The implementation of the ASTRI Mini-Array gamma-ray experiment at the Observatorio del Teide, Tenerife

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ABSTRACT

The ASTRI Mini-Array is a gamma-ray experiment led by INAF with the partnership of the Instituto de Astrofisica de Canarias, Fundacion Galileo Galilei, University of Sao Paulo, North-West University S.A., and Observatoire de Geneve. It is being implemented at the Observatorio del Teide Tenerife. The nine (9) Cherenkov dual-mirror aplanatic telescopes of 4 m diameter are positioned at an average distance from each other of 160 m. Thanks to the unprecedented field-of-view (10.5 deg) of the ASTRI telescopes, the MA will allow us to observe the gamma-ray sky from a few up to a few hundred TeVs with competitive flux sensitivity and enhanced angular resolution. The curved focal plane of the camera is covered with SiPM sensors and is equipped with fast front-end electronics. The control SW will allow us to operate the Mini-array remotely, while a dedicated off-site Data Center in Italy will process the scientific products every night. The ASTRI Mini-Array represents a pivotal instrument to perform groundbreaking measurements very soon. In this paper, we will review the implementation plan of the ASTRI Mini-Array and report on the ongoing construction.

Keywords: Imaging Atmospheric Cherenkov Telescopes (IACTs), very high-energy gamma rays, ASTRI, Schwarzschild-Couder telescopes, Cherenkov telescopes array

1. INTRODUCTION

The ASTRI Mini-Array project aims to build, deploy, and operate a set of 9 wide-field Cherenkov telescopes of the 4 meters class at the Observatorio del Teide in Tenerife (Spain). The ASTRI acronym stands for *"Astrofisica con Specchi a Tecnologia Replicante Italiana"* ("Astrophysics with Mirrors based on Italian Replication Technology"), with a direct reference to the method invented by INAF to produce low-cost mirrors for Cherenkov Telescopes in ground-based gamma-ray astronomy [1].

The ASTRI Mini-Array is being installed and will be operated by INAF in collaboration with IAC (a hosting agreement has been formalized between the two institutes). Other minor Italian partners in the implementation are the Universities of Perugia and Padova, as well as INFN. The University of Sao Paulo, Brazil, and North-West University/South Africa, the Observatoire/Université de Geneve, Switzerland, are key international partners. Critical support is given by the Fundación Galileo Galilei (FGG), the Spanish Foundation with governance under INAF control, specifically established to manage the TNG and other INAF projects in the Canary Islands. All these Institutes are also directly participating in

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the effort in terms of financial support and in-kind contributions. INAF started the ASTRI project in 2010 within the context of the *"Progetti Bandiera"* ("Flagship programs") of the Italian Ministry for Researcher and University (MUR, formerly MIUR) and, in this context, the end-to-end prototype ASTRI-Horn Cherenkov telescope, based on the innovative dual-mirror Schwarzschild-Couder aplanatic configuration and small plate-scale, has been developed and installed at the INAF "M.C. Fracastoro" observing station in Serra La Nave (Mount Etna, Sicily).

With this telescope, several technologies and innovative sub-systems were developed.
INAF developed the cold-glass replication technology in collaboration with the Media Lario Italian firm (https://www.medialario.com) that has been used for making the aspherical mirror tiles forming the primary mirror [2]. Other critical technical skills that were acquired yielded the hot forming method for making the 1.8 m secondary monolithic mirrors, the innovative Cherenkov ASTRI camera prototype based on small pixel size SiPM sensors [3], and the newly designed read-out approach also making use of the *ad hoc* CITIROC ASIC developed in the context of a collaboration between INAF and the French company WEEROC (https://www.weeroc.com), completed by our control software, ICT systems, and data analysis pipes and archive [4,5,6]. Significant results include the first proof of the optical behavior of a Schwarzschild- Couder system [7] and the first detection of the Crab in gamma-rays at energies higher than 3 TeV with a dual mirror system [8].

The ASTRI dual-mirror telescopes will allow the ASTRI team to perform observations of the extended air showers with wide-field (10.5^{o} diameter). This IACT system may allow us to open a new observational band with Cherenkov telescopes in the 1 – 100 TeV (and beyond) energy band. To this end, the telescopes are arranged in a proper array configuration, with large reciprocal distances to perform wide-field stereoscopic observations, according to the paradigm proposed by J. Hillas and never proven so far with experiments, albeit Monte Carlo simulations yield excellent results [9]. The ASTRI Mini-Array will be the ideal complement to other gamma-ray experiments located in the northern hemisphere based on different detection methods like LHAASO and HAWC because ASTRI has a much better angular resolution (0.05^{o} versus > 0.25^{o}). Compared to other IACT arrays already operating in the northern hemisphere like MAGIC and VERITAS, ASTRI has been designed to work at much higher gamma-ray energies (see Table 1 for a comparison). Compared to CTA-N, under implementation, ASTRI observing strategy will be based on long observations to catch in the 1-100 TeV energy range the weak signals from Pevatrons and other high-energy galactic and extragalactic sources.

Table 1. Main Parameters of the ASTRI Mini-Array compared to other gamma-ray experiments in the North hemisphere.

	ASTRI Mini-Array	**MAGIC**	**VERITAS**	**HAWC**	**LHAASO**
Location	Tenerife, Canary Islands	La Palma, Canary Islands	Arizona, USA	Mexico	Tibet, China
Detection Method	IACT – 9 dual-mirror small telescopes (4 m diam)	IACT – 2 large telescopes (17 m diam)	IACT – 4 medium size telescopes (12 m diam)	Water Cherenkov	Water Cherenkov + scintillators
Field-of-View	10.5^{o}	3.5^{o}	3.5^{o}	2sr	2sr
Angular resolution	0.05^{o}	0.07^{o}	0.07^{o}	0.15^{o}	0.25^{o}
Energy Resolution	12 % (10 TeV)	16% (1 TeV)	17% (1 TeV)	30 % (10 TeV)	30 % (100 TeV)
Energy Range	0.3 – 200 TeV	0.05-20 TeV	0.08-30 TeV	0.1-100 TeV	0.1 – 1500 TeV

The SST-2M ASTRI Mini-Array installed in Tenerife will be able to verify several technical aspects regarding the wide-field IACT array of telescopes, as e.g.:

- the broad field-of-view capability to detect very high-energy showers with the light emission located at a distance up to a few hundred meters from the shower center;
- performing deep observations of several hundred hours pointing to a few selected targets to compare the actual performance with the results of the Monte Carlo simulations;

- the reliability and cost consolidation of the adopted technologies given the future implementation of a much larger array, e.g. SST-CTA in Chile;
- the second level stereoscopic trigger approach that will be carried out for the first time “post –facto” via software;
- the data-handling chain that will be based on techniques of data treatment inspired by space applications;
- the use of the so-called *“variance method”* implemented in the ASTRI Cherenkov camera to monitor the sky and control the alignment of all telescopes, with the possibility to perform post-facto corrections;
- tests of stellar intensity interferometry in the visible wavelength band, previously developed by Hambury-Brown and Twiss, that will be carried out on bright stars in the visible band with very long baselines (hundreds of meters), allowing, in principle, to obtain angular resolutions as good as 50 micro-arcsec [10].

It should be noted that the ASTRI Mini-Array is intended to be a precursor to the much more ambitious CTAO project [11] of an array of more than 50 SST (4 m diameter) telescopes that will be deployed on the southern site in Paranal (a specific paper about that is presented in these proceedings [12]).

Once the technical aspects are proven, thanks to the unprecedented flux sensitivity achievable with the ASTRI Mini-Array in the 1 TeV – 100 TeV band, the ASTRI team will perform fascinating scientific studies on a range of gamma-ray energies so far just poorly explored with the present IACT Cherenkov telescopes (the flux sensitivity is shown in Fig. 1). We expect to perform the complete commissioning and technology verification, also testing the scientific performance of the array by early 2025. After that, the scientific observations will start.

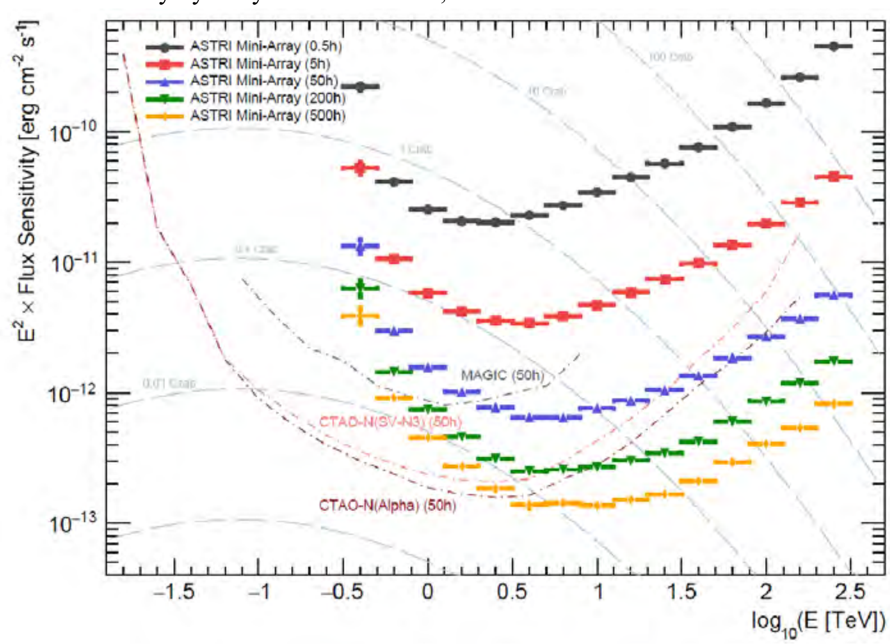


Figure 1. On-axis point-like source differential sensitivity of the ASTRI Mini-Array (at a zenith angle of 20) for five exposure times: 0.5 (dark-gray), 5 (red), 50 (blue), 200 (green), and 500 (orange) hours. The differential sensitivities of other instruments – MAGIC (50 hours) and CTAO-N (50 hours), for both science verification (SV) and after the entire construction phase (2028) – are shown for comparison.

The ASTRI collaboration has recently published a set of papers [13,14,15,16] that provides a detailed description of the Mini-array, as well as a presentation of its science core program (that will be carried out in 3-4 years starting in 2025, after the completion of the Mini-array,), complemented with in-depth presentations of the galactic and extragalactic objectives that will be pursued after the first phase when the ASTRI Mini-Array will be run as an observatory.

In this paper, we will focus on the aspects related to the implementation of the site infrastructure and telescopes, also describing the program's status.

2. THE ASTRI MINI-ARRAY SCHEMATIC OVERVIEW AT THE INFRASTRUCTURE LEVEL

Figure 2 details the geographical deployment and logistics of the ASTRI Mini-Array. In Tenerife Island, at the Observatorio del Teide (OT), the array of telescopes with all the auxiliary instrumentation, the local control room, and the on-site data center will be located, while the main Array Operation Center will be at the IAC facilities in San Cristobal de la Laguna. In Italy, the off-site archive and data analysis center will be located in Rome, while remote Array operations centers will be distributed all over the country. 10 Gbit connection between the Observatorio del Teide and La Laguna is granted, while a dedicated 10 Gbit connection to Italy is under evaluation.

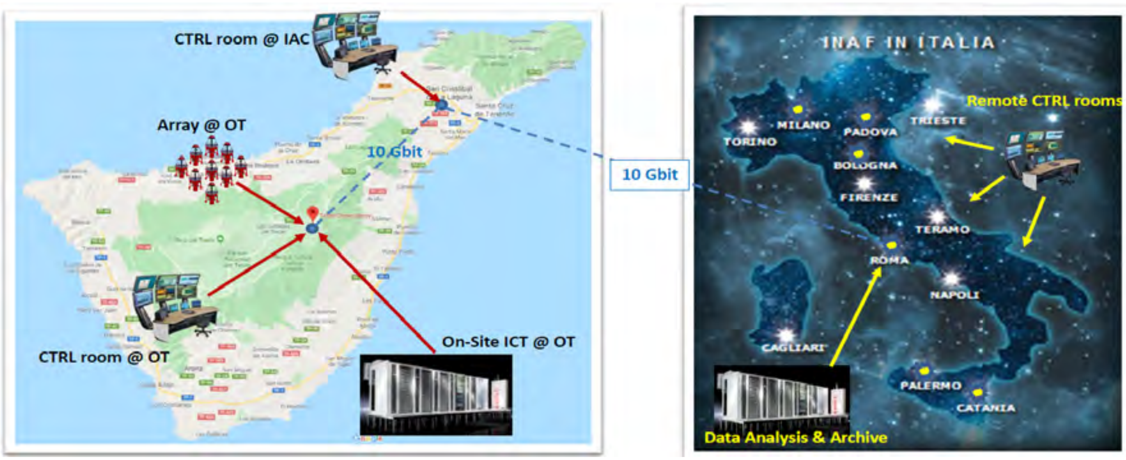


Figure 2. Geographical distribution of the ASTRI Mini-Array (left image from Google map).

The layout of the ASTRI Mini-Array at the Teide Observatory is shown in Figure 3. The following systems will form the ASTRI Mini-Array at the observational site: a) nine (9) telescopes, each placed in a dedicated area; b) a control room hosted at Themis observatory building; c) a data center hosted at the OT Residencia building; d) a LIDAR, placed in a dome made available by IAC; e) two meteorological towers (nearby ASTRI-6 and ASTRI-2); f) access roads to telescopes; g) trenches, cable ducts, cable pits for power, data, timing, and safety and security networks, including electrical cables and optical fibers; h) medium-to-low voltage transformer station with UPS and diesel generator for power backup placed between the Themis building and ASTRI-3; i) illuminator: a device to calibrate the telescopes that will not be permanently mounted at the site. It will be mounted on the Gregor solar telescope (https://www.mps.mpg.de/solar-physics/gregor-telescope), and the light source will reach all the telescopes of the ASTRI Mini-Array.

Figure 3: ASTRI Mini-Array general Layout The figure shows the final positions for the 9 telescopes, the roads to access each of them, the position of the two meteorological towers, the current position of the LIDAR, and that of the local control room (@Themis) and the data center (@Residencia). (Image obtained with Open Street Map editor).

In Figure 4, the physical architecture of the ASTRI Mini-Array is shown, including all the subsystems apart from the telescopes. The figure focuses on the connections between the onsite ICT (named Data Centre in the figure) and the peripheral systems (telescopes, auxiliaries, operators) through the three main networks, the safety network, the time distribution system network, and the generic network where data and commands are exchanged. The internal elements and connections are also shown for the data center and the telescopes.

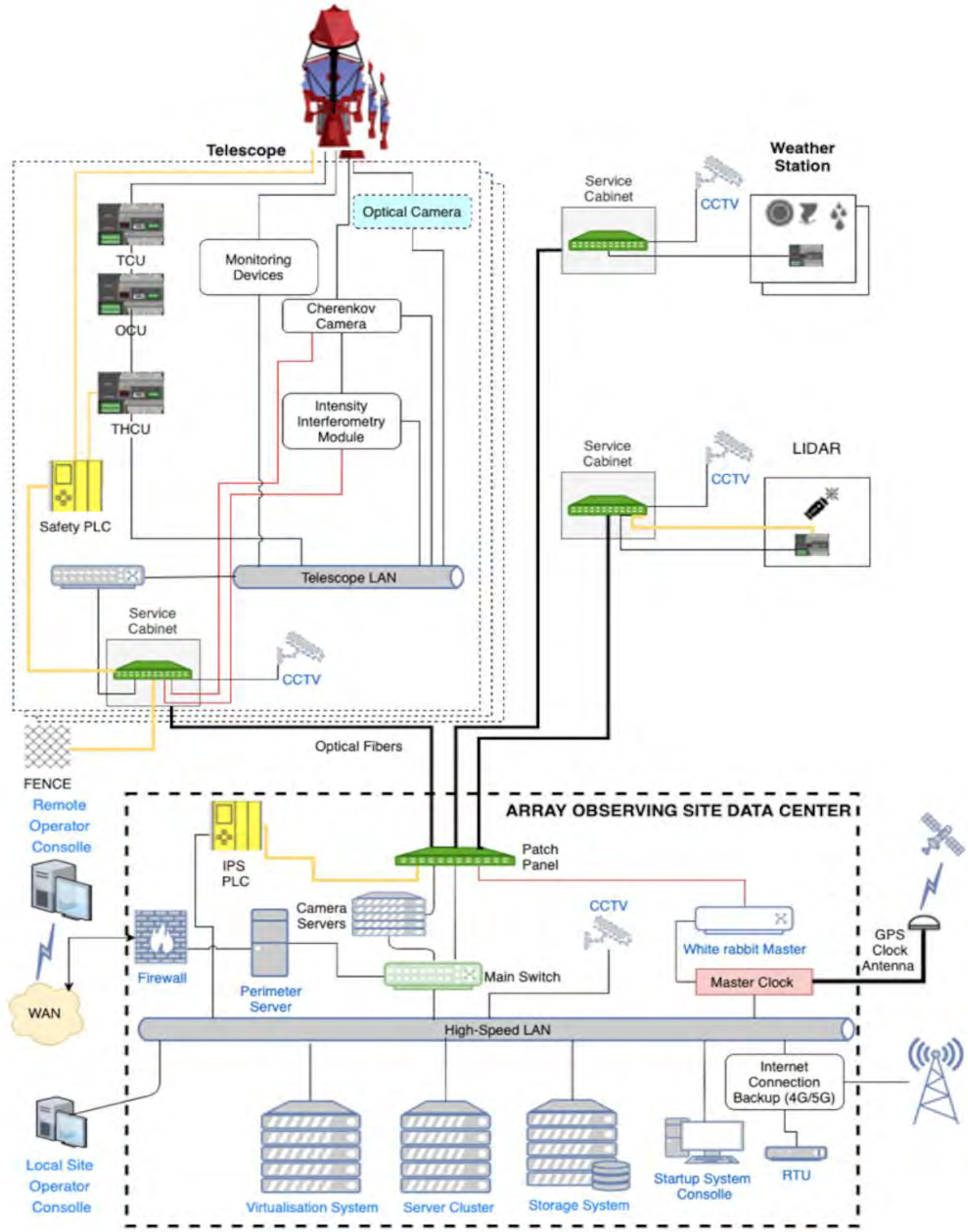


Figure 4. The ASTRI Mini-Array physical architecture. Black lines represent standard network cables or optical fibers; yellow lines represent safety-certified cables or optical fibers; red lines represent white-rabbit certified cables or optical fibers.

3. THE SITE INFRASTRUCTURE

The main elements that make the site infrastructure subsystem are the following:

- **Civil Works**, i.e., everything related to the construction works needed to support the deployment and the operation of the ASTRI Mini-Array, e.g., the foundations for telescopes and auxiliary instrumentation, roads connecting the telescopes, trenches for power, and communication network, buildings for the power transformer station.
- **Power Supply Network** includes all the hardware systems from the power transforming station at the Teide Observatory that are needed to supply electric power to all the Mini-array subsystems. The power supply is based on two sub-networks: a) the medium voltage network **-** which includes a) the power transforming station and the power backup systems (i.e., UPS and emergency power generator), and b) the low voltage network, which includes all the power line connections from the main switchboard to the peripherals and the auxiliary devices such as the secondary electrical cabinet serving ASTRI-2,4,5,6,7 or the power section of all the service cabinets.
- **Telecommunication Network** (Figure 5) includes all the hardware necessary to communicate from the data center to the control room, the telescopes, the auxiliary instrumentation, and the outside world. Local internal networks (data centers, telescopes, etc.) are part of the reference subsystems.

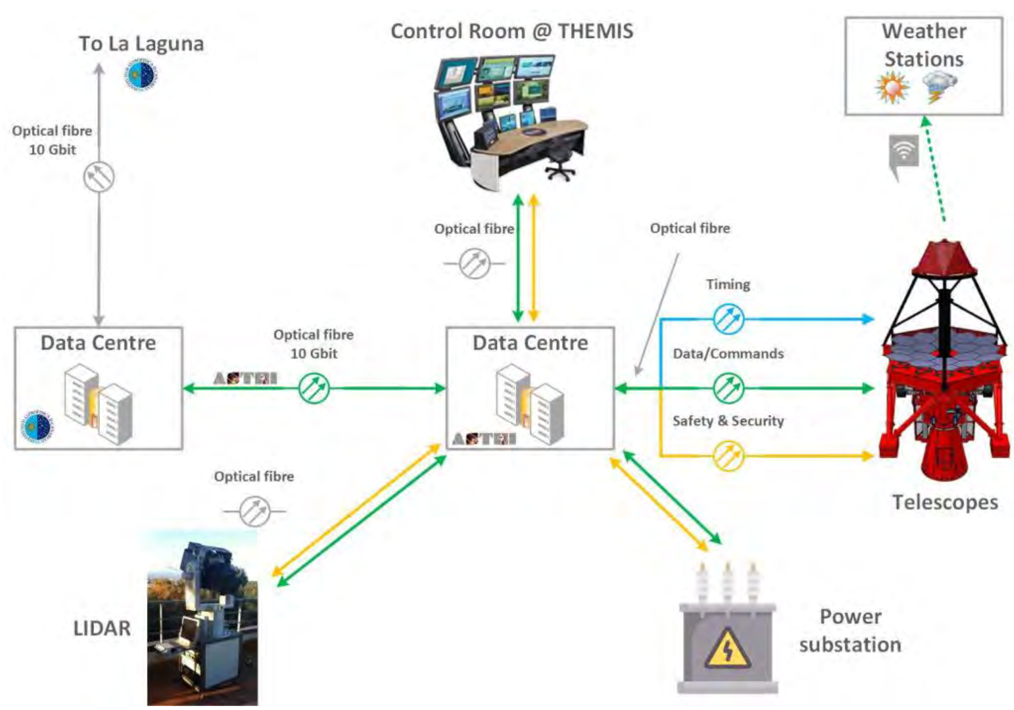


Figure 5. Concept architecture of ASTRI Mini-Array Telecommunication Network. Yellow lines are the safety and security network, the blue line is the time synchronization system network, and green lines represent the data, commands, and monitoring networks. Weather stations are Wi-Fi connected to the closest telescope.

4. THE TELESCOPE

Figure 6 is a 3D model of the telescope of the ASTRI Mini-Array. A detailed description of the telescope and its subsystem can be found, e.g., in Reference [13]. The ASTRI telescope is based on the following subsystems: i) The Optical Assembly; ii) the Mechanical Structure Assembly; iii) The Cherenkov Camera; iv) The Stellar Intensity Interferometry Instrument (SI3); v) The Auxiliary Assemblies; vi) The Telescope Protection System; vii) The Telescope Control System.

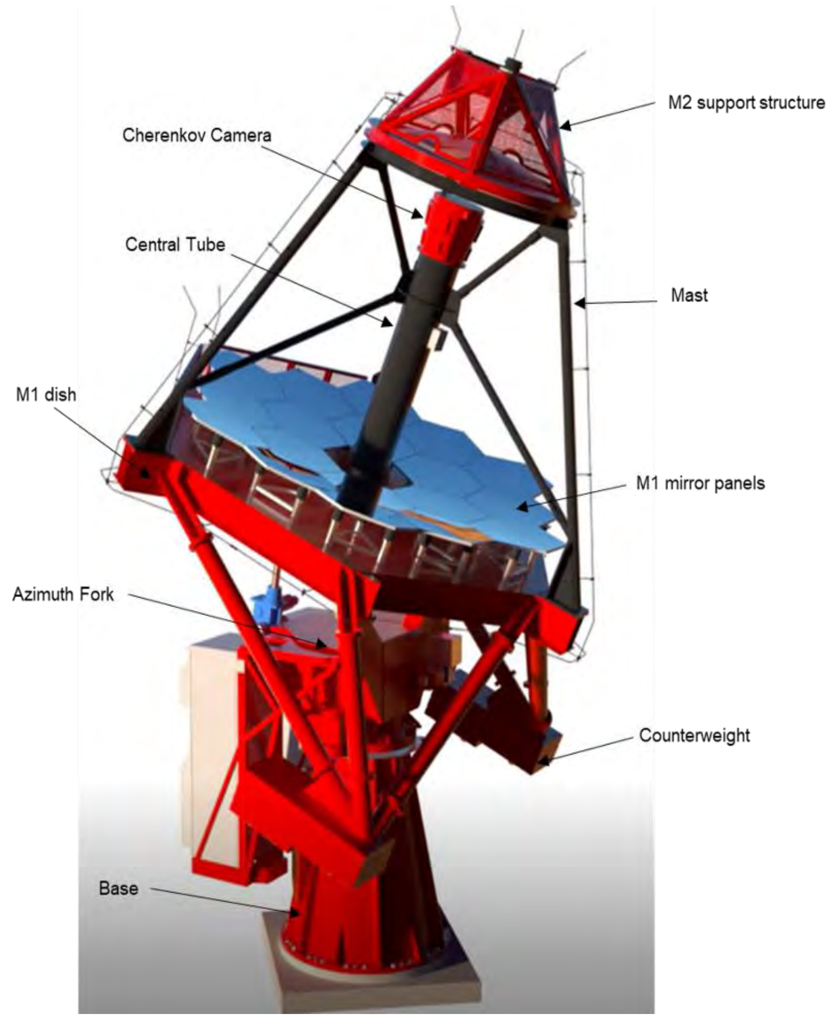


Figure 6. 3D model of a telescope of the ASTRI Mini-Array. Some of the optomechanical components are explicitly indicated.

Figure 7 shows a rendering of the ASTRI camera being developed by INAF in collaboration with the CAEN SpA/ EIE GROUP SRL industrial consortium. The camera mechanical assembly includes several components, usually called the *"camera body."* The camera body is, by definition, from the point of view of mechanical design, the complete deliverable object containing the controls, the detectors, the internal image processor, the thermal system, and the associated circuitry. Moreover, the camera body includes the specific interface to the mechanical structure of the telescope. The camera is equipped with a light-tight lid to prevent accidental sunlight exposure of the focal surface detectors, catastrophic in case of direct light reflected by the mirrors, and contemporary to perform relative detector calibration during daylight. The camera Thermal Control System primarily provides the thermal control of the SiPM sensors in the focal plane, stabilizing and equalizing the SiPMs temperature.

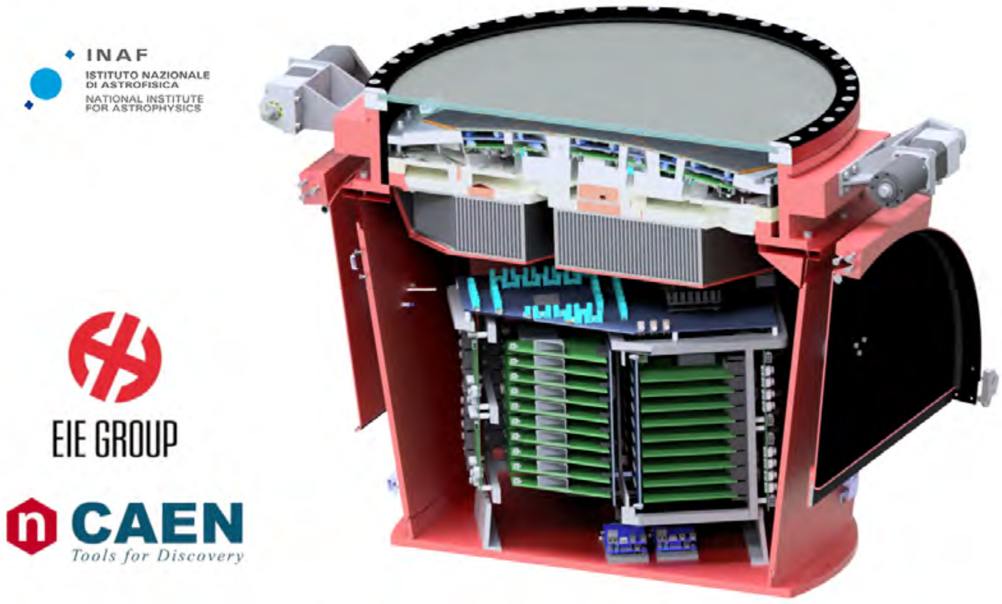


Figure 7. 3D rendering of the ASTRI camera being developed by INAF and the industrial consortium CAEN SpA / EIE GROUP SR using as a reference the Camera Prototype mounted on the ASTRI-Horn telescope.

5. THE IMPLEMENTATION PLAN AND ITS MANAGEMENT

The On-site Implementation of the ASTRI Mini-Array will follow an incremental approach defined by different phases. Several parallel tasks will be executed for each stage to reach the objectives. The main steps, divided by the full On-Site implementation of the ASTRI Mini-Array, are displayed in Figure 8 and described in the following sub-sections. The production of telescopes is taking place in two batches. According to two contracts, three (3) units are manufactured in the first batch and the remaining six (6) in the second. This means there will be about 9 months between the delivery on site of the third telescope (expected in December 2022) and the installation of the fourth telescope. Furthermore, the production of the Cherenkov cameras is going-on in parallel to the telescope's production, with the first camera expected to be available for on-site testing in spring 2023. The implementation approach hereafter described reflects these facts, aiming to complete the array in early 2025 (possible delays would depend, of course, on the current complicated international situation, which is impacting the procurement of materials and electronic components).

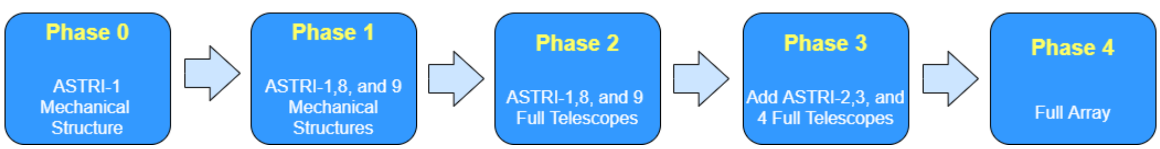


Figure 8. Scheme of the ASTRI Mini-Array implementation phases.

5.1 Phase 0

The purpose of phase 0, which is almost completed, is to install and test the mechanical structure of the ASTRI-1 telescope using the ASTRI Mini-Array power and telecommunications networks and a preliminary version of the control software. For this reason, several subsystems of the ASTRI Mini-Array have already been entirely or partially implemented in this phase. The site infrastructure construction started in October 2021 and will be completed by September 2022. All the civil works have been completed, including those related to the data center, the control room, and the transformer station. The power and telecommunication network for the first three telescopes (ASTRI-1, ASTRI-8, and ASTRI-9) have been implemented.

The control room has been installed and hosted at the premises of the Themis solar telescope (https://lesia.obspm.fr/perso/jean-marie-malherbe/posters/Themis.pdf). In the data center, a preliminary version of the onsite ICT, named mini-ICT, has been installed and tested. The provisional mini-ICT will allow the management of the first three telescopes singularly. The weather station (located nearby the ASTRI-6 foundations) has been installed. A preliminary version of a few SCADA software subsystems is ready to operate the available subsystems. This includes, but is not limited to, the telescope control software and the monitoring and alarm systems. The local control software of the telescope is being completed. Finally, the electromechanical structure of the telescope and its auxiliary systems have been integrated and tested, with the optics of the primary and secondary mirrors mounted on the telescope.

5.2 Phase 1

Phase 1 will start with the arrival of the second telescope to be installed (the delivery on-site is expected in November 2022), and it is meant to install and test the mechanical structure of the ASTRI-8 and ASTRI-9 telescopes, to align and test their optics. For this second task, the optical camera and the removable actuator system will be ready and operational, including the procedures to perform the alignments. The onsite final ICT installation will start during this phase.

5.3 Phase 2

Phase 2 will start with the arrival of the first Cherenkov Camera (the engineering camera#0) at the site (in spring 2023). The purpose of Phase 2 is to have the first seed of the ASTRI Mini-Array operating, that is, the set of the first batch of telescopes fully equipped and tested and working as an array. Onsite ICT will certainly be ready when the second camera is delivered. With the completion of the onsite ICT, all the hardware subsystems essential to the ASTRI Mini-Array will be completed. Based on the White Rabbit technology (https://white-rabbit.web.cern.ch), the time distribution system will be tested as soon as the first camera arrives. At that time, a preliminary version of the SCADA software (mini-SCADA) will be in place to start system (Mini-array level) tests. If system tests at the technical level are satisfactory, then the scientific verification of the performance of the ASTRI Mini-Array would start using the three available telescopes. In this case, the connection with the offsite data center in Rome should be operational (first tests already in phase 0 with the mini-ICT). The Archive System, the Data Processing Software, and the Simulation Software will be tested and become operative. We plan to complete Phase 2 before fall 2023.

5.4 Phase 3 and Phase 4

Phase 3 will start with the delivery of the fourth telescope (first of the second batch) to the site, expected for fall 2023. This telescope will likely be installed at the ASTRI-2 platform to complete the installation of the Meteo-2 station. ASTRI-3 and ASTRI-4 will follow, closing Phase 3. From west to east, the building will continue with ASTRI-5, ASTRI-6, and finally ASTRI-7. Phase 4 will end the site implementation of the ASTRI Mini-Array, bringing the system to the commissioning phase and operations.

6. AN UPDATE ON THE PHASE 0 IMPLEMENTATION

At the time of the preparation of the present paper, Phase 0 of the ASTRI Mini-Array implementation is under completion. Figure 9 shows pictures representing the different steps of implementing the foundation for the ASTRI 1 telescope. The ASTRI-1 telescope was preassembled and tested at the premises of the EIE GROUP SRL firm (http://www.eie.it) in Mira (Venezia, Italy, see Figure 10 - A). After having dismounted the main components, the telescope was shipped to Tenerife and successfully installed at the site of Observatorio del Teide in the summer of 2022 on the ASTRI-1 foundation (Figure 10 – B; in Figure 11, a couple of pictures taken during the installation of the telescope basement are shown). Figure 12 shows a view of the ASTRI-1 telescope at night. The telescope is undergoing other tests on the control system, while the optical alignment will be carried out by October 2022.

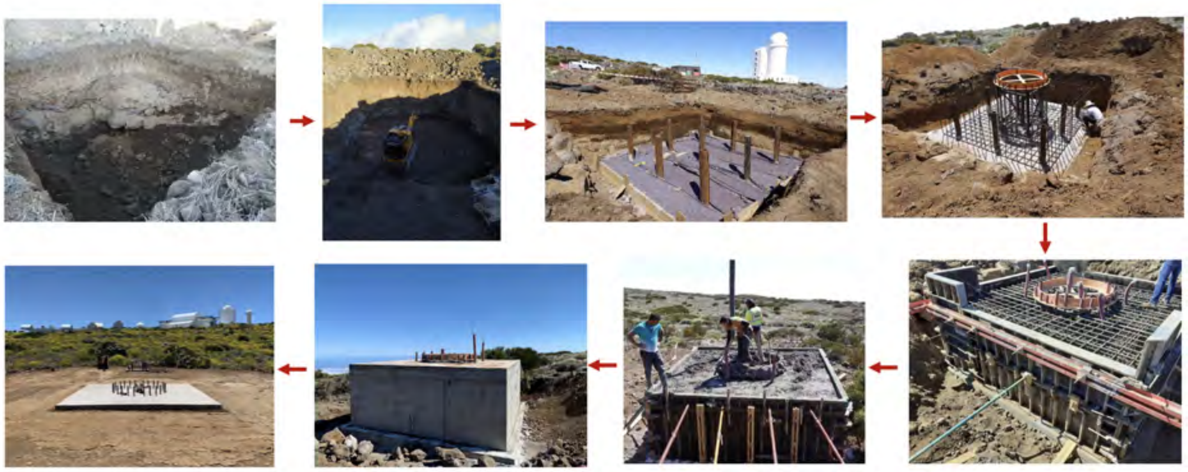
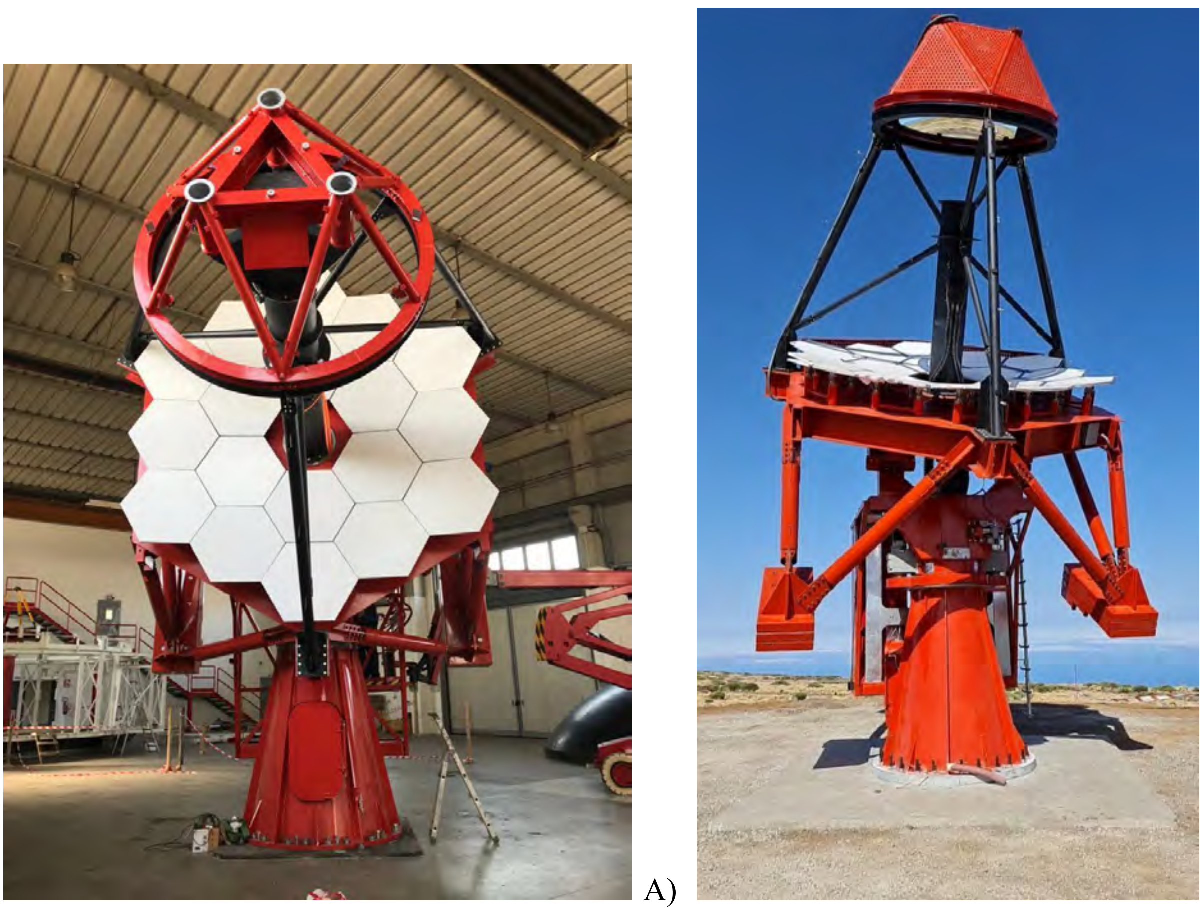


Figure 9. Different steps of implementing the ASTRI-1 foundation, from digging the hole (October 2021) to the completion, are ready to host the ASTRI-1 telescope (late spring 2022).



A) B)

Figure 10. The ASTRI-1 telescope (A)being pre-mounted at the premises of the EIE GROUP SRL firm in Mira (Venezia, Italy) and (B) installed at the ASTRI site on the Observatorio del Teide (Tenerife, Canary Islands, Spain).

Figure 11. Installation of the telescope basement at the ASTRI site (left) and assembly of the M1 dish (right).

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Figure 12. The ASTRI-1 telescope by night at the Observatorio del Teide astronomical site (courtesy of T. Marchiori, EIE GROUP).

7. CONCLUSIONS

This paper presents the implementation plan of the ASTRI Mini-Array IACT gamma ray experiment based on nine 4 meters dual mirror Cherenkov telescopes. The program aims at proving the behavior of the IACT arrays made of small telescopes for observing the gamma-ray sky up to 100 TeV and beyond with unprecedented angular resolution. The ASTRI Mini-Array and its telescopes are pathfinders of the SST (Small Size Telescopes) array that will be implemented at the CTAO southern site in Paranal (Chile). The program has almost completed Phase 0, with the implementation of the civil works at the astronomical location of the Observatorio del Teide and the successful installation of the first telescope, ASTRI-1.

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