

Using muon rings for the optical calibration of ASTRI-1 telescope: preliminary results

Teresa Mineo,^{a,*} Davide Mollica,^a Antonio Alessio Compagnino,^a Gloria Maria Cicciari,^b Ciro Bigongiari^{c,d} and Francesco Gabriele Saturni^c for the ASTRI Project

^aINAF - IASF Palermo, via U. La Malfa 153, 90146 Palermo, Italy

^bDipartimento di Fisica, Università di Palermo, via Archirafi 36, Palermo, Italy

^cINAF - OA Roma, Via Frascati 33, I-00078 Monte Porzio Catone (Roma), Italy

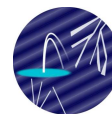
^dASI - Space Science Data Center, Via del Politecnico s.n.c., I-00133 Roma, Italy

E-mail: teresa.mineo@inaf.it, davide.mollica@inaf.it

The ASTRI Mini-Array, an array of nine innovative Imaging Atmospheric Cherenkov Telescopes, is an INAF project devoted to the study of gamma-ray sources emitting at very high-energy in the TeV spectral range. It is situated at the Teide Astronomical Observatory, Instituto de Astrofísica de Canarias, on Mount Teide in Tenerife (Canary Islands, Spain), where the first telescope, named ASTRI-1, is already operational since mid-2024. The analysis of muon ring images, which are observed by almost any Imaging Atmospheric Cherenkov Telescope during standard data-taking, is a standard method used to calibrate optical throughput and monitor the optical point spread function. This method has also been adopted in the ASTRI Mini-Array calibration plan as one of the techniques for calibrating these parameters.

In this contribution, we present preliminary results from the analysis performed to identify muon candidates and the reconstruction procedures applied using the AmuSoft code, one of the calibration software tools developed for the ASTRI Mini-Array telescopes, on data collected by ASTRI-1 during its commissioning while observing the Crab Nebula.

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



ICRC 2025

The Astroparticle Physics Conference
Geneva July 15-24, 2025

*Speaker

1. Introduction

The ASTRI Mini-Array [1] marks a major step forward in very high-energy (VHE) gamma-ray astronomy, particularly at energies up to and beyond 100 TeV. Developed by the Italian National Institute for Astrophysics (INAF), this array of atmospheric Cherenkov imaging telescopes (IACTs) is currently being installed at the Teide Astronomical Observatory, Instituto de Astrofísica de Canarias, on Mount Teide in Tenerife (Canary Islands, Spain). The first telescope in the array, ASTRI-1, has been operational since mid-2024, a second unit, ASTRI-3, is going to start its commissioning phase (see Figure 1) and five more telescopes of the array are under deployment. Composed of nine dual-mirror telescopes, the ASTRI Mini-Array is optimized for wide-field observations ($\sim 10^\circ$ field of view) and is expected to significantly enhance our understanding of the most energetic processes in the universe. Its scientific objectives include probing the origin of cosmic rays, studying extragalactic background light, investigating gamma-ray bursts and multi-messenger transients, and exploring fundamental physics at extreme energies [2].

Calibration of each telescope in the array is essential to ensure accurate and reliable scientific results. Muon rings offer a robust and well established technique for calibrating imaging atmospheric Cherenkov telescopes (IACTs), and they are one of the calibration methods planned for ASTRI Mini-Array [3]. Since muons are produced naturally and frequently during regular observations, their use enables continuous calibration without interrupting science operations.

High-energy cosmic rays interacting with the Earth's atmosphere generate extensive air showers that include muons. As these muons travel through the atmosphere at speeds exceeding the phase velocity of light in the medium, they induce Cherenkov radiation. When muons pass near the telescope and travel nearly parallel to its optical axis, they can produce distinctive ring-shaped images on the camera, which are used for calibration purposes.

The geometrical parameters of the muon ring and the distribution of light along it enable a complete reconstruction of the geometrical and physical properties of the incident muon. The center of the ring provides the muon arrival direction, while the ring radius corresponds to the Cherenkov angle from which the muon energy can be determined, given the refractive index of the atmosphere. The ring width is primarily influenced by the telescope's optical point spread function (PSF), as the divergence of Cherenkov photons is negligible compared to optical aberrations. This makes the ring width a direct diagnostic of the telescope's optical alignment and an effective tool for monitoring eventual degradation in optical PSF. Moreover, by fitting the observed light intensity distribution along the muon ring with an appropriate model, it is possible to evaluate the overall telescope efficiency (optical throughput) [4]. In the case of ASTRI-1, this includes the reflectivity of both the primary and secondary mirrors, the transmission of the protective window located in front of the camera, and the photon detection efficiency of the SiPMs detectors.

In this paper, we present an analysis of muon events recorded by ASTRI-1 during two nights of observations of the Crab Nebula, carried out during the commissioning phase. These nights were selected to investigate potential variations in detection efficiency, as the observed shower rates differ by approximately 10%, despite nearly identical weather conditions.

2. ASTRI-1

ASTRI-1 is the first telescope installed on Mount Teide in Tenerife of the ASTRI Mini-Array. After the calibration of its optics and sensors, it completed its commissioning phase with an extensive observing campaign on the Crab Nebula. Data collected during this period have been used to extract the source spectrum up to ~ 10 TeV [5].



Figure 1: ASTRI-1 and ASTRI-3: the first two telescope of the ASTRI Mini-Array installed on Mount Teide in Tenerife (Canary Islands, Spain).

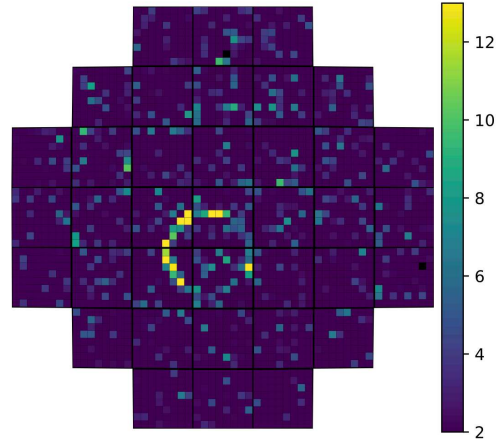


Figure 2: Example of muon ring observed on January 21, 2025 and identified with the selection procedure implemented in *A-MuSoft*

The telescope design is based on the ASTRI-Horn one [6], the ASTRI prototype installed at Serra La Nave (Etna, Sicily). However, unlike ASTRI-Horn, the ASTRI-1 camera has the capability to record not only the signal intensity but also the pixel trigger time, the time at which a pixel exceeds a predefined threshold, recorded only when this condition is met. This new feature significantly improves the identification of muon events compared to ASTRI-Horn, where a dedicated and more complicated selection procedure was implemented to identify muons. That earlier method was used in 2018 to measure the telescope efficiency before a substantial degradation in mirror reflectivity caused by an eruption of Mount Etna [7].

ASTRI-1 telescope was calibrated to meet its design requirements: the on-axis optical point spread function (PSF) contains 80% of the light within a single pixel (0.19°); the gain variation across the entire focal plane is approximately 4%, and the average optical cross-talk is lower than 5% [8]. These calibration results confirm the optical quality and uniform detector response of ASTRI-1 essential for accurate muon image reconstruction. Moreover, maintaining tight control over gain and optical cross-talk is particularly important for minimizing systematic uncertainties in the reconstruction of muon events.

3. Data Reduction and analysis

During its commissioning phase, ASTRI-1 observed the Crab Nebula from September 2024 to March 2025. For the majority of this period, the maximum shower rate, evaluated from cleaned

events, remained stable under consistent weather conditions. However, beginning on January 24, 2025, an increase of approximately 10% in the shower rate was observed (see Fig. 1 in [5]).

To investigate whether this variation could be attributed to a change in the telescope efficiency, two nights were selected for detailed muon analysis: January 21 and January 28, just before and after the observed increase in the rate. Since both nights experienced similar weather conditions (average temperature $\sim 3^\circ$ and humidity $\sim 50\%$ on January 21; average temperature $\sim 8^\circ$ and humidity $\sim 10\%$ on January 28), atmospheric variability can be ruled out as the cause of the change in shower rate.

The data for the two selected nights, as listed in Table 1 along with the corresponding exposure times, were retrieved from AMAS¹, the ASTRI Mini-Array archive. Data reduction and calibration were carried out using *A-SciSoft*, the ASTRI official scientific data reduction and analysis software package [9]. The coefficients used to convert signal amplitude into photo-electron (pe) units were derived from dedicated calibration runs [8].

Muon candidate identification within the background of proton-induced events, as well as their reconstruction, was performed using the *A-MuSoft* code [10]. This tool outputs a list of candidate muon events along with their reconstructed parameters (ring center and radius, ring width, distance of the muon impact point from the primary mirror center and telescope efficiency).

The method used to identify muon candidates relies on the duration of the recorded events. Cherenkov photons produced by muons impacting the primary mirror typically exhibit a time spread lower than ten nanoseconds. In contrast, events with significantly longer durations are generally associated with extensive air showers. This temporal characteristic provides an effective criterion for distinguishing muon-induced events from shower events. *A-MuSoft* selects only the pixels in the image triggered by exceeding the set signal threshold and computes the time difference between the first and last triggered pixels. The time window used to classify muon candidates considers both the intrinsic duration of the event and the delays introduced by the readout electronics chain.

Using simulated muon events, we estimated that the applied criterion includes approximately 70% of the events. Figure 2 shows an example of a muon candidate identified using this method.

Table 1: The table shows the date and exposure of the data considered in the analysis, together with the rate of the "good muons" and the values of the average and σ of the efficiency and ring width distributions accumulated along the whole observation night.

| Date | Exposure | Muon rate | Efficiency | | Ring Width | |
|--------------|----------|-------------------|----------------|---------------|-------------------|-------------------|
| | | | Average | σ | Average | σ |
| (yyyy/mm/dd) | (h) | (μ/s) | (%) | (%) | (deg) | (deg) |
| 2025/01/21 | 4.3 | 0.036 \pm 0.001 | 11.3 \pm 0.1 | 1.2 \pm 0.1 | 0.071 \pm 0.001 | 0.019 \pm 0.001 |
| 2025/01/28 | 6.3 | 0.029 \pm 0.001 | 11.9 \pm 0.1 | 1.3 \pm 0.1 | 0.069 \pm 0.001 | 0.018 \pm 0.001 |

A small subset of the muon candidates (approximately 10%), referred to as "good muons," was selected to evaluate the ASTRI-1 telescope's efficiency and to measure the ring width. The selection criteria were based on three conditions: (i) the quality of the fit used to reconstruct the muon ring parameters, requiring a reduced chi-squared value of $\chi_{red}^2 < 3$; (ii) the spatial location of the ring on the focal plane, with only fully contained rings being accepted; and (iii) the muon

¹<https://amas.oa-roma.inaf.it/>

impact point, which was required to lie between the primary and secondary mirrors. The rate of selected “good muons” is reported in Table 1.

For each observing run, a histogram of the “good muon” efficiency was generated and fitted with a Gaussian function. The mean of the Gaussian was taken as the average efficiency for the run, while the σ represents the spread of efficiency values within that run. An identical procedure was applied to determine the average and σ of the muon ring width.

Furthermore, by combining data from all runs within a single observation night, nightly histograms were produced. These were similarly analyzed to compute the average values and the σ for each night.

4. Results

The average and σ of the efficiency and ring width distributions for the two selected nights, derived from the analysis described in the previous section, are summarized in Table 1. In addition, Fig.3 and Fig.4 present the run-by-run values of efficiency and ring width, respectively, plotted as a function of the proton rate. These proton rates were computed after applying the standard image cleaning procedure as detailed in [5].

Figure 3 shows that the efficiency measured in each run remains stable throughout the night for both data sets. However, a clear difference is observed between the two nights: the telescope efficiency significantly varies from one night to the other. The ratio of the average efficiency values indicates a difference of approximately $5.3\% \pm 1.2\%$

In contrast, the ring width shows no significant variation either within each night or between the two nights, as illustrated in Fig. 4. In this case, the average value computed across both nights is 0.070 ± 0.001 deg, and it is indicated by a continuous horizontal line in the figure.

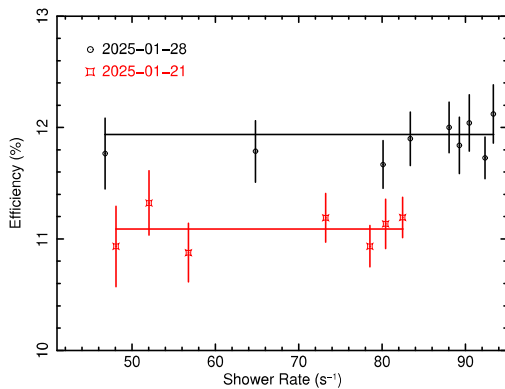


Figure 3: Efficiency measured in each run as function of the shower rate. Black circles are relative to January 21, while red squares to January 28. The continuous line is the average efficiency of the night.

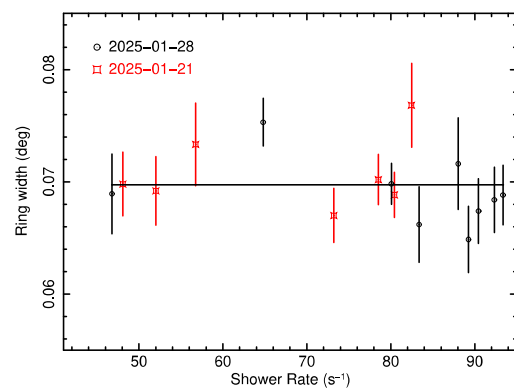


Figure 4: Ring width measured in each run as function of the shower rate. Black circles are relative to January 21, while red squares to January 28. The continuous line is the average value of the ring width of the two nights.

5. Conclusion

We presented the results of the muon analysis on two nights of the Crab observation campaign performed during ASTRI-1 commissioning. The two data sets were selected to investigate the increase in the maximum rate observed after January 24, 2025. Our analysis shows that the telescope efficiency actually increased by $\sim 5\%$ compatible with an increase of $\sim 10\%$ in the rate. This increase on the telescope efficiency could be due to some rain in the days before January 24, 2025 that could have cleaned the primary mirror from dust. The analysis of the full data set from the entire observation campaign will serve to consolidate these results and provide a more comprehensive assessment of the variability in the telescope's efficiency. This extended analysis will also improve the statistical significance of the current findings and help to identify any long-term trends or systematic effects in the instrument's performance. Additionally, it will allow for cross-checks with other calibration methods, contributing to the overall robustness of the ASTRI Mini-Array calibration strategy. Such insights are essential to ensure the long-term stability and scientific reliability of the array, particularly as more telescopes are deployed and operational. Moreover, this analysis also serves as a valuable test case, demonstrating the effectiveness of muon-based calibration for the CTA Small-Sized Telescopes (SSTs), for which ASTRI-1 can be considered a strong precursor. The results presented here highlight the potential of this technique to monitor and maintain the optical and detection performance of SST-class instruments under real observing conditions.

Acknowledgments

This work was conducted in the context of the ASTRI Project (<http://www.astri.inaf.it/en/library/>). This paper went through the internal ASTRI review process.

References

- [1] 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.
- [2] S. Vercellone, *The ASTRI Mini-Array Core Science Program*, in *7th Heidelberg International Symposium on High-Energy Gamma-Ray Astronomy*, p. 118, Dec., 2024.
- [3] T. Mineo, M.C. Maccarone, L.A. Antonelli, F. Ambrosino, P.G. Bruno, A. Bulgarelli et al., *Tools and Procedures for the ASTRI Mini-Array Calibration*, in *37th International Cosmic Ray Conference*, p. 197, Mar., 2022, DOI.
- [4] M. Gaug, S. Fegan, A.M.W. Mitchell, M.C. Maccarone, T. Mineo and A. Okumura, *Using Muon Rings for the Calibration of the Cherenkov Telescope Array: A Systematic Review of the Method and Its Potential Accuracy*, **243** (2019) 11 [1907.04375].
- [5] S. Crestan, S. Lombardi, L. Barrios, C. Bigongiari, A. Bonollo, P. Bruno et al., *ASTRI-1: Early data and Performance*, in *39th International Cosmic Ray Conference*, July, 2025.

- [6] G. Leto, G. Bellasai, C. Bigongiari, B. Biondo, G.E. Bruno, M. Capalbi et al., *Status and performance of the ASTRI-Horn dual mirror air-Cherenkov telescope after a major maintenance and refurbishment intervention*, in *38th International Cosmic Ray Conference*, p. 729, Sept., 2024.
- [7] T. Mineo, M.C. Maccarone, A. Compagnino, M. Capalbi, O. Catalano, G. Contino et al., *Muon calibration of the ASTRI-Horn telescope: preliminary results*, in *36th International Cosmic Ray Conference (ICRC2019)*, vol. 36 of *International Cosmic Ray Conference*, p. 744, July, 2019, DOI [[1907.09197](https://doi.org/10.1017/proc.2019.197)].
- [8] D. Mollica, O. Catalano, G. Contino, M. Capalbi, M. Corpora, F.P. LoGerfo et al., *Calibration of the ASTRI-1 telescope camera*, in *39th International Cosmic Ray Conference*, July, 2025.
- [9] S. Lombardi, L.A. Antonelli, C. Bigongiari, M. Cardillo, E. Fedorova, S. Gallozzi et al., *The Data Processing System of the ASTRI Mini-Array Project*, in *38th International Cosmic Ray Conference*, p. 682, Sept., 2024.
- [10] D. Mollica, S. Iovenitti, T.Mineo, A.A. Compagnino, M. Capalbi, F. Lucarelli et al., *The ASTRI Mini-Array calibration software system*, in *39th International Cosmic Ray Conference*, July, 2025.