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# The ASTRI Mini-Array calibration software system

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The ASTRI Mini-Array is an INAF project aimed to observe astronomical sources emitting at very high-energy in the TeV spectral band. It consists of an array of nine innovative Imaging Atmospheric Cherenkov Telescopes that are an evolution of the double-mirror ASTRI-Horn telescope operating since 2014 at the INAF "M.G. Fracastoro" observing station (Italy). The array is being installed at the Teide Astronomical Observatory, Instituto de Astrofisica de Canarias, Tenerife (Spain). The ASTRI Mini-Array telescopes require several calibration procedures for all subsystems forming the telescopes and for the entire array. These procedures have the final aim to define all quantities necessary to achieve a correct end-to-end processing of the scientific data, as well as to monitor the health of the telescopes. A dedicated software system is needed to perform all the required calibrations: the main inputs are different data acquired by the Cherenkov cameras during the scientific observation runs (the camera $Variance$ channel and Cherenkov muon rings) and during the calibration runs both with the camera internal calibration system and with the Illuminator (an external device to uniformly illuminate the telescopes). The calibration Software can be organised into four major groups depending on the telescope components or calibration elements: Optics Calibration Software, Camera Calibration Software, Pointing Calibration Software, and Optical Throughput Software. This work presents an overview of the ASTRI Mini-Array calibration software system and the plan to validate some of its parts using ASTRI-Horn data.

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## 1. Introduction

The ASTRI Mini-Array [1] is an INAF project aimed to observe astronomical sources emitting at very high-energy in the TeV spectral band. It consists of an array of nine innovative Imaging Atmospheric Cherenkov Telescopes (IACT), that are an evolution of the double-mirror ASTRI-Horn telescope [2] successfully tested since 2014 and operating at the INAF "M.G. Fracastoro" observing station (Serra La Nave, Mount Etna, Italy). The array is being installed at the Teide Astronomical Observatory, Instituto de Astrofisica de Canarias (IAC), on Mount Teide (~2400 m a.s.l.) in Tenerife (Canary Islands, Spain). It will be operated by INAF on the basis of a host agreement with IAC. ASTRI Mini-Array will observe very high-energy (E > 1 TeV) sources with a sensitivity at energies greater than a few TeV better than that reachable by the other IACTs currently in operation [3]. Furthermore, the ASTRI Mini-Array will perform intensity interferometry of a selected sample of bright sources, and, for this purpose, each telescope will be equipped with a Stellar Intensity Interferometer Instrument [4].

The optics, both of ASTRI-Horn and of ASTRI Mini-Array telecopes, is characterized by a dual-mirror design in a Schwarzschild-Couder configuration with a 4.3 m diameter segmented primary mirror, and a monolithic 1.8 m diameter secondary mirror. It focuses on the ASTRICAM Silicon photomultiplier Cherenkov camera, organized in Photon Detection Modules (PDMs), that presents two innovative solutions: i) the signal acquisition is based on a peak-detector technique, and ii) and the variance of each pixel is continuously computed at the not occurrence of PDM triggers with the $Variance$ procedure[1] [5–7]. The ASTRI Mini-Array camera is the upgraded version of the one mounted on ASTRI-Horn [5].

The ASTRI Mini-Array telescopes require several calibration procedures both for all subsystems forming the telescopes (mount, optical system, Cherenkov camera) and for the entire array. These procedures have the final aim to define all the quantities necessary to achieve a correct reduction, processing and analysis of the scientific data of Cherenkov telescopes, as well as the monitor of the health of the telescopes and of their sub-systems. The design of an overall calibration strategy is a broad band activity, which requires interaction between the hardware teams of the different telescope components and the groups involved in atmospheric monitoring, array control, data analysis and Monte Carlo simulations [8].

The concept of the software produced for the single telescope calibration is presented in the following sections, while the one relative to the array is referred to a following paper.

## 2. ASTRI Mini-Array calibration of single telescopes

The ASTRI Mini-Array calibration plan foresees, as a first step, the calibration of each single telescope including the camera calibration, the absolute calibration of the optical throughput[2] and of the pointing precision [8]. The plan is based on procedures that use data from the $Variance$ procedure and from the camera internal calibration system together with muon ring images. $Variance$ data are proportional to the photon flux impinging on the camera pixel [6], and they are acquired by

[1]computed in ADC count as $\frac{\sum ADC^2}{N} - (\frac{\sum ADC}{N})^2$ where $N$ is number of sample

[2]i.e. the average telescope efficiency. It includes the mirror total reflectivity, the filter transparency and the SiPM photon detection efficiency.



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**Figure 1:** ASTRI-1 the first ASTRI Mini-Array telescope under installation on Mount Teide in Tenerife (Canary Islands, Spain).

**Figure 2:** ASTRI-Horn telescope installed on Mt.Etna (Italy) at the INAF "M.G. Fracastoro" observing station.

each Cherenkov camera together with scientific data. They can be used to measure the level of the night sky background (NSB) indirectly and to monitor the presence of stars in the telescope field of view (FoV) allowing to measure with high accuracy, the effective pointing of the telescope [9]. Moreover, with $Variance$ data it is possible to reveal misalignment among mirror panels and check for any degradation of the optical point spread function (PSF) [9]. They are also used for some hardware calibration procedures of the camera such as the evaluation of the breakdown voltage in each pixel of each PDM or the maximum current that can be supplied to PDMs.

Muon ring images, acquired during normal data taking as part of hadronic air showers, are commonly used for the calibration of Cherenkov telescopes. The total number of photons hitting the mirror, fundamental for the evaluation of the telescope optical throughput, is reconstructed from the geometrical properties of the ring and from the light distribution along it. In addition, the ring width, mainly due to the optics aberrations since the Cherenkov photons have a negligible divergency, allows us to monitor the PSF. The application of this method to small telescopes has been already proved effective with data from the ASTRI-Horn prototype [10].

Besides calibration with $Variance$ data and muon rings images, the ASTRI Mini-Array Cherenkov cameras are also equipped with an internal calibration system based on an optical fiber (FOC) illuminated by blue and green laser diodes (continuously or in pulsed light mode), specific designed to monitor the gain and the pedestal of each pixel. The array calibration system includes also specifically devoted external auxiliary instruments among which the Illuminator [11] designed to measure the actual spectral and temporal response of each ASTRI Mini-Array telescope at any off-axis angle. It is a portable ground-based device that uniformly illuminates the telescope's aperture with a reference photon flux.

Some of the calibration procedures will be replicated with different independent data, tools and auxiliary devices. This redundancy and the possibility of cross-checking among the various outcomes will result in a more precise and consistent evaluation of the calibration coefficients and of their systematics.

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## 3. The ASTRI Mini-Array Calibration Software

The dedicated Calibration Software for the ASTRI Mini-Array is a collection of modules (or tools) that perform the analysis of the relevant data to test their compliance with respect to the nominal calibration values and to evaluate the quantities necessary for analysing scientific data. Its main inputs are data acquired from the telescope during the scientific observation runs (the camera $Variance$ channel and Cherenkov muon rings), and during the calibration runs performed with the Illuminator, together with data acquired by the camera from the FOC. The calibration software can be organized into four major groups as follows:

- *Optics Calibration Software*: it includes all software procedures necessary to reduce and analyse the calibration data acquired for the monitoring of the PSF and of the efficiency of each panel of the primary mirror [9, 10]. For the PSF calibration, both $Variance$ data and muon images are used; the former monitor the PSF using the size of the images produced on the focal plane by stars, the latter considers the width of the rings (see sect. 2).
  The panel efficiency can be obtained from the muon ring analysis, when a sufficient number of events with the impact points in the considered panel is available.

- *Camera Calibration Software*: it includes all software procedures to test the correct functioning of the camera and to provide the parameters necessary for the scientific analysis [12, 13]. This calibration tools uses $Variance$ data as well as data specifically produced for calibration purpose as, for example, the pulse-height distributions used to determine/monitor the gain, the pedestal and the optical cross-talk of each camera pixel. In addition, the list of calibration procedures includes, among the others, the evaluation of the SiPM breakdown voltage, the PDM temperature sensors relative calibration, the trigger channels alignment and the evaluation of the maximum current that can be supplied to the PDMs.

- *Pointing Calibration Software*: it includes all software procedures to monitor the pointing of the telescope and verify the pointing model [9]. This code allows us to constantly monitor the pointing direction of the telescope with respect to the camera geometric center using astrometrical information to identify the stars in the field of view.

- *Optical Throughput Evaluation/Monitoring Software*: it includes all software procedures to evaluate and monitor the telescope optical throughput. In this case, three different types of procedures and software are implemented, each based on a different method: using the Illuminator, using muons rings and using $Variance$ data [6, 10].

All calibration procedures provide some outputs in form of either reports, or fits files or tables. These will contain the results of the analysis and all the necessary intermediate parameters, together with a flag to highlight differences with respect to the expected, nominal values. In case of discrepancy with respect to the nominal values, a human action and decision is always foreseen. Following the same strategy, the archive containing the nominal calibration parameters (CALDB) will not be automatically updated, but any decision on variations is competence of the Calibration Database Manager (see below) after consulting the other figures involved in the calibration.



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### 3.1 Calibration procedure actors

The calibration procedures require the definitions of some figures representing the involved actors; these include humans as well as system components. The main human actors associated with the ASTRI Mini-Array Calibration Software System are:

- *Calibration Manager* that defines the calibrations methods and the instruments needed to calibrate the whole ASTRI Mini-Array system;
- *Instrument Scientist* an instrument expert, capable of diagnosing problems and devising corrective actions based on recorded data. This actor supports operations and maintenance.
- *Data Quality Scientist* responsible for monitoring the quality of pipeline-produced data products and calibrations. Discusses problems with Instrument Scientist, Calibration Manager and, in case, informs the Calibration Database (CALDB) Manager.
- *Calibration Database (CALDB) Manager* responsible for versioning and archiving the Calibration Software data products in the Calibration Database (CALDB).

Along with the human actors, the Calibration Software system interfaces with the ASTRI Mini-Array Supervisory Control and Data Acquisition (SCADA) System [14], which controls all operations carried out during the observations, including the calibration procedures, and the ASTRI Mini-Array Data Processing System [15], which is in charge of the scientific data reduction and analysis, including data calibration.

### 3.2 The Calibration Software and the ASTRI Mini-Array archives

The Calibration Software interfaces with several repositories and databases of the ASTRI Archive System [14] for the input data and for the output calibration parameters. These are listed below:

- *Bulk Archive*: the database that stores the data products of the Cherenkov Camera (raw data and higher-level data up to DL2 [15]);
- *CALDB*: a dedicated calibration database that stores instrumental and precomputed quantities, such as the Instrument Response Functions, needed throughout the entire scientific data reduction chain.
- *Performance Archive*: a dedicated database storing reduced engineering and auxiliary data, used to perform mid-term and long-term performance studies as well as predictive studies.
- *Monitoring Archive*: the archive that stores all the Monitoring Data Model sub-types (e.g. monitor assemblies, environmental data) acquired by the Monitoring System.

Some of the codes will be used by the camera hardware teams to determine the set of parameters needed to optimize its performances for the observation purpose; these parameters will be stored into a dedicated archive (*System Configuration Database*).



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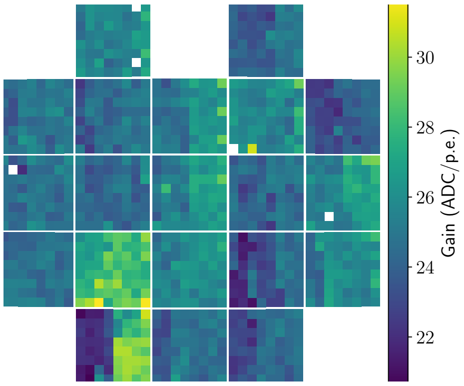


**Figure 3:** Map of the ASTRI-Horn SiPMs gains derived from pulse-height distribution spectra obtained using the internal camera calibration system.

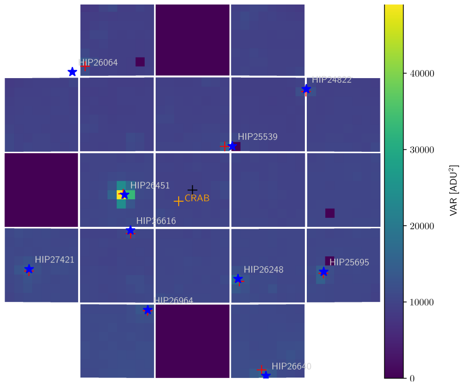


**Figure 4:** *Variance* image relative to a Crab observation with ASTRI-Horn; red crosses represent the reconstructed position of the stars indicated by blue stars.The angular size of a PDM is $1.5^o \times 1.5^o$

## 4. ASTRI-Horn

The ASTRI-Horn experience has been fundamental for the design of the ASTRI Mini-Array telescopes, and it is the test bench for most of the calibration procedures and codes. We report here a few examples of application of the calibration procedures described above.

Fig. 3 shows the map of the gain for all the focal plane pixels computed from the camera calibration procedure that uses the pulse-height distributions obtained from the FOC. A detailed description of the procedure can be found in [12].

A specific calibration procedures to evaluate the flat-field correction coefficients to be applied to *Variance* data has been implemented and fully tested with ASTRI-Horn [13]. This procedure is fundamental for using the *Variance* data in the pointing calibration procedures. The capability of these data to identify the position of stars in the FoV and to gain astrometric information is presented in Fig. 4. This represents one of the *Variance* frame (1.24 s integration time) where the blue stars are the position of the stars, as from the catalogue, while the red crosses identify the reconstructed positions. Whenever it is possible to identify several stars in the FoV, as in the example in Fig. 4, a precision better that $1'$ on the position of the observed source can be achieved. For a detailed description of this calibration tool and results see [9].

Moreover, ASTRI-Horn has been used to test calibrations procedures that use the auxiliary instrument UVscope [16] able to measure the absolute flux of the diffuse night sky background. In particular, it was possible to evaluate the maximum current supplied to the PDMs and the variation of the optical throughput that affected the telescope after one Etna eruption, by comparing *Variance* data with UVscope fluxes [17]. For this procedure, only the method, not the code, can be transferred to ASTRI Mini-Array telescopes being UVscope replaced with an upgraded new version.

## 5. Conclusion

The Calibration Software provides the tools to fulfill the requirements for a successful calibration strategy for the ASTRI Mini-Array telescopes. The effectiveness of these calibration procedures



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and software have been already verified with ASTRI-Horn. This provided a precious test bench for the detailed verification also foreseen for the ASTRI Mini-Array telescopes.

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## 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 [2208.04571].

[2] G. Leto and et al, *Status and performance of the ASTRI-Horn dual mirror air-Cherenkov telescope after a major maintenance and refurbishment intervention*, in *Pro. 38th ICRC, Nagoya, Japan, PoS(ICRC2023)729*, July, 2023.

[3] S. Lombardi, L.A. Antonelli, C. Bigongiari, M. Cardillo, S. Gallozzi, J.G. Green et al., *Performance of the ASTRI Mini-Array at the Observatorio del Teide*, in *37th International Cosmic Ray Conference*, p. 884, Mar., 2022, DOI.

[4] L. Zampieri, G. Bonanno, P. Bruno, C. Gargano, L. Lessio, G. Naletto et al., *A stellar intensity interferometry instrument for the ASTRI Mini-Array telescopes*, in *Optical and Infrared Interferometry and Imaging VIII*, A. Mérand, S. Sallum and J. Sanchez-Bermudez, eds., vol. 12183 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, p. 121830F, Aug., 2022, DOI.

[5] O. Catalano, M. Capalbi, C. Gargano, S. Giarrusso, D. Impiombato, G. La Rosa et al., *The ASTRI camera for the Cherenkov Telescope Array*, vol. 10702 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, p. 1070237, July, 2018, DOI.

[6] A. Segreto, O. Catalano, M.C. Maccarone, T. Mineo, A. La Barbera and F.T. Cta Astri Project, *Calibration and monitoring of the ASTRI-Horn telescope by using the night-sky background measured by the photon-statistics ("variance") method*, in *36th International Cosmic Ray Conference (ICRC2019)*, vol. 36 of *International Cosmic Ray Conference*, p. 791, July, 2019 [1909.08750].

[7] G. Sottile, O. Catalano, G. La Rosa, M. Capalbi, C. Gargano, S. Giarrusso et al., *ASTRI SST-2M camera electronics*, vol. 9906 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, p. 99063D (2016), DOI.

[8] 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.



PoS(ICRC2023)733

[9] S. Iovenitti, S. Lombardi, O. Catalano, G. Leto, G. Sironi, D. Mollica et al., *A new observing season for the ASTRI-Horn Cherenkov telescope: enhanced techniques for pointing calibration, astrometry, and PSF monitoring*, in *Pro. 38th ICRC, Nagoya, Japan, PoS(ICRC2023)836*, July, 2023.

[10] 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 [1907.09197].

[11] A. Segreto, M.C. Maccarone, O. Catalano, B. Biondo, C. Gargano, G. La Rosa et al., *The absolute calibration strategy of the ASTRI SST-2M telescope proposed for the Cherenkov Telescope Array and its external ground-based illumination system*, in *Ground-based and Airborne Telescopes VI*, H.J. Hall, R. Gilmozzi and H.K. Marshall, eds., vol. 9906 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, p. 99063S, July, 2016, DOI.

[12] D. Mollica, O. Catalano, G. Contino, M. Capalbi, M. Corpora, F.P. Lo Gerfo et al., *Calibration strategy of the ASTRI Mini-Array Cherenkov cameras*, in *Proc. 38th ICRC, Nagoya, Japan, PoS(ICRC2023)765*, July, 2023.

[13] G. Contino, O. Catalano, D. Mollica, B. Biondo, M. Capalbi, M. Corpora et al., *Flat-field calibration procedure of the ASTRI Mini-Array Cherenkov cameras using night sky background observations*, in *Proc. 38th ICRC, Nagoya, Japan, PoS(ICRC2023)739*, July, 2023.

[14] A. Bulgarelli, F. Lucarelli, G. Tosti, V. Conforti, N. Parmiggiani, J.H. Schwarz et al., *The Software Architecture and development approach for the ASTRI Mini-Array gamma-ray air-Cherenkov experiment at the Observatorio del Teide*, vol. 12189 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, p. 121890D, Aug., 2022, DOI.

[15] S. Lombardi, C. Bigongiari, M. Cardillo, E. Fedorova, S. Gallozzi, F. Lucarelli et al., *The Data Processing System of the ASTRI Mini-Array Project*, in *Pro. 38th ICRC, Nagoya, Japan, PoS(ICRC2023)682*, July, 2023.

[16] M.C. Maccarone, G. La Rosa, O. Catalano, S. Giarrusso, A. Segreto, B. Biondo et al., *UVscope and its application aboard the ASTRI-Horn telescope*, *Experimental Astronomy* (2021) [2103.02233].

[17] A.A. Compagnino, T. Mineo, M.C. Maccarone, O. Catalano, S. Giarrusso and D. Impiombato, *Evaluating the night sky background directly from the signal images detected by the ASTRI telescopes*, *Experimental Astronomy* **53** (2022) 1017.

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