Publication Year	2022
Acceptance in OA	2025-03-24T15:26:15Z
Title	The data processing, simulation, and archive systems of the ASTRI Mini-Array project
Authors	LOMBARDI, Saverio, LUCARELLI, Fabrizio, BIGONGIARI, Ciro, GALLOZZI, Stefano, CARDILLO , MARTINA, MASTROPIETRO, Michele, SATURNI, Francesco Gabriele, VISCONTI, Francesco, ANTONELLI, Lucio Angelo, BULGARELLI, ANDREA, CAPALBI, Milvia, CATALANO, Osvaldo, COMPAGNINO, Antonio Alessio, CONFORTI, Vito, CRESTAN, Silvia, CUSUMANO, Giancarlo, D'AI', Antonino, GERMANI, STEFANO, GIULIANI, Andrea, IOVENITTI, Simone, LA PAROLA, VALENTINA, MACCARONE, MARIA CONCETTA, MINEO, TERESA, MOLLICA, Davide, PAGLIARO, ANTONIO, PARMIGGIANI, Nicolo', PERRI, Matteo, Pintore, Fabio, SCUDERI, Salvatore, TOSTI, Gino, VERCELLONE, Stefano, ZAMPIERI, Luca
Publisher's version (DOI)	10.1117/12.2629362
Handle	http://hdl.handle.net/20.500.12386/36936
Serie	PROCEEDINGS OF SPIE
Volume	12189

The Data Processing, Simulation, and Archive Systems of the ASTRI Mini-Array Project

Saverio Lombardi[a,b], Fabrizio Lucarelli[a,b], Ciro Bigongiari[a,b], Stefano Gallozzi[a],
Martina Cardillo[c], Michele Mastropietro[a], Francesco Gabriele Saturni[a,b], Francesco Visconti[a],
Lucio Angelo Antonelli[a], Andrea Bulgarelli[d], Milvia Capalbi[e], Osvaldo Catalano[e],
Antonio Alessio Compagnino[e], Vito Conforti[d], Silvia Crestan[f], Giancarlo Cusumano[e],
Antonino D'Aì[e], Stefano Germani[g], Andrea Giuliani[f], Simone Iovenitti[h], Valentina La Parola[e],
Maria Concetta Maccarone[e], Teresa Mineo[e], Davide Mollica[e], Antonio Pagliaro[e],
Nicolo Parmiggiani[d], Matteo Perri[a,b], Fabio Pintore[e], Salvatore Scuderi[h], Gino Tosti[g],
Stefano Vercellone[h], and Luca Zampieri[i], for the ASTRI Project[l]

[a]INAF, OA Roma, Via Frascati 33, I-00078 Monte Porzio Catone, Italy
[b]ASI – Space Science Data Center, Via del Politecnico s.n.c., I-00133, Rome, Italy
[c]INAF, IAPS Roma, Via Fosso del Cavaliere 100, I-00133 Roma, Italy
[d]INAF, OAS Bologna, Via Piero Gobetti, 101, I-40129 Bologna, Italy
[e]INAF, IASF Palermo, Via Ugo la Malfa, 153, I-90146 Palermo, Italy
[f]INAF, IASF Milano, Via Alfonso Corti 12, I-20133 Milano, Italy
[g]Università di Perugia, Via Alessandro Pascoli, I-06123 Perugia, Italy
[h]INAF, OA Brera, Via Brera, 28, I-20121 Milano, Italy
[i]INAF, OA Padova, Vicolo Osservatorio 5, I-35122, Padova, Italy
[l]`http://www.astri.inaf.it/en/library/`

ABSTRACT

The ASTRI Mini-Array is an international project led by the Italian National Institute for Astrophysics (INAF) to build and operate an array of nine 4-m class Imaging Atmospheric Cherenkov Telescopes (IACTs) at the *Observatorio del Teide* (Tenerife, Spain). The system is designed to perform deep observations of the galactic and extragalactic gamma-ray sky in the TeV and multi-TeV energy band, with important synergies with other ground-based gamma-ray facilities in the Northern Hemisphere and space-borne telescopes. As part of the overall software system, the ASTRI (*Astrofisica con Specchi a Tecnologia Replicante Italiana*) Team is developing dedicated systems for Data Processing, Simulation, and Archive to achieve effective handling, dissemination, and scientific exploitation of the ASTRI Mini-Array data. Thanks to the high-speed network connection available between Canary Islands and Italy, data acquired on-site will be delivered to the ASTRI Data Center in Rome immediately after acquisition. The raw data will be then reduced and analyzed by the Data Processing System up to the generation of the final scientific products. Detailed Monte Carlo simulated data will be produced by the Simulation System and exploited in several data processing steps in order to achieve precise reconstruction of the physical characteristics of the detected gamma rays and to reject the overwhelming background due to charged cosmic rays. The data access at different user levels and for different use cases, each one with a customized data organization, will be provided by the Archive System. In this contribution we present these three ASTRI Mini-Array software systems, focusing on their main functionalities, components, and interfaces.

Keywords: Gamma-ray instruments, Software, Data Processing, Simulations, Archive, ASTRI Mini-Array

---

Further author information: (Send correspondence to S. Lombardi)
S. Lombardi: E-mail: saverio.lombardi@inaf.it

Software and Cyberinfrastructure for Astronomy VII, edited by Jorge Ibsen,
Gianluca Chiozzi, Proc. of SPIE Vol. 12189, 121890P · © 2022 SPIE
0277-786X · doi: 10.1117/12.2629362

1. INTRODUCTION

The study of very high-energy (VHE, E $>$ $O(0.1)$ TeV) sources is one of the "hot-topic" of the current and future gamma-ray astronomy. Indeed, the emission of photons in the TeV energy range is strictly related with the most energetic phenomena in the Universe, capable to accelerate a single proton up to 10^{20} eV. These photons are emitted when particles are accelerated around compact objects, such as gamma-ray bursts (GRBs), jets formed by active galactic nuclei (AGNs), pulsars and supernova remnants (SNRs), as well as in larger environments (e.g. galactic winds in starburst galaxies), through interaction of cosmic rays (CR) and by elusive processes expected from dark matter (DM) particles.[1, 2]

Huge steps forward in the gamma-ray astronomy have been done in the last years thanks to current ground-based instruments such as particle sampling arrays (PAS), like HAWC, LHAASO, and Tibet AS γ,[3] and Imaging Atmospheric Cherenkov Telescopes (IACTs), like H.E.S.S.,[4] MAGIC,[5] and VERITAS.[6] Furthermore, in recent years the multi-messengers astrophysics has become fundamental thanks to the chance to exploit channels different from the electromagnetic one, like gravitational waves (GWs) and neutrinos. Multi-messengers analysis of source signal can be very useful to understand extra-galactic sources and, consequently, the origin of Ultra High-Energy Cosmic Rays (UHECRs) and the process at the base of GRBs, just to mention a few examples. Given this "state of the art", the scientific community is looking forward to have data from the next-generation IACTs: the ASTRI Mini-Array[7, 8] and, especially, the Cherenkov Telescope Array Observatory (CTAO).[9] Their unprecedented sensitivity and angular resolution in the VHE band could clarify the nature of the gamma-ray emission from already detected sources and discover new ones.[10, 11]

The ASTRI Project was born as an INAF Flagship Project[12–14] aimed to develop an end-to-end prototype of the CTAO Small-Sized Telescope (SST)[15] in dual-mirror configuration, the ASTRI-Horn telescope.[16, 17] The telescope has been installed at the INAF "M.C. Fracastoro" observing station in Serra La Nave (Mt. Etna, Italy) and is currently in operation. The second phase of the project is related to the development and installation of an array of nine ASTRI-like telescopes, the ASTRI Mini-Array, at the *Observatorio del Teide* in Tenerife (Spain). Its first telescope, ASTRI-1, has been delivered on site in June 2022 and other two telescopes, ASTRI-8 and ASTRI-9, will be installed by fall 2022.[8] These first three telescopes will be ready to take data during 2023, thus allowing us to start soon the verification and validation phase of the stereoscopic system and providing first scientific observations of astrophysical targets. The completion of the full array is foreseen in a few years.

The ASTRI Mini-Array will be able to study in great detail relatively bright sources[*] with an angular resolution of ∼3 arcmin and an energy resolution of around 10% at an energy of about 10 TeV, with rather little degradation up to 100 TeV.[18] The first four years of observations will be dedicated to specific science topics.[11] Among them, we mention: observation of selected candidate PeVatrons (Tycho, Galactic Center, ...); study of the extra-galactic background light (EBL); studies of fundamental physics (e.g., search for axion-like particles signatures in deep observation of selected BL Lac blazars, like Mkn 501 and 1ES 0229+200). Besides the main core science programs, a fraction of the observation time will be dedicated to observations of selected Galactic (PWNe, SNRs, ...)[19] and extra-Galactic targets (high synchrotron peak and extreme blazars; dark matter candidates; starburst galaxies).[20] In particular, taking advantage of the wide ASTRI field of view (∼10°), which allows to simultaneously investigate more than one source during the same pointing, we will perform deep observation of complex Galactic regions, such as the Cygnus region or the Galactic Center. Follow-up observations of selected transient and multi-messenger astrophysics phenomena (GRBs, GWs, and very high-energy neutrinos) are also foreseen.

Besides the major efforts going on for the development, verification, and deployment on site of all hardware components, the ASTRI Team is hardly working as well on the development of all software tools that are needed to pre-process, reduce and analyze the upcoming data collected with the Mini-Array, and to store data at different levels for their best dissemination and exploitation. These software tools are mainly part of the Data Processing, Simulation, and Archive Systems. In the following sections, we present an overview of those systems. In Section 2 we present the Data Processing System with all its components; in Section 3 we explain the simulation tools and setup; in Section 4 we describe the organization of the Archive System. In Section 5 we briefly summarize the

---

[*] $E^2 \times$Flux on the order of $10^{-12}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ at 10 TeV.

main results achieved so far with the developed software tools. Finally, in Section 6, we provide a brief summary and outlook.

2. THE DATA PROCESSING SYSTEM

The ASTRI Mini-Array *Data Processing System* (DPS) is a collection of software components which are in charge of preparing, calibrating, reducing, and analysing the raw Cherenkov (or data level zero, DL0) data acquired during the observations up to the generation of high-level science-ready data products (DL3) and standard science products (DL4/5). The DPS system is also in charge of providing suitable data check and calibration products, as well as performing the data reduction of the Stellar Intensity Interferometry Instrument (SI3) data.

The main software components of the DPS are:

- *Stereo Event Builder* (SEB): it performs the off-line software stereo array trigger;[21]
- *Cherenkov Data Pipeline* (CDP): it is in charge of the calibration, reconstruction, selection, and automated scientific analysis of Cherenkov data;[22, 23]
- *Intensity Interferometry Data Pipeline* (IIDP): it performs reconstruction and scientific analysis of SI3 data;[24]
- *Calibration Software*: it is a collection of software libraries that implements all the algorithms needed to perform the calibration of the ASTRI Mini-Array devices, at both single-telescope and array level, and to extract suitable calibration factors for the processing of scientific data.[25]

Raw Cherenkov data contain the information of the signals induced by nanosecond flashes in the UV-blue band, emitted by cosmic rays and astrophysical gamma rays through the Cherenkov effect in the atmosphere, which are collected by the reflective surface and recorded by the fast-response pixelized camera of the telescopes. In order to process the Cherenkov data up to the final data levels, the following data processing steps are envisaged. The raw data acquired by each telescope of the array are transferred (immediately after acquisition) to the off-site ASTRI Data Center and archived, along with other ancillary data. A preliminary step for the proper execution of the full end-to-end data processing chain is the execution of the *Cherenkov Camera Preprocessing*. This software component belongs to the ASTRI Mini-Array Data Acquisition System[26] and converts single-telescope scientific raw data from binary format into the FITS standard format,[27] which is adopted as common input/output (I/O) data format for each DPS subsystem. After this preliminary step, the SEB software component performs the off-line software trigger for the identification of stereoscopic Cherenkov events induced by the same extensive air shower on more than one array telescope. The next steps of the data processing are performed by the CDP software component, through the use of the `A-SciSoft` software package.[22, 23] The raw Cherenkov data, containing the full information available per camera pixel (integrated signal amplitude in ADC-counts and arrival time of the Cherenkov light emitted by the showers), are calibrated separately for each telescope. In this step, the pixel signal is extracted and converted into physically meaningful units (photoelectrons, pe), by means of suitable calibration factors extracted by dedicated Calibration Software tools. The calibrated data of each telescope undergo, then, an image cleaning procedure aimed to remove pixels which most likely do not belong to a given Cherenkov shower image. After the cleaning procedure, the resulting images are parameterized.[28] Once the single-telescope-wise parameters are available, the data of each single telescope can be reconstructed by means of suitable single-telescope-wise look-up-tables (LUTs) for the gamma/hadron separation, arrival direction estimation, and energy reconstruction. It is worth noting that this last step is optional in the standard stereoscopic data reduction chain, but it is obviously mandatory in the case of single-telescope data taking (foreseen e.g. during the commissioning phase of the system). Successively, the data coming from the different telescopes are merged, taking advantage of the pieces of information extracted by means of SEB software tools. In this step, a set of array-wise shower parameters are computed as well. Once the array-wise parameters are available, the data are further reduced by means of suitable array-wise LUTs. These LUTs, along with single-telescope-wise ones, are generated from dedicated Monte Carlo (MC) simulations by means of specific software modules implemented in `A-SciSoft`. After the application of the array-wise LUTs to the data, the parameters for gamma/hadron separation, arrival direction estimation, and energy reconstruction are available for each Cerenkov event, i.e. the data are fully reconstructed. The fully reconstructed Cherenkov events are then selected through the application of optimized analysis cuts in order to get the final reduced event-lists. These, together with the observation-related Instrument Response Functions (IRFs) (generated from dedicated MC simulations by means of specific software modules implemented in `A-SciSoft`, as in the case of LUTs) and data-filtering tables (good time intervals, GTI) constitute the so-called high-level science-ready data (DL3) to be delivered to the Science Users. An automated scientific analysis pipeline is also envisaged in order to provide the Science Users with standard science products (DL4/5) for reference. Figure 1 depicts a schematic view of the functional design of the end-to-end Cherenkov data processing chain executed by the ASTRI Mini-Array Data Processing System.

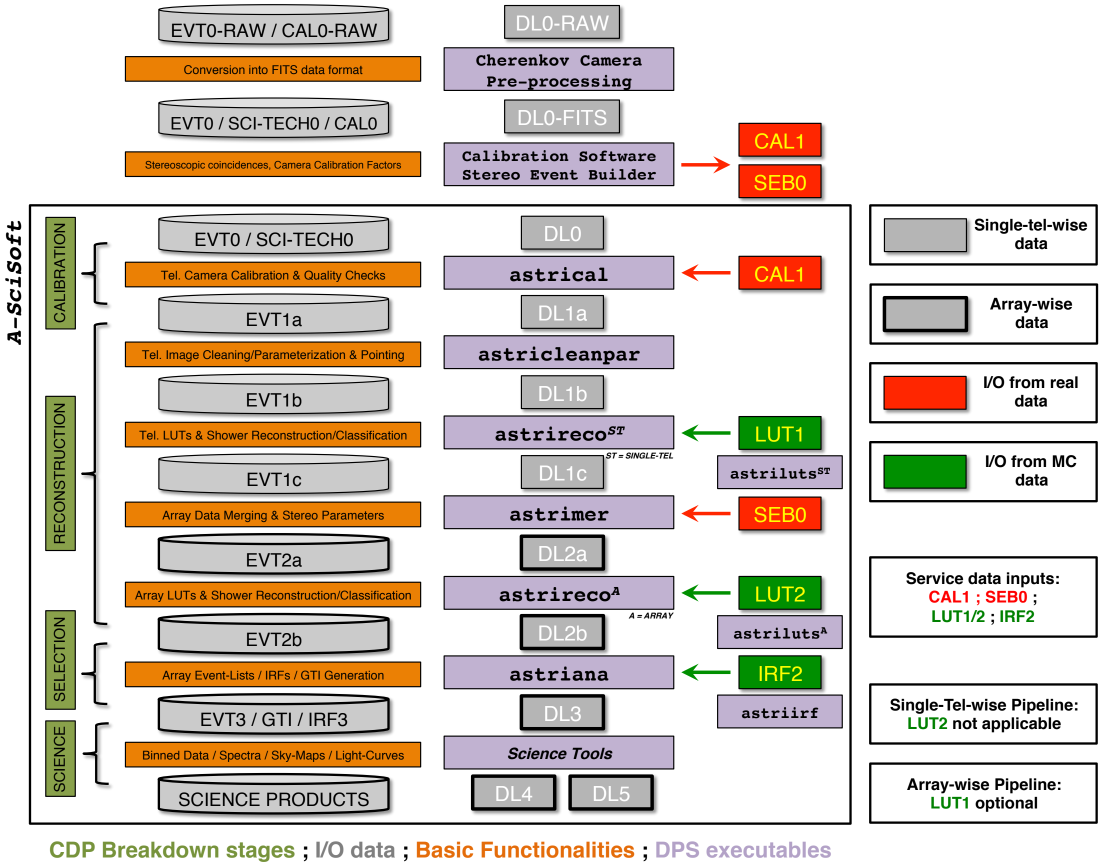

Figure 1. Schematic view of the end-to-end Cherenkov data processing chain executed by the ASTRI Mini-Array Data Processing System (DPS), starting from the pre-processing stage down to the generation of high-level science-ready data (DL3) and automated science products (DL4/5). From left to right, functional Cherenkov Data Pipeline (CDP) breakdown stages (which make use of the `A-SciSoft` software tools) are shown as olive green boxes, I/O data as grey cylinders, basic software functionalities as light maroon boxes, data levels as grey boxes (thin: telescope-wise data; thick: array-wise data), and data processing executables as light purple boxes. CDP service data inputs, i.e. CAL1, SEB0, LUT1/2 and IRF2, are obtained by running the Calibration Software, Stereo Event Builder (SEB), and CDP for MC data, respectively.

Two types of end-to-end scientific data processing levels are foreseen: a *short-term* standard analysis, to be automatically run at the end of each Observation Run[†], as soon as the scientific raw data are transferred to the off-site ASTRI Data Center, in order to allow a scientific quick look of the on-going observations; and the *long-term* standard analysis, which shall produce consolidated high-level science-ready data and reduced IRFs

---

[†] An Observation Run is defined as the minimum block of array data taking that provides a self-consistent set of raw scientific data reducible up to DL5. The typical duration of an Observation Run is on the order of a few tens of minutes.

for final scientific analysis and publication of results. The short-term data analysis pipeline shall make use of pre-computed calibration factors and coarse LUTs/IRFs, while the long-term data analysis pipeline shall be based on the best available calibration factors, LUTs, and IRFs.

The following subsections provide some additional information on the main software components of the DPS, along with a brief description of its software framework and development infrastructure.

2.1 Stereo Event Builder

The DPS – *Stereo Event Builder* (SEB) is the software component that performs the off-line stereo array trigger of the Cherenkov events recorded by the telescopes of the ASTRI Mini-Array. This step is needed because no hardware stereoscopic trigger has been planned on-site. The array trigger acts on information sent by each triggered telescope (like the trigger timestamps and the telescope status) to select Cherenkov shower signatures using stereoscopic information. A stereo array trigger occurs when a time coincidence between at least two triggered telescopes within a predefined time window is found. The inputs of the SEB system are the single-telescopes DL0 data, belonging to the same Observation Run, already converted to FITS format by the Camera Pre-Processing and stored in the ASTRI Bulk Archive. Together with these data, the SEB makes also use of Alt-Azimuth pointing data containing the pointing direction of the telescopes, previously created and stores in the Bulk Archive by the Supervisory Control And Data Acquisition System[29] (SCADA). The system shall assign a unique identifier to each stereo event based on a run identifier and a stereo event sequential numbering. After the array trigger accomplishment, the SEB shall store the stereo information in a separate FITS file (SEB0). The generated stereo files shall be archived and ready for use by the DPS – Cherenkov Data Pipeline. More details about the SEB system and the algorithm used for the software identification of the stereo Cherenkov events can be found in.[21]

2.2 Cherenkov Data Pipeline

The DPS – *Cherenkov Data Pipeline* (CDP) is the software component that performs data reduction and analysis of the Cherenkov events observed by the ASTRI Mini-Array. The main goal of the system is to reconstruct the physical characteristics of the astrophysical gamma rays (and background cosmic rays) from the raw Cherenkov data collected by the ASTRI Mini-Array telescopes during the observations of the scientific targets. The full scientific data reduction and analysis shall be obtained by means of the `A-SciSoft` software package.[22, 23] Initially conceived primarily for the analysis of the ASTRI-Horn data, `A-SciSoft` was nevertheless designed and coded since its inception to perform also the stereoscopic analysis of an array of ASTRI-like telescopes. `A-SciSoft` is organized in four distinct functional breakdown stages (*Calibration*, *Reconstruction*, *Selection*, and *Science*), which can be executed one after the other as an end-to-end pipeline allowing a data reduction from raw level (DL0) to the high-level science-ready data (DL3). DL3 data will be delivered to the Science Users who shall analyze them by means of dedicated ASTRI Science Analysis Tools or by publicly available ones, like `Gammapy`[30] and the `ctools`,[31] to get the final science products, such as the binned reduced data (DL4) and detection plots, sky-maps, source spectra, and light-curves (DL5). Science products shall be also generated, in an automated way, by the CDP at the end of the reduction pipeline. In the case of the short-term analysis pipeline, preliminary science products shall be generated and used as a feedback for the operators about the on-going observations within less than one hour from the data taking. In the case of the long-term analysis pipeline, instead, standard science products shall be generated as a reference for the Science Users.

In addition to the reduction of real data, the CDP is also used to reduce and analyze MC simulated data produced by the ASTRI Mini-Array Simulation System (see Section 3). In particular, the CDP for MC data is exploited to compute suitable single-telescope and/or array-wise LUTs and low-level global IRFs (specifically IRF2, covering all of the instrumental phase-space) for real Cherenkov data reconstruction and selection.[17, 22, 23] LUTs are achieved by training a machine learning algorithm with MC simulated data (and, possibly, real data) and used by the CDP for the gamma/hadron separation, arrival direction estimation, and energy reconstruction of the real Cherenkov events. IRFs, instead, include the following quantities: effective collection area, energy and angular resolution, and residual background rate as a function of energy, zenith and azimuth pointing, and gamma-ray source position.

2.3 Intensity Interferometry Data Pipeline

Besides observations of very high-energy gamma-ray sources, the ASTRI Mini-Array will also perform stellar Hambury-Brown intensity interferometry observations of a selected sample of bright sources, extending the duty cycle and scientific outcome of the array. Each telescope of the array will be equipped with an interferometry module that allows us to obtain angular resolutions down to 50 micro-arcsec, thanks to its very long baselines (hundreds of meters). The DPS – *Intensity Interferometry Data Pipeline* (IIDP) is in charge of performing data reconstruction and scientific analysis of the Stellar Intensity Interferometry Instrument (SI3). More details about these type of observations, the ASTRI Mini-Array interferometric system, and the related data reduction can be found in.[24]

2.4 Calibration Software

The ASTRI Mini-Array requires several calibration procedures for both all subsystems composing the telescopes (mount, optical system, Cherenkov camera) and the entire array. These procedures are ultimately intended to provide all the calibration quantities and factors necessary to achieve proper processing of the scientific data acquired by the Cherenkov telescopes, as well as to monitor the health of the telescopes and their subsystems.[25] The DPS – *Calibration Software* is a collection of software tools that reduces and analyzes all the data produced during the calibrations of the system. This includes:

- *Optics Calibration Software*: it includes all software procedures needed to reduce and analyze calibration data acquired for the monitoring of the Point Spread Function (PSF) and the panel efficiency of the telescope primary mirrors;
- *Cherenkov Camera Calibration Software*: it includes all software procedures to test the correct functioning of the Cherenkov cameras and to provide the necessary factors for the calibration of scientific data;
- *Pointing Calibration Software*: it includes all software procedures to monitor the correct pointing of the telescope and verify the input pointing model;[32]
- *Optical Throughput Evaluation/Monitoring Software*: it includes all software procedures to evaluate and monitor the telescope optical throughput (in particular, using detection and evaluation of Cherenkov muon rings).

The Calibration Software tools shall also manage and analyze data obtained by the calibration procedures executed to perform inter-telescope and array calibration as well as atmosphere characterization using a dedicated LIDAR instrument.

2.5 Software framework

We adopt the best practices of software development of minimal external dependencies, agile software development method, continuous integration (CI), testing, deployment and software quality assurance. We use standard `C++11` for computing intensive algorithms and `python3` for event related computations and pipelining of DPS executables. Concerning the CDP, `A-SciSoft` depends essentially on four libraries included in the `HEASoft`[‡] astronomical software package: `cfitsio`, `CCfits`, `hdutils`, and `hoops/ape`, needed for I/O, Calibration Database (CALDB) interface, and parameter system handling, respectively. The SEB software makes also use of these libraries. Standard `CCfits` usage caused severe data bloating and sub-optimal performance due to data duplication in internal `CCfits` data containers. For this reason, I/O critical parts of the software required the application of `cfitsio`'s low-level `fits_*_tblbytes` routines obtaining less than half the memory footprint when reading and writing files and about ×7 faster I/O with respect to `CCfits`.[22] Machine learning software modules use the "pydata stack" and the `scikit-learn`[§] implementation of the Random Forest (RF) algorithm.[33]

[‡] http://heasarc.nasa.gov/lheasoft/

[§] https://scikit-learn.org/

2.6 Development infrastructure

We leverage an INAF hosted `GitLab`[¶] instance for CI and deployment of DPS software, and in particular of `A-SciSoft`. Test data and machine learning models and relative training data are managed with `dvc` ("git for data"). A `SonarQube`[‖] instance is linked with the CI system statically analyzing code at each commit and producing charts and metrics of code quality and test coverage. We deploy `A-SciSoft` in both `docker`[**] and `singularity`[††] containers for reproducibility of results and deployment on High Performance Computing (HPC) infrastructure. The compute nodes in the ASTRI Data Center are foreseen to be organized as an HPC cluster, issuing a set of tasks managed by an queuing system like `slurm`[‡‡], whereas the automatic task orchestration for the MC data, *short-term*, and *long-term* pipelines is foreseen to be managed with `apache airflow`[*], allowing for an easy task scheduling, integration with the Archive System and continuous monitoring for data warnings and possible processing errors.

3. THE SIMULATION SYSTEM

The ASTRI Mini-Array *Simulation System* is a collection of software components which are in charge of generating all simulated data needed for the ASTRI Mini-Array Project. Detailed Monte Carlo (MC) simulations are indeed fundamental essentially in all phases of project. In the design and development phase, MC simulations are used to optimize the telescope positions in the array, to fully characterize the (scientific) performance of the system, and to define and test data analysis methods that are eventually exploited for the processing of real data. Moreover, simulations are needed for calibration purposes and for the development of ancillary instruments. In the commissioning and operation phase, instead, MC simulations are used to provide auxiliary inputs for the reconstruction of real Cherenkov events (through the generation and application of suitable LUTs) and to provide the response of the system to gamma-ray astrophysical observations (by means of the IRFs).[22, 23]

3.1 Simulation chain

The simulation of the Cherenkov events recorded by IACTs comprises two steps: *i)* the simulation of the development of particle cascades in the atmosphere with the associated emission of Cherenkov light and *ii)* the simulation of the response of the telescopes to the impinging light. In the adopted ASTRI simulation chain, the first step is carried out with the `CoRSiKa` software package[†], a program for detailed simulation of extensive air showers initiated by high-energy cosmic ray particles (photons, protons, atomic nuclei, electrons). Such particles are tracked through the atmosphere until they undergo reactions with the air nuclei, at which stage the program simulates the generation of Cherenkov radiation.[34] The transmission of Cherenkov light from the emission point to the telescope and the detector response are instead simulated with the `sim_telarray` software package,[35] which can be flexibly configured at run-time depending on the telescope system. At the end of the simulation chain, the final MC simulations are stored in the Simulation Archive (see Section 4).

Both steps of the simulation chain are usually very demanding in terms of computing power and disk space, with the first one often dominating the overall computing needs. It is worth remembering that the Cherenkov imaging technique achieves a very high hadronic background rejection and therefore huge numbers of hadronic events need to be simulated in order to properly estimate the performance. To cope with such requirements, massive productions of simulated events are usually carried out using distributed computing systems like `EGEE`[‡]. Although these distributed systems have been leveraged for ASTRI MC productions generated to date, extensive use of the resources of the upcoming ASTRI Data Center in Rome is expected, particularly in the commissioning and operation phase of the ASTRI Mini-Array (see Section 4).

[¶] https://about.gitlab.com/

[‖] https://www.sonarqube.org/

[**] https://www.docker.com/

[††] https://apptainer.org/

[‡‡] https://slurm.schedmd.com/

[*] https://airflow.apache.org/

[†] https://www.iap.kit.edu/corsika/.

[‡] https://eu-egee-org.web.cern.ch/index.html.

3.2 MC productions

The first massive production of MC simulations for the ASTRI Mini-Array at the Teide Observatory site, called "ASTRI-MA-Prod1", was carried out in spring 2020 and released in fall 2020. For this production, we simulated gamma rays coming from a point-like source – at a zanith angle (ZA) of 20° and an azimuth angle (AZ) of 180° – alongside with diffuse gamma-rays, electrons, and protons with incoming directions uniformly distributed in a cone with 10° radius centered on the point-like source direction. The energy of all primary particles was thrown according to a power-law energy spectrum with spectral index equal to -1.5, to ensure enough simulated event statistics in the highest energy bins (above several tens of TeV). The ASTRI-MA-Prod1 production was fully reduced and analyzed with the `A-SciSoft` software package[22, 23] to provide the first evaluation of the system performance and to generate suitable IRFs to be eventually adopted for scientific studies related to the ASTRI Mini-Array Science Core Program.[11]

A new massive production, called "ASTRI-MA-Prod2", has been started in fall 2020 and it is still on-going. The purpose of this new production is to characterize the performance of the system at different zenith and azimuth pointing directions. In fact, the performance of any IACTs system significantly depends on the actual zenith pointing directions. In addition, since the layout of the ASTRI Mini-Array is actually quite elongated, its performance is expected to show not-trivial dependencies with respect to azimuth pointing direction, particularly for medium and high ZAs. Moreover, compared with the previous MC production, the ASTRI-MA-Prod2 takes into account the final positions of the ASTRI Mini-Array telescopes at the Teide Observatory site, officially approved in fall 2020[§].

The first sub-production of the ASTRI-MA-Prod2, called "ASTRI-MA-Prod2_20deg" – i.e. simulations at a ZA of 20° – was launched in fall 2020 and completed in early 2021. With the only exception of the telescope positions, the simulation steering parameters used for the ASTRI-MA-Prod2_20deg were the same used for the previous production. Compared to ASTRI-MA-Prod1, the new production increased the number of generated events, comprising two different azimuth orientations: AZ=$0, 180°$. This sub-production has been fully reduced and analyzed with `A-SciSoft` in order to update the the assessment of the system performance[18] (see Section 5).

In Table 1, the main parameters adopted to produce each particle data set of the ASTRI-MA-Prod1 and ASTRI-MA-Prod2_20deg productions are shown.

particle type (particle component)	spectral slope	energy range [TeV]	view cone radius [deg]	scatter radius [m]	azimuth angle [deg]	zenith angle [deg]	total number of simulated showers
ASTRI-MA-Prod1							
gamma (point-like)	-1.5	0.1 – 330	0	2000	180	20	10^7
gamma (diffuse)	-1.5	0.1 – 330	10	2400	180	20	10^8
electron	-1.5	0.1 – 330	10	2400	180	20	10^8
proton	-1.5	0.1 – 600	10	2400	180	20	10^9
ASTRI-MA-Prod2_20deg							
gamma (point-like)	-1.5	0.1 – 330	0	2000	0/180	20	$4{\cdot}10^7$
gamma (diffuse)	-1.5	0.1 – 330	10	2400	0/180	20	$4{\cdot}10^8$
electron	-1.5	0.1 – 330	10	2400	0/180	20	$2{\cdot}10^8$
proton	-1.5	0.1 – 600	10	2400	0/180	20	$2{\cdot}10^9$

Table 1. Main parameters describing the MC air shower simulations in the so-called ASTRI-MA-Prod1 and ASTRI-MA-Prod2_20deg productions so far generated for the ASTRI Mini-Array at the Teide Observatory site.

[§] The assigned positions of two telescopes of the array, ASTRI-8 and ASTRI-9, have been modified in fall 2020 due to the unavailability of previously selected positions at the Teide Observatory site.

3.3 Simulation plan

As mentioned above, simulations carried out so far by the ASTRI Simulation Team have considered only observations of sources at ZA=20°. Furthermore, the Night Sky Background (NSB) considered in the simulations has been set to dark conditions, i.e. when the Moon is well below the horizon. However, many scientifically interesting targets for the ASTRI Mini-Array can be observed from the Teide Observatory site only at medium-to-large ZAs. In addition, the possibility to extend the data taking during weak and moderate moon conditions is particularly important in order to increase the overall duty cycle of the system. For these reasons, the ASTRI-MA-Prod2 will cover different zenith and azimuth pointing directions – namely, ZA=$20°, 40°, 60°$ and AZ=$0°, 90°, 180°, 270°$ – with different level of the NSB (corresponding to different moon conditions, from weak to strong). After the ASTRI-MA-Prod2_20deg sub-production, the so-called ASTRI-MA-Prod2_60deg – i.e. simulations at a ZA of 60° – will be generated. In this way, it will be possible to provide the ASTRI Mini-Array performance and IRFs in the two ZA edges of the expected ZA range of nominal observations. The sub-productions at the intermediate ZA of 40° will follow. The simulation of different levels of NSB, instead, does not require the re-simulation of the development of atmospheric showers each time. Hence, we will start to study the effect of the moon light on the ASTRI Mini-Array performance by re-running the `sim_telarray` simulation code on the available atmospheric showers (produced by `CoRSiKa`), setting different values of NSB, and re-processing the data with the scientific pipeline. According to preliminary evaluations of the performance of the Silicon Photo-Multipliers (SiPMs) equipping the Cherenkov cameras, the ASTRI Mini-Array should safely take data with a flux of diffuse light up to ∼18 times the nominal NSB flux in dark conditions[¶]. The performance of the ASTRI Mini-Array will be eventually evaluated at five different levels of NSB, corresponding to different moon phases and Moon-to-target angular separation, for each foreseen telescope pointing direction. These NSB levels has been determined by re-scaling the synthetic NSB spectra produced with the `SkyCalc` software[‖] [36, 37] for different moon-light levels and angular distances to the observed sky brightness at the Teide Observatory site in the $UBVR$ bands.

The simulation plan described above covers more or less the entire early phase of the ASTRI Mini-Array site implementation. As soon as the Cherenkov camera will be installed on the first telescope at the Teide Observatory site (foreseen in early 2023), we will continue the validation process of the simulation chain, started in December 2018 with the real data taken with the ASTRI-Horn telescope.[17] Such a process will require many iterative comparisons between data acquired with the first camera(s), both calibration and scientific data, and data simulated with different sets of input parameters. The comparison will be carried out firstly at pixel level and then at image level for each camera available. As soon as at least two cameras will be installed, we will start to reconstruct events in stereoscopic mode and to perform comparisons at a higher level too. This process will involve the simulation of many different samples of calibration and scientific data with different sets of steering parameters. Each sample is usually not very demanding in terms of CPU, disk space and overall time to be simulated, but the large number of needed samples can quickly lead to a considerable amount of computing and storage resources. For these reasons, the resources at the Data Center in Rome have been properly dimensioned to take also into account the MC simulations needs.

4. THE ASTRI ARCHIVE SYSTEM

The ASTRI Mini-Array *Archive System* plays a central role in the whole observing life-cycle of the array, which goes from observation preparation and execution, to data processing and dissemination of the high-level science-ready data (DL3) and automated science products (DL4/5) to the Science Users (see Figure 2). The Archive System is a software and hardware service that shall provide storage and organization for all persistent information (data, data products, and metadata) generated for and by the ASTRI Mini-Array systems and defined through the ASTRI Mini-Array data models,[29] such as: observing projects and observation schedules; raw and reduced scientific data; device monitor and auxiliary data; system configuration data; logs of all operations, etc.

The complete ASTRI Mini-Array Archive System shall be composed by the following logical units:

[¶] The present reference value of the NSB flux in dark condition is 0.24 ph $\mathrm{ns^{-1}\ cm^{-2}\ sr^{-1}}$ in the $300 \div 650$ nm band.

[‖] http://www.eso.org/observing/etc/doc/skycalc/helpskycalc.html

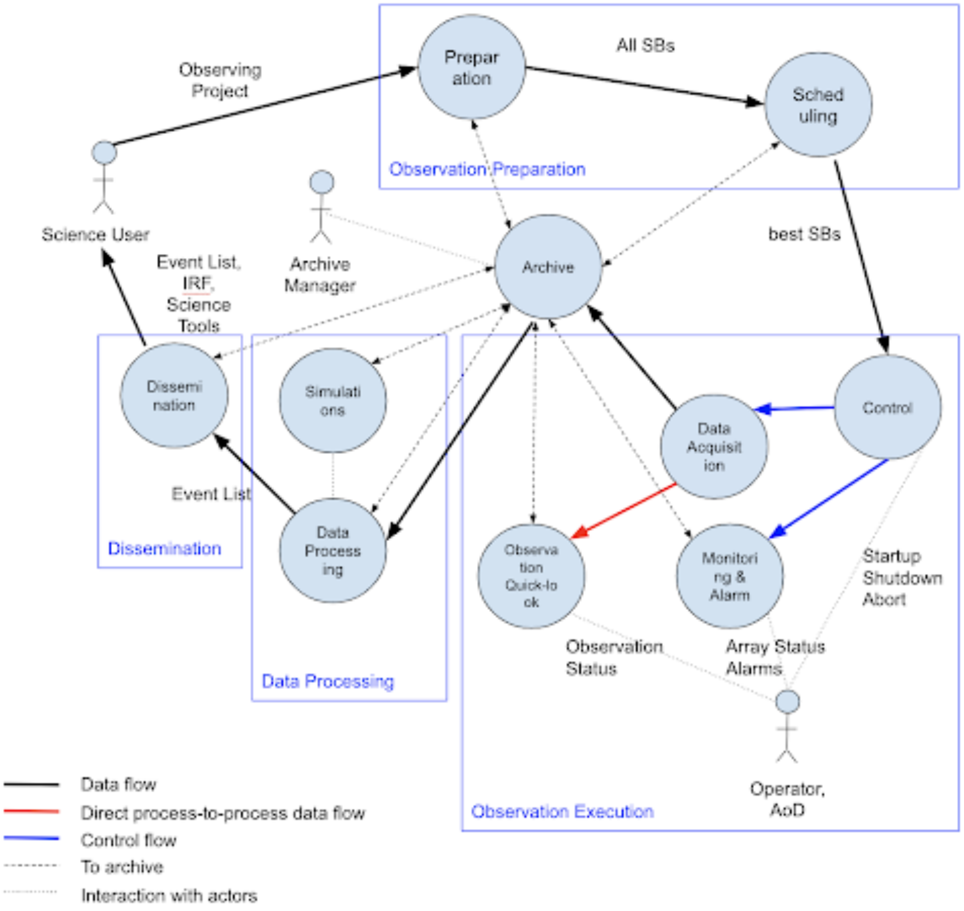

Figure 2. The ASTRI Mini-Array observing life-cycle and its global information and data flow. The dashed lines directed to/from the Archive indicate that a) all data is saved and can be retrieved from the Archive, and b) that the physical data flow may be handled by the Archive.

- *Bulk Archive*: it stores raw data from the Cherenkov cameras, the stellar intensity interferometer modules, and other assemblies; it also stores intermediate data products generated by the DPS components as well as data calibration products;
- *Science Archive*: it stores the observing projects and the related observation plans (as scheduling blocks); the science results: high-level science-ready data (event-lists and IRFs); good-time data intervals (GTI); automated science products generated by the DPS – CDP; service and ancillary data (like telescope mount pointing info, observation execution information, ...) captured during the acquisition runs by the Data Capture mechanism;[29]
- *Simulation Archive*: it contains all MC data samples simulated by the Simulation System for different Mini-Array configurations;
- *System Configuration Database* (SCDB): it stores the System Configuration Data Model;
- *Monitoring Archive*: it stores all the Monitoring Data Model sub-types (e.g. monitor assemblies, environmental data, ...) acquired by the ASTRI Mini-Array Monitoring System;
- *Alarm Archive*: it stores the alarms produced by all components and the monitoring data acquired by the Alarm System to generate alarms;

- *Quality Archive*: it stores Cherenkov and intensity interferometry observations quality results produced by the ASTRI Mini-Array Online Observation Quality System[38] (OOQS), and the data quality check reports generated by the DPS System;
- *Log Archive*: it stores the logs produced by all components and then acquired by the ASTRI Mini-Array Logging System;
- *Calibration Database* (CALDB): it is a dedicated database that stores CAL1, LUTs, IRFs, and other instrumental and pre-computed quantities available for being used throughout the entire scientific data processing chain;
- *Performance DB*: it is a dedicated database storing reduced engineering and auxiliary data, used to perform mid-term and long-term performance studies as well as predictive studies.

4.1 The ASTRI Data Center and the ICT infrastructure

The ASTRI Mini-Array Archive System is composed of two physically separated units: an *On-site Archive System* at the Array Observing Site and an *Off-site Archive System* hosted at the ASTRI Data Center in Rome. While the complete and permanent ASTRI Mini-Array Archive System will be deployed at the ASTRI Data Center, the On-site Archive System shall temporary host monitoring, logging, alarm, quality control, and configuration DB services running during the ASTRI operations. It shall be synchronized with the Off-site Archive System through a proper data transfer system. Raw data acquired during the observations with the ASTRI Mini-Array will be stored in a Local Bulk Repository and immediately transferred to the off-site Bulk Archive. In what follows, we describe the main Information and Communication Technology (ICT) infrastructure components of the ASTRI Data Center and the logical organization of the Off-site Archive System. A description of the on-site ICT infrastructure, particularly during the commissioning phase of the system, can be found in.[39]

The ASTRI Mini-Array Archive System shall rely on a proper ICT infrastructure in order to achieve the functional scenarios detailed in the top level software architecture.[29] The Data Center in Rome will host the long-term data Archive of the ASTRI Mini-Array, storing and preserving all data produced during the Mini-Array operations. Moreover, the Data Center shall guarantee enough computing and storage resources to run the scientific data processing pipelines and the ASTRI Mini-Array simulations needed to reconstruct real data, characterize the detector response and assess the Mini-Array scientific performance. The Data Center will also host services to support Science Users in all phases of the Observing Project execution, from the proposal submission to the retrieval of the high-level science-ready data to be analyzed with appropriate science tools (see Section 2).

The ASTRI Data Center shall fulfill the following high-level requirements in term of performance:

- *Bandwidth*: an efficient, fast, high throughput and low-latency connection of at least 10 Gbit/s;
- *Computing*: an efficient and managed queuing system to run and manage multiple jobs;
- *Storage*: easily horizontal-scalable storage resources, for long-term storage to be silent-corruption free;
- *Easy Access*: an suitable access to a very large amount of data and metadata, for different users and use cases;
- *OAIS compliance*: the ASTRI Data Center shall be compliant with the Open Archival Information System (OAIS) paradigm[**].

A distributed archive solution will be adopted for the physical deployment of the Archive, with three main nodes distributed among the following computing centers: the INAF – *Osservatorio Astronomico di Roma* (OAR) center (hosting the central storage and computing nodes), the INFN – *Laboratori Nazionali di Frascati* (LNF) center (where a direct access to the Data Grid infrastructure is provided), and the Space Science Data Center

---

[**] See https://public.ccsds.org/pubs/650x0m2.pdf.

(SSDC) of the Italian Space Agency (ASI) (with possibility to interface the high-level ASTRI Science Archive with the multi-wavelength SSDC facilities and Science Tools services[††]). The Array Observing Site will feed the ASTRI Mini-Array Archive System with all scientific data and monitoring DB dumps needed to characterize and analyze Mini-Array data (along with calibration and simulation data). The physical architecture of the Archive System at the ASTRI Data Center is depicted in Figure 3.

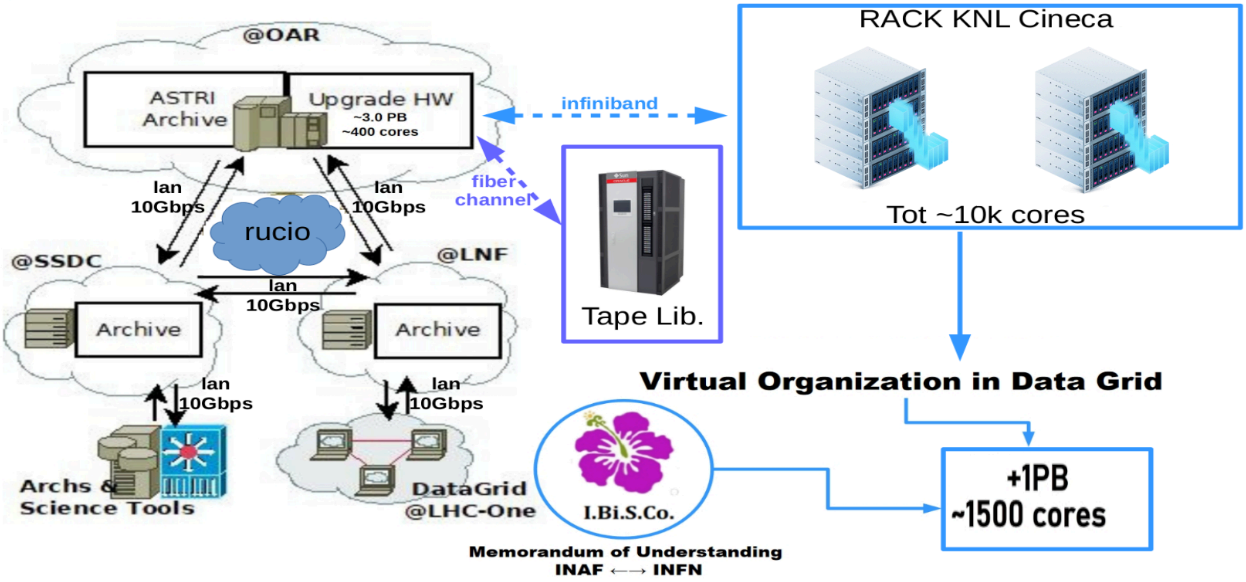

Figure 3. Physical view of the ASTRI Data Center: the startup configuration shall be composed of three archive nodes federated together. Data organization, management, and access between the three archive nodes will be managed using the `Rucio` open-source software framework.[40]

4.2 Storage dimensioning and computing resources

The ASTRI Data Center has been preliminary dimensioned according to the expected data production rate. In the conservative observing case (a high Cherenkov event rate of ∼1 kHz per telescope, with full array in operation), it is expected to be around 2.5 PB/yr, including scientific data produced at different data reduction level (from DL0 up to DL5), some hundreds of TB for each MC production, and a few tens of TB/yr due to data from the monitoring, logging, configuration, alarm, and quality archives[‡‡]. In addition to this, the SI3 Modules are expected to produce around 1.2 PB/yr of raw data.[24]

The Data Center is being implemented and will consist of several machines with different roles. The bulk data storage and high-performance computing, hosted by the main Archive node at the INAF-OAR computing center, will be accomplished by 15 dedicated workstations whose resources are virtually aggregated together and provided as a single cluster, with an initial (hot) storage capacity of ∼3.4 PB. The ASTRI MC simulations will be mainly executed on the INFN-LNF data-GRID node, within a dedicated ASTRI Mini-Array Virtual Organization (VO). For that purpose, the INFN-LNF node was upgraded to provide additional ∼1500 cores of computing power and ∼1 PB of data storage on GRID. Additional computing power resources could be added in a Data Grid perspective to improve computing performance in a Virtual Organization dedicated to the project.

[††] See https://www.ssdc.asi.it/.

[‡‡] In the nominal observing case (a Cherenkov event rate of ∼150 Hz per telescope, with full array in operation) the overall data production rate is around 0.5 PB/yr.

Finally, it is foreseen to periodically backup bulk raw data into external storage devices (e.g, tape libraries) for disaster recovery. Thus, the startup ICT configuration shall contain a backup tape-library facility to guarantee disaster recovery and backup for all life-time of the project. The initial (cold) storage capacity will be of ∼1 PB, extendable to ∼30 PB.

5. MAIN ACHIEVEMENTS

The software tools and procedures developed within the ASTRI Mini-Array Data Processing System and Simulation System have been so far tested by means of real data taken with the ASTRI-Horn telescope and dedicated Monte Carlo (MC) productions.

5.1 Real data results

In the case of real data processing, the application of performing analysis tools implemented in `A-SciSoft` to data collected with the ASTRI-Horn telescope in 2018, during an observational campaign on the Crab Nebula, led to the first detection of the source with a Cherenkov telescope in dual-mirror Schwarzschild-Couder configuration.[17] Figure 4 shows the so-called detection plot of the source, where an excess corresponding to a statistical significance of 5.4σ above an energy threshold of ∼3 TeV was detected in the fiducial signal region of the on-source data. This achievement has represented an important step towards the validation of the dual-mirror optical design for ground-based gamma-ray astronomy applications.

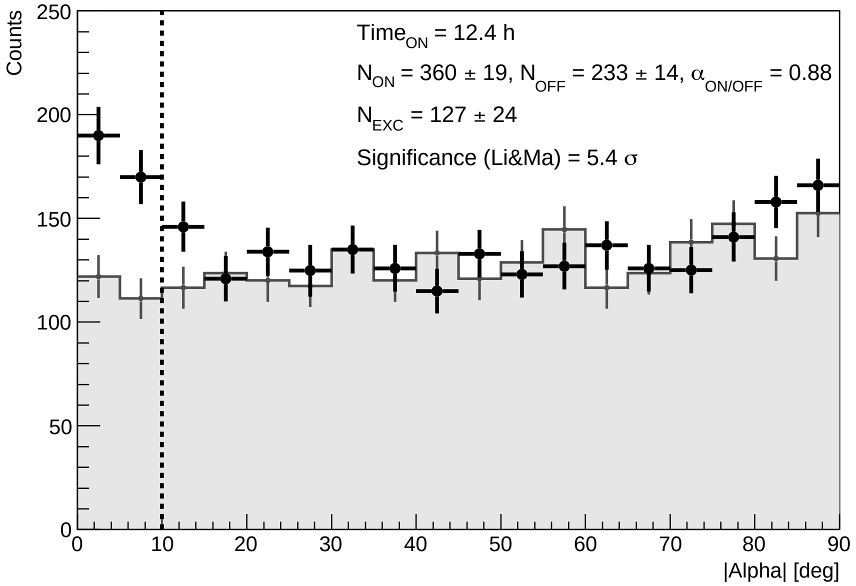

Figure 4. Detection plot of the Crab Nebula, above an energy threshold of ∼3 TeV, achieved with the ASTRI-Horn telescope. The black distribution represents the on-source data, while the grey distribution the control background data. The region between zero and the vertical dashed line (at 10°) represents the fiducial signal region. See[17] for more details.

5.2 Monte Carlo data results

In the case of MC data processing, detailed studies of the expected performance of the ASTRI Mini-Array at the Teide Observatory site were performed by means of the so-called ASTRI-MA-Prod1[11] and ASTRI-MA-Prod2_20deg[18] productions (see Section 3). Figure 5 shows one of the main ASTRI Mini-Array performance figures achieved from ASTRI-MA-Prod2_20deg, i.e. the on-axis differential flux sensitivity for five exposure times (ranging from 0.5 hours to 500 hours). The achieved results have demonstrated the significant capabilities of the instrument for observations in the TeV and multi-TeV energy band, particularly important for simultaneous and follow-up observations with other present- and next-generation gamma-ray observatories located in the Northern Hemisphere.

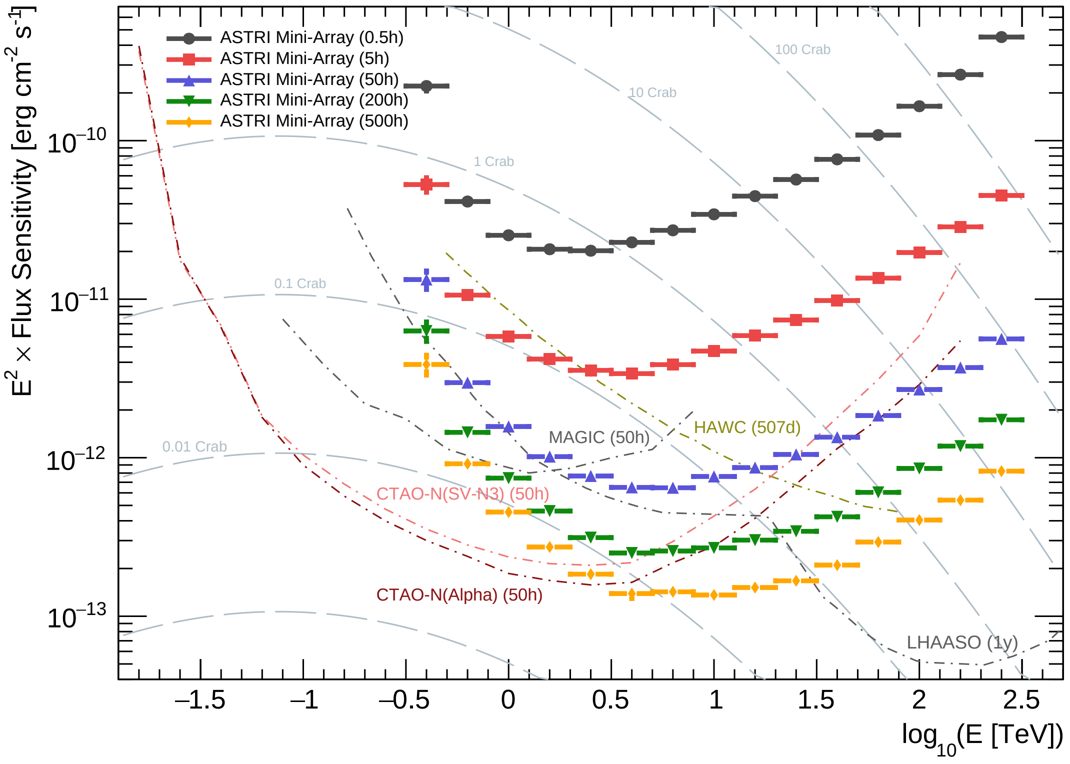

Figure 5. On-axis point-like source differential sensitivity of the ASTRI Mini-Array (at a zenith angle of 20°) for five exposure times: 0.5 (dark gray), 5 (red), 50 (blue), 200 (green), and 500 (orange) hours. The differential sensitivities of other instruments (MAGIC, HAWC, LHAASO, and CTAO-N) are shown for comparison. See[18] for more details.

6. SUMMARY AND OUTLOOK

The ASTRI Project is highly active in the context of the very high-energy (VHE) astronomy. On the one hand, the deployment of the ASTRI Mini-Array, an array of nine 4-m class Imaging Atmospheric Cherenkov Telescopes (IACTs), is taking place at the *Observatorio del Teide* (Tenerife, Spain): the first three telescopes are expected to perform first data taking by 2023, while the completion of the array is foreseen in a few years.[8] On the other hand, the CTAO will make use of the ASTRI telescope structure and mirrors for its Small-Sized Telescopes (SSTs),[15] which implies a deep involvement of the ASTRI activities in the CTA framework as well.

In the light of this huge commitment, the ASTRI Team is working hard on hardware and software development and implementation. From the software point of view, current efforts are focused on developing and delivering all software systems that are needed to plan, collect, reduce, analyze, disseminate and exploit the scientific data of the Mini-Array. In this contribution, we have presented three main Software Systems – Data Processing, Simulation, and Archive – describing their main functionalities, components, and interfaces. First tests of these systems have already been successfully carried out by means of real data taken by the ASTRI-Horn prototype telescope and dedicated Monte Carlo simulations. A major step towards the deployment and validation of all these software systems will be achieved in the commissioning phase of the first three telescopes on site, expected to start in 2023.

ACKNOWLEDGMENTS

This work was conducted in the context of the ASTRI Project thanks to the support of the Italian Ministry of University and Research (MUR) as well as the Ministry for Economic Development (MISE) with funds specifically assigned to the Italian National Institute of Astrophysics (INAF). We acknowledge support from the Brazilian Funding Agency FAPESP (Grant 2013/10559-5) and from the South African Department of Science and Technology through Funding Agreement 0227/2014 for the South African Gamma-Ray Astronomy Programme. The Instituto de Astrofísica de Canarias (IAC) is supported by the Spanish Ministry of Science and Innovation (MICIU). This work has also been partially supported by H2020-ASTERICS, a project funded by the European Commission Framework Programme Horizon 2020 Research and Innovation action under grant agreement n. 653477. The ASTRI Project is becoming a reality thanks to Giovanni "Nanni" Bignami and Nicolò "Nichi" D'Amico, two outstanding scientists who, in their capability of INAF Presidents, provided continuous support and invaluable guidance. While Nanni was instrumental to start the ASTRI telescope, Nichi transformed it into the Mini-Array in Tenerife. Now the project is being built owing to the unfaltering support of Marco Tavani, the current INAF President. Paolo Vettolani and Filippo Zerbi, the past and current INAF Science Directors, as well as Massimo Cappi, the Coordinator of the High Energy branch of INAF, have been also very supportive to our work. We are very grateful to all of them. Nanni and Nichi, unfortunately, passed away but their vision is still guiding us. This article has gone through the internal ASTRI review process.

REFERENCES

[1] Hinton, J. A. and Hofmann, W., "Teraelectronvolt Astronomy," *Annual Review of Astronomy & Astrophysics* **47**, 523–565 (Sept. 2009).

[2] De Angelis, A. and Mallamaci, M., "Gamma-ray astrophysics," *European Physical Journal Plus* **133**, 324 (Aug. 2018).

[3] Di Sciascio, G., "Ground-based Gamma-Ray Astronomy: an Introduction," in [*Journal of Physics Conference Series*], *Journal of Physics Conference Series* **1263**, 012003 (June 2019).

[4] Aharonian, F. et al., "Observations of the Crab nebula with HESS," *A&A* **457**, 899–915 (Oct. 2006).

[5] Aleksić, J. et al., "Performance of the MAGIC stereo system obtained with Crab Nebula data," *Astropart. Phys.* **35**, 435–448 (Feb. 2012).

[6] Weekes, T. C. et al., "VERITAS: the Very Energetic Radiation Imaging Telescope Array System," *Astropart. Phys.* **17**, 221–243 (May 2002).

[7] Scuderi, S. et al., "The ASTRI Mini-Array of Cherenkov telescopes at the Observatorio del Teide," *Journal of High Energy Astrophysics* **35**, 52–68 (2022).

[8] Pareschi, G. et al., "The implementation of the ASTRI Mini-Array gamma-ray experiment at the Observatorio del Teide, Tenerife," in [*Ground-based and Airborne Telescopes IX*], Guzman, J. C. and Ibsen, J., eds., *Proc. of SPIE* **12182** (2022).

[9] Acharya, B. S. et al., "Introducing the CTA concept," *Astroparticle Physics* **43**, 3–18 (Mar. 2013).

[10] Acharya, B. S. et al., [*Science with the Cherenkov Telescope Array*], World Scientific Press (2019).

[11] Vercellone, S. et al., "ASTRI Mini-Array core science at the Observatorio del Teide," *Journal of High Energy Astrophysics* **35**, 1–42 (2022).

[12] Pareschi, G. et al., "The Dual-mirror Small Size Telescope for the Cherenkov Telescope Array," in [*International Cosmic Ray Conference*], *International Cosmic Ray Conference* **33**, 1151 (Jan. 2013).

[13] Giro, E. et al., "The ASTRI-Horn telescope validation toward the production of the ASTRI Mini-Array: a proposed pathfinder for the Cherenkov Telescope Array," *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **11119**, 111191E (Sept. 2019).

[14] Scuderi, S., "The ASTRI Program," in [*European Physical Journal Web of Conferences*], *European Physical Journal Web of Conferences* **209**, 01001 (Sept. 2019).

[15] Tagliaferri, G. et al., "The Small-Sized telescopes of the Cherenkov Telescope Array Observatory," in [*Ground-based and Airborne Telescopes IX*], Guzman, J. C. and Ibsen, J., eds., *Proc. of SPIE* **12182** (2022).

[16] Giro, E. et al., "First optical validation of a Schwarzschild Couder telescope: the ASTRI SST-2M Cherenkov telescope," *A&A* **608**, A86 (Sept. 2017).

[17] Lombardi, S. 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," *A&A* **634**, A22 (Feb. 2020).

[18] Lombardi, S. et al., "Performance of the ASTRI Mini-Array at the Observatorio del Teide," in [*37th International Cosmic Ray Conference. 12-23 July 2021. Berlin*], 884 (Mar. 2022).

[19] D'Aì, A. et al., "Galactic Observatory Science with the ASTRI Mini-Array at the Observatorio del Teide," *Journal of High Energy Astrophysics* **35**, 139–175 (2022).

[20] Saturni, F. et al., "Extragalactic Observatory Science with the ASTRI Mini-Array at the Observatorio del Teide," *Journal of High Energy Astrophysics* **35**, 91–111 (2022).

[21] Germani, S. et al., "The Stereo Event Builder software system of the ASTRI Mini-Array project," in [*Software and Cyberinfrastructure for Astronomy VII*], Guzman, J. C. and Ibsen, J., eds., *Proc. of SPIE* **12189** (2022).

[22] Lombardi, S. et al., "ASTRI SST-2M prototype and mini-array data reconstruction and scientific analysis software in the framework of the Cherenkov Telescope Array," in [*Software and Cyberinfrastructure for Astronomy IV*], Chiozzi, G. and Guzman, J. C., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **9913**, 991315 (July 2016).

[23] Lombardi, S. et al., "ASTRI data reduction software in the framework of the Cherenkov Telescope Array," in [*Software and Cyberinfrastructure for Astronomy V*], Guzman, J. C. and Ibsen, J., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **10707**, 107070R (July 2018).

[24] Zampieri, L. et al., "A Stellar Intensity Interferometry Instrument for the ASTRI Mini-Array telescopes," in [*Optical and Infrared Interferometry and Imaging VIII*], Guzman, J. C. and Ibsen, J., eds., *Proc. of SPIE* **12189** (2022).

[25] Mineo, T. et al., "Tools and Procedures for the ASTRI Mini-Array Calibration," in [*37th International Cosmic Ray Conference. 12-23 July 2021. Berlin*], 197 (Mar. 2022).

[26] Conforti, V. et al., "The Array Data Acquisition System software architecture of the ASTRI Mini-Array Project," in [*Software and Cyberinfrastructure for Astronomy VII*], Guzman, J. C. and Ibsen, J., eds., *Proc. of SPIE* **12189** (2022).

[27] Pence, W. D. et al., "Definition of the Flexible Image Transport System (FITS), version 3.0," *A&A* **524**, A42 (Dec. 2010).

[28] Hillas, A. M., "Cerenkov Light Images of EAS Produced by Primary Gamma Rays and by Nuclei," in [*19th International Cosmic Ray Conference (ICRC19), Volume 3*], *International Cosmic Ray Conference* **3**, 445 (Aug. 1985).

[29] Bulgarelli, A. et al., "The Software Architecture and development approach for the ASTRI Mini-Array gamma-ray air-Cherenkov experiment at the Observatorio del Teide," in [*Software and Cyberinfrastructure for Astronomy VII*], Guzman, J. C. and Ibsen, J., eds., *Proc. of SPIE* **12189** (2022).

[30] Deil, C. et al., "Gammapy - A prototype for the CTA science tools," in [*35th International Cosmic Ray Conference (ICRC2017)*], *International Cosmic Ray Conference* **301**, 766 (Jan. 2017).

[31] Knödlseder, J. et al., "GammaLib and ctools. A software framework for the analysis of astronomical gamma-ray data," *A&A* **593**, A1 (Aug. 2016).

[32] Iovenitti, S. 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*], Guzman, J. C. and Ibsen, J., eds., *Proc. of SPIE* **12186** (2022).

[33] Breiman, L., "Random Forests," *Machine Learning* **45**, 5–32 (Jan. 2001).

[34] Heck, D. et al., [*CORSIKA: a Monte Carlo code to simulate extensive air showers.*], Report FZKA 6019 (1998).

[35] Bernlöhr, K., "Simulation of imaging atmospheric Cherenkov telescopes with CORSIKA and sim_telarray," *Astropart. Phys.* **30**, 149–158 (Oct. 2008).

[36] Noll, S. et al., "An atmospheric radiation model for Cerro Paranal. I. The optical spectral range," *A&A* **543**, A92 (July 2012).

[37] Jones, A. et al., "An advanced scattered moonlight model for Cerro Paranal," *A&A* **560**, A91 (Dec. 2013).

[38] Parmiggiani, N. et al., "The Online Observation Quality System Software Architecture for the ASTRI Mini-Array Project," in [*Software and Cyberinfrastructure for Astronomy VII*], Guzman, J. C. and Ibsen, J., eds., *Proc. of SPIE* **12189** (2022).

[39] Gianotti, F. et al., "ASTRI Mini-Array On-Site Information and Communication Technology infrastructure," in [*Software and Cyberinfrastructure for Astronomy VII*], Guzman, J. C. and Ibsen, J., eds., *Proc. of SPIE* **12189** (2022).

[40] Barisits, M. et al., "Rucio: Scientific data management," *Computing and Software for Big Science* **3**, 11 (Aug 2019).