PROCEEDINGS OF SCIENCE

Pointing accuracy of the ASTRI Mini-Array: measurement and monitoring

Simone Iovenitti,[a,*] Stefano Germani[b] and Gino Tosti[b] for the ASTRI project[c]

[a] *INAF - Osservatorio astronomico di Brera, via E. Bianchi 46, 23807, Merate, Italy.*

[b] *Università degli Studi di Perugia, via A. Pascoli snc, 06123, Perugia, Italy.*

[c] http://www.astri.inaf.it/en/library/

E-mail: simone.iovenitti@inaf.it

ASTRI is an international project led by the Italian National Institute for Astrophysics (INAF) aimed at the construction and operation of an array of nine Imaging Atmospheric Cherenkov Telescopes (ASTRI Mini-Array) at the Observatorio del Teide in Tenerife. The primary goal of the project is to study gamma-ray astrophysical sources in the very high-energy domain, particularly at multi-TeV energies. The first telescope of the array, ASTRI-1, is now fully operational, with its commissioning phase initiated in 2024. The ASTRI camera, mounted at the focal plane, is designed to detect the very fast Cherenkov flashes produced by the incoming cosmic radiation. However, the camera is endowed with a secondary output, the so-called Variance mode, providing low-resolution images of the night sky background. Variance data are adopted for the monitoring of the pointing, using astrometry techniques and the stars in the field of view. However, due to the large pixel size of the Cherenkov camera, only a modest precision is achieved. To complement the variance technique with higher resolution images, a Pointing Monitoring Camera (PMC) is installed on the back of the secondary mirror of each telescope. The PMC system acquires images of the sky with a machine vision camera in the direction pointed by the telescopes and performs an astrometry check on a dedicated computer hosted in the telescope electronics cabinet. The astrometry results are forwarded to the Telescope Control System to be used as input for the telescope autoguide. This solution ensures a higher precision, but to ensure the accuracy of the pointing of the Cherenkov camera it is crucial to characterize the offset between PMC and Variance data.

This contribution will describe the systems (Variance and PMC) used to monitor and control the pointing of the telescope, together with the relative alignment characterization of these two systems. Moreover, an overview of preliminary performances resulting from the ASTRI-1 commissioning activities in terms of pointing and tracking precision will be shown.

39th International Cosmic Ray Conference (ICRC2025)
15–24 July 2025
Geneva, Switzerland

*Speaker

PoS(ICRC2025)695

Figure 1: The ASTRI-1 telescope at the Observatorio del Teide (Tenerife, Spain).

1. Introduction

The project ASTRI (acronym of *Astrofisica con Specchi a Tecnologia Replicante Italiana* [1]) is an Italian initiative led by INAF (Istituto Nazionale di Astrofisica) aimed at studying cosmic gamma-ray sources up to 300 TeV and beyond, thanks to the realization of a new type of Imaging Atmospheric Cherenkov Telescope (IACT). In fact, the ASTRI telescopes present a long series of technological novelties. First of all, they implement a modified Schwarschild-Couder optical design, with a segmented primary mirror of 4.3 m and a monolithic secondary of 1.8 m. This solution provides ASTRI with a large aplanatic Field of View (FOV) of almost 11° and a quasi-flat response of the Point Spread Function (PSF) in terms of size. Second, ASTRI is the first IACT equipped with a Cherenkov camera based on Silicon Photo-Multipliers (SiPM) sensors, arranged in 37 tiles of 64 pixels, each with a sky-projected angular size of 11'. The validation of such a system was carried out successfully in 2019, with the detection of the Crab nebula with the prototype instrument ASTRI-Horn [2], installed in Italy. In the following years, a more ambitious project has been carried on, the realization of 9 identical ASTRI telescopes to be installed at the Observatorio del Teide (Tenerife, Spain), the Mini-Array [3]. At the moment, the first telescope (ASTRI-1, shown in figure 1) has already finished its commissioning phase, while the other instruments are under construction or at their Assembly Integration Verification (AIV) on site. Several calibrations and system characterizations have been carried out on ASTRI-1 during its commissioning. In particular, we studied the precision and the accuracy of the pointing performances, that represent a challenge for ASTRI (and IACTs in general), as explained below.

2. The challenge of pointing calibration

Cherenkov telescopes are peculiar instruments. They typically present a large pixel size (few arcminutes) but they need to meet pointing requirements of only tens of arcseconds. For this reason, in general, the scientific camera at the focal point of the telescope is not adequate for pointing calibration, as it is designed for imaging wide Cherenkov flashes and not for achieving a fine angular resolution. Furthermore, the camera electronics is optimized to filter steady or slow-

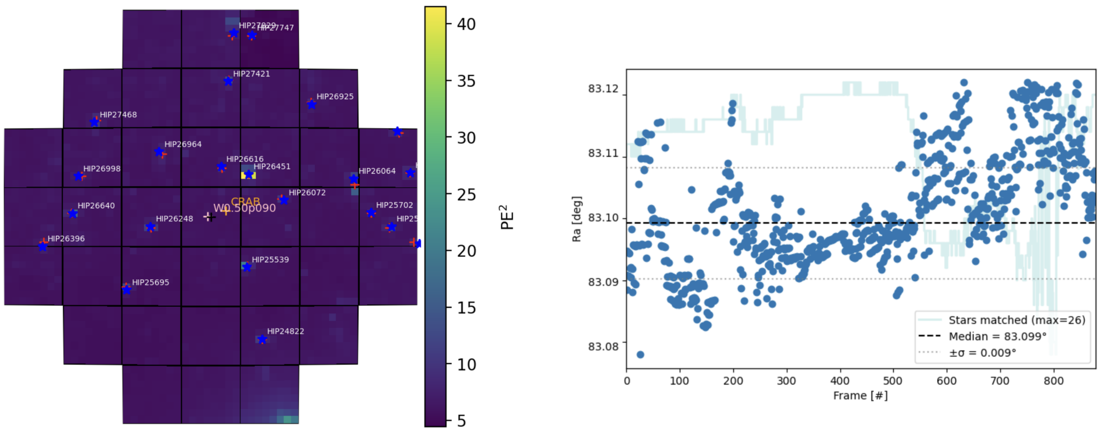

Figure 2: A typical VAR image processed with our custom astrometry software V-STAR (*left*). Time evolution of VAR astrometry in a typical observing run in tracking mode (*right*).

varying signals (the so-called Night Sky Background, NSB), resulting in a telescope that is able to catch nanosecond atmospheric flashes, but is almost blind to starlight. Fortunately, in our case, the ASTRI Cherenkov camera is endowed with an ancillary output producing images of the NSB, the Variance data (VAR, [4]). They represent a goldmine for monitoring and calibration purposes, as they are our unique chance to inspect the FOV of the instrument. However, their resolution is coarse, as large as the pixel size (which is tailored to match the Point Spread Function PSF of the optical system), as it is shown in figure 2. For this reason, every ASTRI telescope hosts a Pointing Monitoring Camera (PMC) [5], an auxiliary device mounted on the back of the secondary mirror. The PMC pixel scale is about 6.5 arcsec with a field of view of about 5.6×3.7 deg; several tests in different conditions have shown that the astrometry of the PMC images (Figure 3 *left*), based on the *Astrometry.net* library [6], can be performed with an angular resolution better than one arcsec. The PMC is used for the pointing model of the telescope after a fine characterization of the offset between its pointing direction and the optical axis of the telescope. This ensures a very high pointing *precision* during scientific observations. Using the PMC feedback to guide the telescope tracking (Autoguide), a sky position can be pointed with a resolution of a few arcseconds as shown in Figure 3 (right). However, a potential systematic error could arise from a possible offset between the PMC and the Cherenkov camera, worsening the *accuracy* of the whole system. In fact, the PMC has a different optical system with respect to the ASTRI camera, and hence a fine characterization of their arrangement is mandatory. To this end, a dedicated technique based on the stars' sidereal motion around the North Celestial Pole (NCP) has already been developed and implemented [7]. However, as described below, astrometry data are regularly taken during standard scientific data taking, both with VAR and PMC. Is it possible to obtain a good cross-characterization of the two instruments using data from regular observations as well? To answer this, we studied in detail the astrometry of the two imaging systems, using specific techniques and the data selection reported below.

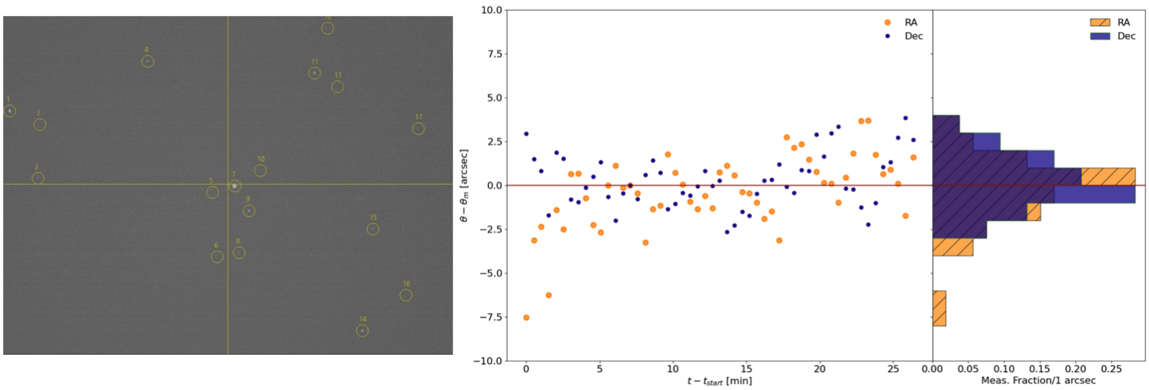

Figure 3: An example of a PMC image with its astrometry (*left*). In a typical observing run the pointing of the telescope in time, measured with the PMC astrometry, is very stable (*right*).

3. Data selection

A typical VAR image is shown in figure 2, *left*. The FOV of 10.8°, the angular resolution 11' and the limit magnitude about 8 mag (V-band). They are acquired automatically in parallel to scientific data at the frequency of about 1 Hz. The astrometry of such images is carried out by V-STAR [8], a custom software developed on purpose for the ASTRI curved focal surface. In good observing conditions, when several stars are visible, the astrometry solution is well constrained, and the sky coordinate of the camera center is calculated with a typical uncertainty of < 2 arcmin on every image.
A typical PMC image is shown in figure 3, *left*. Its control system is equipped with an OPC-UA server, which features a state machine and receives commands from the telescope control system. The astrometry procedure can automatically be applied to the acquired images, providing the sky coordinates of the PMC pointing direction. PMC images are acquired at regular intervals during the observation runs, at a rate of typically 2 or 3 images/minute. Nominal operations foresee the use of a PMC-based auto-guiding tracking system for observations.
During the commissioning of ASTRI-1, several runs in tracking mode were taken in the Crab region, using different wobble pointing directions. Every observing run lasts about half an hour, collecting hundreds of VAR images and tens of PMC images. The full observing campaign covered a wide range of azimuth and elevation angles[1]. Moreover, to allow the standard Cherenkov data reduction, several hours "off-target" were also acquired, with the telescope pointing a fixed alt-az direction, in staring mode. Following the criteria of the ASTRI Data Quality-Check pipeline [9], we made a selection of the data available for the present study. In particular, we considered a data set composed of 35 scientific observing runs (22 tracking the Crab Nebula, with different wobble angles, and 13 in alt-az fixed mode), for a total of ~11 hours. On these runs we carried out our analysis, as explained below.

[1] In that season, the Crab culminates at more than 80 degrees.

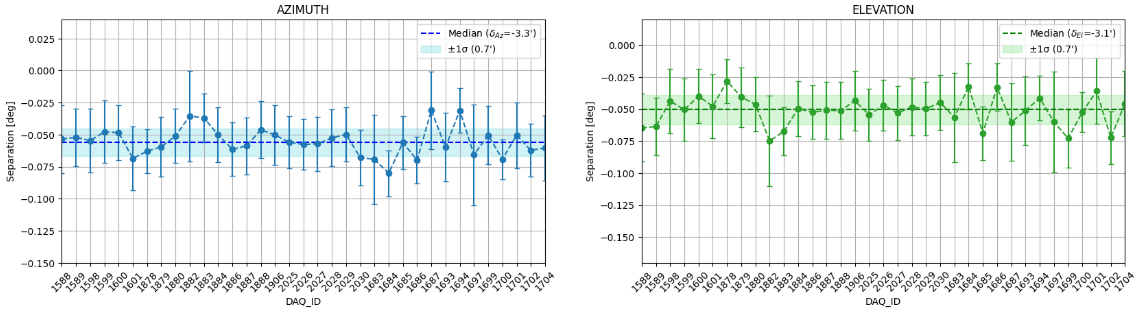

Figure 4: Astrometry derived PMC-VAR angular separation in Azimuth (*left*) and Elevation (*right*) for different acquisition runs. The height of the plots in the y direction corresponds to the size of 1 pixel of the ASTRI Cherenkov camera (11')

4. Analysis

In our analysis we assume that, at first approximation, the angular offset between the PMC and the Cherenkov camera is constant and independent of the pointing direction of the telescope. Any second order effect related to the telescope elevation angle, resulting for example from mechanical flexures, is not considered in the present study.

For every observing run selected, we considered the median value of astrometric positions from both VAR and PMC, converted to the horizontal coordinate system. In fact, astrometry routines provide results in the equatorial system (Ra-Dec), but the ASTRI mount is Alt-Azimuthal, hence the eventual offset between the cameras will be easily detectable in the horizontal frame[2].

The analysis is carried out separately for the Azimuth and the Altitude coordinate, and checked independently with the PMC and VAR reduction software environment. The separation $S = C_{PMC} - C_{VAR}$ between the coordinates center of PMC and VAR is shown in figure 4. In both cases (Alt and Az) the offset is remarkably constant, given the measurements uncertainty, due to VAR coarse resolution. It is important to notice that the range of the plots in the y axis corresponds to the size of the Cherenkov camera pixel (11'). Therefore, the measured reported here is highly sub-pixel. Combining all the data, our final measurement of the separation S between the Cherenkov camera and the PMC is:

$$\begin{aligned} S_{Az} &= (-3.1 \pm 0.6)', \\ S_{El} &= (-3.3 \pm 0.7)'. \end{aligned} \tag{1}$$

5. Conclusion and outlook

In this contribution, we presented a study to characterize the angular offset between the ASTRI Cherenkov camera and the Pointing Monitoring Camera used for the telescope auto-guide during tracking observations. The separation that we measured is $S_{Az} = (-3.1 \pm 0.6)'$ and $S_{El} = (-3.3 \pm 0.7)'$. The PMC astrometry resolution is very high, of the order of a few arcseconds. However, due to the large pixel size of the Cherenkov camera, the astrometry at the ASTRI focal plane with VAR images has a lower precision, of the order of 1 arcminute. Despite this, VAR astrometry has

[2] The bottom of the cameras is always parallel to the ground.

a good accuracy level (it uses the same detectors as scientific data). Therefore, considering both the systems as we did above, it is possible to combine the precision of the PMC with the accuracy of the VAR, improving the quality of the total telescope pointing reconstruction offline, which is crucial for Cherenkov data reduction. The analysis presented here is carried out using only data from regular observing activity, without dedicating a time-slot to the cross-calibration of PMC and VAR, as other methods (more precise) require. The study presented here concerns the ASTRI-1 telescope but will be performed for all the telescopes of the ASTRI Mini-Array.

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/. The Ministero dell'Istruzione dell'Università e della Ricerca (MUR) is acknowledged for financial support through the program "Dipartimenti di Eccellenza 2018-2022" (Grant SUPER-C). This paper went through the internal ASTRI review process.

References

[1] A. Giuliani et al., *Status of the astri program: technology and science with wide-field aplanatic iact telescopes*, vol. Proc. 38th ICRC, Nagoya, Japan, PoS(ICRC2023)892, 2023.

[2] S. Lombardi et al., *First detection of the Crab Nebula at TeV energies with a Cherenkov telescope in a dual-mirror Schwarzschild-Couder configuration: the ASTRI-Horn telescope*, *AA* **634** (2020) A22.

[3] S. Scuderi, A. Giuliani, G. Pareschi, G. Tosti, O. Catalano, E. Amato et al., *The astri mini-array of cherenkov telescopes at the observatorio del teide*, *Journal of High Energy Astrophysics* **35** (2022) 52.

[4] A. Segreto, O. Catalano, M.C. Maccarone, T. Mineo, A. La Barbera and ASTRI Project, *Calibration and monitoring of the ASTRI-Horn telescope by using the night-sky background measured by the photon-statistics "variance" method*, in *Proceeding of Science*, vol. 36, p. 791, SISSA Medialab, July, 2019, http://adsabs.harvard.edu/abs/2019ICRC...36..791S.

[5] S. Germani et al., *The pointing monitoring camera hardware and software systems for the astri mini-array project*, vol. Proceedings Volume 12188, Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation V; SPIE Astronomical Telescopes + Instrumentation, Montréal, Québec, Canada, 2022.

[6] D. Lang, D.W. Hogg, K. Mierle, M. Blanton and S. Roweis, *Astrometry.net: Blind astrometric calibration of arbitrary astronomical images*, **137** (2010) 1782.

[7] S. Iovenitti, G. Sironi, E. Giro, A. Segreto, O. Catalano and M. Capalbi, *Assessment of the Cherenkov camera alignment through Variance images for the ASTRI telescope*, *Experimental Astronomy* **53** (2021) 117.

[8] S. Iovenitti, G. Sironi, T. Mineo, M. Capalbi, O. Catalano, S. Lombardi et al., *New pointing calibration technique using star signals in the ASTRI Cherenkov camera and the Variance method*, in *Observatory Operations: Strategies, Processes, and Systems IX*, C.R. Benn, R.L. Seaman and D.S. Adler, eds., (Montréal, Canada), p. 32, SPIE, Aug., 2022, DOI.

[9] E. Molina et al., *To cut or not to cut: data-quality evaluation for the astri mini-array*, vol. Proc. 39th ICRC, Geneva, Switzerland, PoS(ICRC2025), 2025.