported for comparison. The blue circle is the the 1.28σ (i.e. 80 %) contour of the best Gaussian fit.

results is considered for evaluating the definitive parameters.
The name of the routine for the spot analysis just described is V-PSF and it allows us to monitor the imaging properties of the optical systems at any time. Thanks to V-PSF if a mirror segment is tilted by the wind, or broken by the hail, we are able to start immediately further analysis. In fact, also environmental factors (e.g. humidity) may determine an enlargement of the focal spot, as it is shown in figure 7. With the help of auxiliary instruments (weather station, sky quality meter, all-sky camera, and others) we can evaluate whether a maintenance operation is necessary or not.

5. Conclusion

In this work we presented the progresses in the calibration routines that we developed for the ASTRI project, regarding the pointing and the PSF monitoring, together with preliminary results obtained

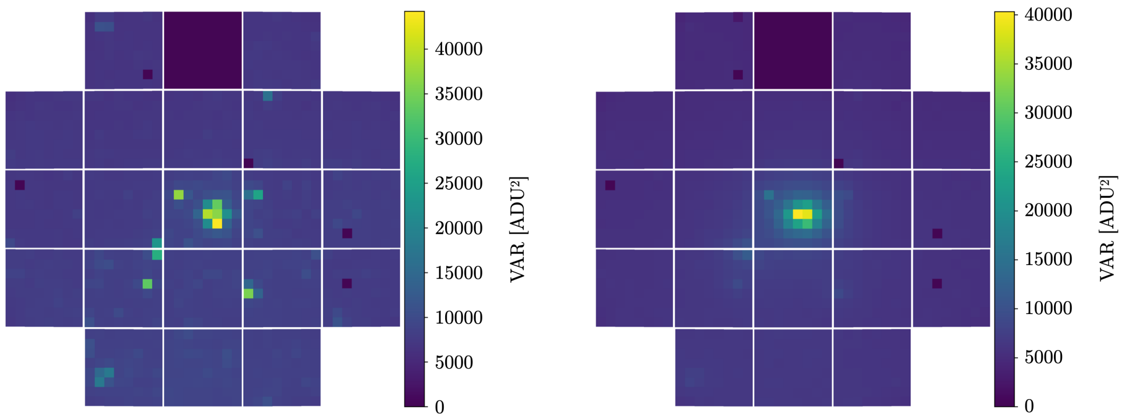

Figure 7: The same stellar field (Vega region) recorded with 75 % humidity (*left*) and 97 % (*right*). In this case, the broadening of the star spots is caused by atmospheric conditions and not by the deterioration of the telescope optical system.

applying these techniques to new data acquired during the last observing campaign of the prototype instrument ASTRI-Horn. The outputs of our analyses are encouraging and they offer the possibility to solve some technical issues like the characterization of the camera alignment to the optical axis, and enhance the accuracy of the whole system. In the next months these methods will be applied also to the incoming ASTRI Mini-Array and possibly also to the Small Sized Telescopes (SSTs) of the future Cherenkov Telescope Array Observatory (CTAO), with adequate modifications.

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