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The ASTRI Mini-Array Gamma-Ray Experiment

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Abstract. The ASTRI Mini–Array is currently being installed in Tenerife at the Observatorio del Teide to explore the gamma-ray sky in the 1-100 TeV energy range with unmatched angular resolution (a few arcminutes) across a wide field of view (10.5^o). The array consists of nine IACTs (Imaging Atmospheric Cherenkov Telescopes), each equipped with a 4-meter diameter dual-mirror system featuring a Schwarzschild-Couder-like optical configuration, functioning as an aplanatic system, and an innovative compact camera that utilizes SiPM (Silicon PhotoMultipliers) sensors. This paper provides a short overview of the ASTRI Mini–Array project regarding its layout, the technologies utilized, and the scientific objectives.

1 Introduction

In 2010, the Italian National Institute for Astrophysics (INAF) started as a flagship project (*Progetto bandiera*) of the Italian Ministry for the Universities and Research (MUR) - the ASTRI program, aiming at the development of ground-based gamma-ray astronomy with IACTs (Imaging Atmospheric Cherenkov Telescopes). The program name, ASTRI, stands for *Astrofisica con Specchi a Tecnologia Replicante Italiana*, an acronym created by Nanni Bignami [1]. This term describes the innovative technique developed by INAF for producing low-cost mirrors used in ground-based gamma–ray astronomy with Cherenkov telescopes, first utilized in the MAGIC telescopes [2]. Within the ASTRI program, the ASTRI Mini–Array project aims to construct, install, and manage nine air–Cherenkov 4-meter dual-mirror class telescopes with a large field of view [3] at the Observatorio del Teide in Tenerife, Spain. The ASTRI Mini–Array depends on an international collaboration that includes the University of Sao Paulo in Brazil, North–West University in South Africa, the University of Geneva, the Fundación Galileo Galilei (FGG, which manages the Telescopio Nazionale Galileo - TNG - on behalf of INAF in the Canary Islands), and the Instituto Astrofisico de Canarias (IAC), which provides the infrastructure site at the Observatorio del Teide in Tenerife and, along with FGG, offers local support.

Before starting the implementation of the ASTRI Mini–Array, INAF decided to develop and install an end-to-end prototype [4]. The telescope, named ASTRI-Horn in honor of Guido Horn D'Arturo, the Italian-Jewish astronomer who invented the tessellated configuration for astronomical mirrors [5, 6], is an air–Cherenkov telescope based on the innovative Schwarzschild-Couder aplanatic dual mirror configuration, now operated at the observing station in Serra La Nave (Mount Etna,

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Sicily). The telescope has produced several significant technological solutions, including the first evidence of the optical behavior of a Schwarzschild-Couder system [7] and the first detection of the Crab in gamma rays with a dual mirror aplanatic system, fitted with a compact camera developed by INAF using SiPM sensors [8]. After developing the ASTRI-Horn pathfinder, INAF started working to set up and operate the ASTRI Mini–Array [9, 10]. Thanks to an agreement between IAC and INAF formalized in 2019, the implementation of the site infrastructure began at the end of 2020 and ended in 2022. The first E2E (end–to–end) telescope has been installed and calibrated, while the other telescopes will be set–up in 2025. Once the technical aspects are proven, thanks to its unprecedented flux sensitivity and vast field of view (10.5^o in diameter), the ASTRI Mini–Array will allow the involved researchers to conduct state-of-the-art scientific studies in the range of gamma–ray energies between 1 TeV – 100 TeV, so far just poorly explored with the present air–Cherenkov telescopes [11].

In this respect, it is essential to note that astroparticle arrays such as HAWC [12] and LHAASO [13], which can monitor vast portions of the gamma-ray sky and integrate signals from individual sources over the years, provide new and remarkable data on emitters reaching several hundreds of TeV (and even beyond up to 2 PeV). However, the coarse angular and energy resolutions in these experiments limits a correct understanding of the observed phenomena. This issue can be addressed with dedicated IACT array experiments specifically developed for air–Cherenkov observations in the 1 – 100 TeV region, such as the ASTRI Mini–Array and, in Tibet, China, LACT [14] (which, however, suffers from the impossibility of making observations during the monsoon season, between April and October). It should be noted that the ASTRI Mini–Array also serves as a pathfinder for the 37 Small-Size Telescopes (SSTs), which have nearly the same optomechanical configuration and will be deployed in Chile at Paranal [15, 16] as part of the Cherenkov Telescope Array Observatory (CTAO) [17]. This paper will briefly review the technological aspects of the ASTRI Mini–Array and discuss its scientific capabilities. It will also report on the preliminary performance of the first of the nine telescopes obtained by observing the Crab Nebula in gamma–rays.

2 Location and layout of the ASTRI Mini–Array

The Canary Islands host two sites renowned for their exceptional astronomical sky conditions, regarded as the most important for ground-based optical, infrared, millimeter and gamma-ray astronomy in Europe. The Observatorio del Teide (OT) is located in Tenerife, whereas the Observatorio del Roque de los Muchachos (ORM) can be found in La Palma; the IAC operates both observatories. In this context, the ASTRI Mini–Array site is located in Tenerife at the OT, at an altitude of ~ 2400 meters in the Izana region of Tenerife Island. The OT site encompasses an area of 50 hectares. It is already well–developed, featuring many facilities (such as a guesthouse, data center, and main roads) and several other operational telescope installations (more than seventy) or other specialized astrophysical instruments. In addition to the support provided by IAC, the ASTRI collaboration can rely on FGG (the Galileo Galilei Foundation), the institution governed by INAF that was established to support the Italian telescopes in the Canary Islands.

The geographical coordinates of the site are 28^o 17’ 60" North – 16^o 30’ 21" West. This location is strategically important, allowing the ASTRI Mini–Array to cover most of the gamma-ray northern sky, with the possibility of also observing part of the southern sky, particularly the Galactic Center region, in Summer. The Canary Islands generally have excellent astronomy conditions because they are close to the Equator and outside the range of tropical storms and monsoons [18–20]. Therefore, the atmosphere in the subtropical region of the Canary Islands is characterized by its excellent stability throughout the year. Observatories, including the ASTRI Mini–Array, are at an altitude of ∼ 2400 m, above the thermal inversion layer *Alisio* (located around 1000-1600 m). This layer separates two well-defined regimes: below it, there is the moist marine boundary layer, and above it, the dry free troposphere. This ensures that the installations are in the free troposphere, above what is known as the *sea of clouds*, where the atmosphere is usually clear and free from turbulence. The Alisio inversion is a quasi-permanent layer, representing 78% of the year. Its altitude and thickness have a seasonal dependence, being higher and thinner during the winter (when it is located between 1350 and 1850 m a.s.l., being only 350 m thick) and lower and thicker during the summer (between 750 and 1400 m a.s.l., being about 550 m thick).

Light pollution from significant civilian developments in Tenerife somewhat affects the night sky, and light from other Canary Islands is also visible. Recent sky quality measurements indicate an average of 20.7 and 21.5 Mag/arcsecond^2 in the V and B filters, respectively. As the ASTRI Mini–Array has a minimum threshold operational energy of 1 TeV (not of a few tens GeV, like e.g. MAGIC), this relatively high background does not significantly impact the flux sensitivity of the experiment. The most challenging environmental conditions usually arise in winter, when cloudy and windy storms (sometimes accompanied by rain and snow) can sometimes affect observations. An average of 77.0%, a fraction of helpful observation time, was obtained from site records, ranging from 72.5% to 83.7%. The quality of the atmosphere is outstanding. The monthly averages of PM10 in the 75th percentile are below 10 μg/m^3 (indicating a very clean environment) throughout the year, except in summer when dust-laden intrusions into Saharan air masses (*calima*) can typically occur for just 1-5 days. The ORM site on La Palma Island is just 100 km from Tenerife, enabling the ASTRI Mini–Array to potentially engage in legacy observational programs in partnership with other IACT telescopes operating at lower gamma-ray energies that are currently active (MAGIC I-II, LST-I) or in development (the complete CTAO northern array). Additional collaborations for simultaneous observations are feasible with the optical telescopes on both ORM and OT like e.g., at ORM the Telescopio Nazionale Galileo (TNG) and Gran Telescopio Canarias (GCT) and, at OT, the Telescopio Carlos Sanchez (TCS). Figure 1 illustrates the layout of the ASTRI Mini–Array at Teide Observatory. The telescopes will be set up within an area of approximately 17 hectares, a strip measuring 650 meters in length and 270 meters in width. The ASTRI Mini–Array design was primarily focused on scientific

Figure 1. Positions of the 9 telescopes of the ASTRI Mini–Array. The picture shows the positions of the 2 meteorological towers, LIDAR, transformer station, local control room, and data center. (from [9]).

performance. However, the team also considered the characteristics of the area, the availability of site infrastructure, operational safety, and the potential impact on the activities of the Teide Observatory. The positioning and spacing of the telescopes have been thoroughly analyzed using Monte Carlo simulations. The findings indicate that a symmetrical configuration, with an approximate reciprocal distance of 250 meters, would provide the best balance, with excellent performance at high energies (10 TeV) preserving a very good sensitivity at lower energies. However, the design had to consider two other critical practical factors. First, it will utilize existing infrastructure, such as roads and trenches, to minimize construction work and costs. Second, it ensures that the ecosystem around the Teide observatory is not negatively affected. The OT is located within the Forest Crown area, near Las Canadas del Teide National Park, a region of great importance because of its natural beauty and unique vegetation. We are dedicated to minimizing the impact on the environment during both the construction and operation of the telescopes. Then, the final layout was chosen as a compromise between the necessity to preserve optimum and regular spacing, the shape of the available area, and the constraints on the position of telescopes due to the existing infrastructure and preserving the natural environment. The layout is asymmetrical, more elongated in the North–East/South–West direction with a median spacing among neighboring telescopes of about 200 m.

3 The telescopes

The ASTRI telescopes utilize an optical design inspired by the Schwarzschild-Couder (SC) configuration and feature an alt-azimuthal mount. Karl Schwarzschild introduced this aplanatic concept in 1905 [21], based on the proper use of two conical reflecting surfaces and optimizing their reciprocal distance and the distance from the focal–plane camera. The design was subsequently refined by Andre Couder in 1926 [22], who also introduced a bent (and not flat) detection surface to better compensate for the curvature of the field. An SC telescope can cover large sky areas while maintaining the necessary angular resolution across a wide field of view. Moreover, the SC system reduces the plate scale, facilitating the design of compact telescopes with small pixels and ensuring isochronous performance. As early as 2007, Vassiliev et al. [23], proposed the SC design for innovative air–Cherenkov telescopes instead of the previously used single-mirror telescopes. The SC design can accommodate small (a few mm) SiPM pixels in compact focal plane cameras instead of the larger photomultipliers and heavy and large cameras used previously. A possible disadvantage is the large vignetting due to the secondary mirror, which may reduce the telescope collecting area. The optical configuration of the ASTRI telescope (i.e. exactly the same adopted for the ASTRI-Horn prototype in Sicily and the SST/CTAO telescopes in Chile, see Figure 2 -A) varies slightly from a pure SC system [24]. Once established, the reciprocal distances between the mirrors and cameras originated from a spherical shape, the profiles of both the primary and secondary mirrors were modeled as polynomials, with their terms optimized according to a merit function. Namely, the merit function was the angular resolution (in terms of 80 % PSF) evaluated across $\sim 10.5^o$ field of view (diameter). It should be noted that the mirrors' profiles are aspheric with significant deviations from the main spherical component. The distance from the primary mirror to the secondary mirror is 3 m, and from the secondary mirror to the camera is 0.52 m. This optical setup provides a plate scale of 37.5 mm/degree, an equivalent focal length of 2150 mm, and an effective area of approximately 5 square meters, a significant aspect of its design. The mirrors are coated with an aluminum layer, featuring a multilayer overcoating of SiO_2 and ZrO_2. This coating provides high durability and reflectivity greater than 90% within the 300 to 500 nm wavelength range, where the Cherenkov signal peaks. The primary mirror (M1, 4 m diameter) is segmented, consisting of 18 hexagonal–shaped panels [26], while the secondary mirror (M2, 1.8 m diameter) is monolithic [27] (Figure 2-B). The primary mirror dish is mounted on an azimuth fork, allowing rotation around the elevation axis from 0^o to $+91^o$. The mast structure that supports the secondary mirror and the camera is placed on top of the primary mirror dish. The ASTRI

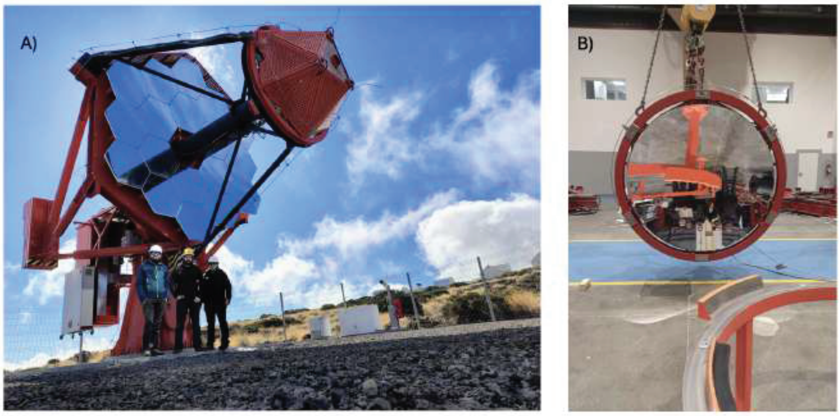

Figure 2. A) The ASTRI-1 telescope already installed at the Observatorio del Teide site. B) The 1.8 m diameter monolithic secondary mirror being mounted on one telescope of the ASTRI series.

electromechanical structure is an optimized version of the ASTRI-Horn prototype telescope, based on lessons learned during its operation to optimize mass, functionality, and maintainability. The SST CTAO telescopes will have almost the same configuration.

4 The cameras

The Cherenkov cameras [28, 29] are highly–compact, being based on SiPM sensors. Hamamatsu Photonics supplied the LVR3 series of SiPM sensors selected by ASTRI for this application. Starting from the camera prototype used in ASTRI Horn, a new camera design and the first enginnering camera was developed thanks to the collaboration with the Weeroc, CAEN SpA, EIE GROUP srl, Nuclear Instruments srl and ZAOT srl companies. The pixels, each measuring 7x7 mm^2 and uncoated, were specifically developed and manufactured by Hamamatsu for the ASTRI project (being normally the size 6x6 mm^2). They are arranged into 8x8 matrices; 2368 pixels are required to cover the telescope's field of view (Figure 3). To accommodate the telescope's curved focal plane (with a curvature radius of 1 m, as per the optical design specifications), 37 matrices are precisely aligned, showcasing the system's accuracy. The optical system, combined with the physical characteristics of the SiPM detectors, yields an angular pixel size of 0.19^o and a field of view of 10.5^o; more than 80 % of the point spread function size fits within the dimensions of a pixel across the entire telescope's field view. The core of the electronics is the CITIROC-1A ASIC, which employs a custom signal shaper peak detector to capture the SiPM pulses. The camera trigger operates topologically, activating when a certain number of adjacent pixels detect a signal above a threshold corresponding to a specific number of photoelectrons. The ASTRI camera's readout electronics are designed to efficiently detect Cherenkov events at a rate exceeding 1000 events per second, with a wide dynamic range of 1 to 1500 photoelectrons per pixel. This capability allows us to observe even under strong moon illumination conditions. The ASTRI camera employs a flat interference filter as the front window to minimize background light from the night sky at wavelengths above 550 nm. This is crucial for maintaining high sensitivity, as the SiPM sensors remain responsive at these wavelengths. After considering the vignetting effects of different parts of the telescope and the reduction caused by the interferential filter, the effective area

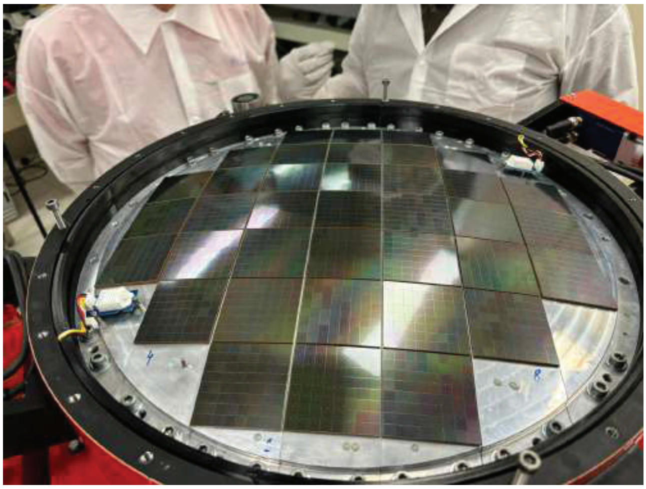

Figure 3. The focal plane made of 2368 pixels SiPM pixels before the installation of the interferential filter.

consistently remains above 5 m^2 across the entire 10.5^o field of view, decreasing by 25 % from the center to the edge of the field.

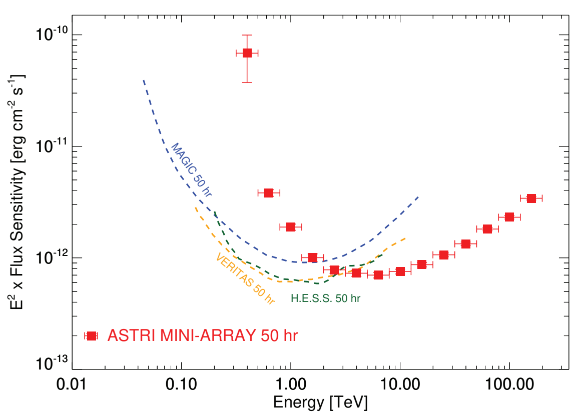

Figure 4. Flux sensitivity (50 h integration) for ASTRI Mini–Array and other already operating IACT arrays.

5 The ASTRI Mini–Array expected performance

The ASTRI Mini–Array will be more sensitive than currently operating IACT systems (see Table 1 and Figure 4), particularly at energies exceeding 1 TeV. This indicates that it will extend the sensitivity range up to 100 TeV and beyond (an energy range rarely explored with IACTs so far). Additionally, productive synergies are anticipated with HAWC and LHAASO, which survey a vast area of the northern sky, with targeted observations aimed at characterizing the morphology of extended sources detected at the highest VHE by these facilities. The wide field of view (10.5^o in diameter) will allow

Table 1. ASTRI performance compared with the other current IACT arrays.

	ASTRI Mini–Array	**MAGIC**	**VERITAS**	**H.E.S.S.**
Location	28° 18’ 04" N	28° 45’ 22" N	31° 40’ 30" N	23° 16’ 18" S
	16° 30’ 38" W	17° 53’ 30" W	110° 57’ 7.8" W	16° 30’ 00" E
Altitude [m]	2390	2200	1268	1800
FoV	~ 10.5°	~ 3.5°	~ 3.5°	~ 5°
Angular Res.	0.05° (30 TeV)	0.07° (1 TeV)	0.07° (1 TeV)	0.06° (1 TeV)
Energy Res.	12% (10 TeV)	16% (1 TeV)	17% (1 TeV)	15% (1 TeV)
Energy Range	(0.3-200) TeV	(0.05-20) TeV	(0.08-30) TeV	(0.02-30) TeV

us to monitor multiple nearby sources simultaneously during a single observation. With a sensitivity that reaches up to 100 TeV and consistent performance across the field of view, we can study, for example, the emissions from extended sources such as supernova remnants (SNRs) and pulsar wind nebulae (PWNs) at energies exceeding 10 TeV. Considering the number of nights without moonlight corrected for a fraction of nights with clear sky and the fractional loss due to bad weather or calima, plus the time loss for technical reasons (10%), we end up with 1000 hours per year of available time for Cherenkov observations in dark conditions. This number increases by at least 50 % if the time with moonlight is added on, with just an increase of the energy from 1 TeV to a few TeV.

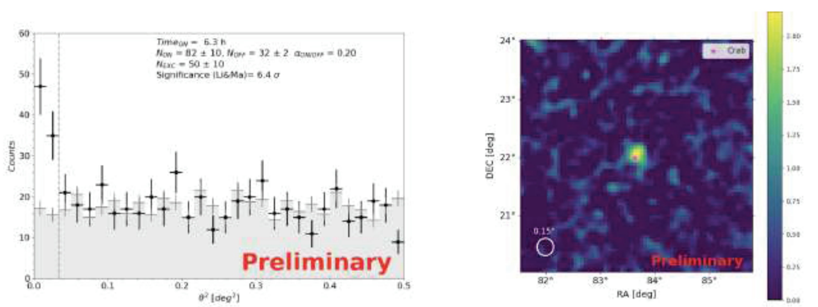

Figure 5. Left: The θ^2 – distributions of the Crab Nebula (ON, black) and the background (OFF, grey) data from quick–look analysis of ASTRI–1 observations (taken on 5–6 Dec 2024) at energies ≥~ 2 TeV. The region between zero and the vertical dashed line represents the fiducial signal region. Right: excess of gamma–rays at the Crab position (Credits: S. Crestan, S. Lombardi and the ASTRI–1 calibration team).

6 Conclusions

The ASTRI Mini–Array is an international project led by INAF to install and operate nine innovative IACT telescopes at the OT site, as a result of a hosting agreement between INAF and IAC. The facility will operate for at least 8 years. It will be the largest IACT array in the northern hemisphere until the CTAO observatory starts operating. It will perform deep observations of the Galactic and extra-Galactic sky at high energies. The complete array will be ready to perform the activities of commissioning and scientific calibration by the end of 2025. Scientific observations will begin in 2026. Compared to currently operating IACT systems (HESS, VERITAS, and MAGIC), the ASTRI Mini–Array will extend the sensitivity up to 100 TeV, an almost never-explored energy range by IACTs. ASTRI complements the HAWC and LHAASO astroparticle experiments, both located in the northern hemisphere, to make focused observations of specific regions of interest. The preliminary results from the first telescope (ASTRI-1) after a quick-look calibration data analysis are promising (Figure 5). The complete series of ASTRI telescopes will be installed by the end of 2025.

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