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The ASTRI Mini-Array simulation system

F. G. Saturni,^{a,b,*} **C. Bigongiari,**^{a,b} **L. A. Antonelli,**^{a} **S. Lombardi,**^{a,b} **F. Lucarelli,**^{a,b} **M. Mastropietro,**^{a} **T. Mineo,**^{c} **G. Pareschi**^{d} **for the ASTRI Project**^{e}

[a] *INAF – Osservatorio Astronomico di Roma, Via Frascati 33, I-00078 Monte Porzio Catone (Roma), Italy*
[b] *ASI – Space Science Data Center, Via del Politecnico s.n.c., I-00133 Roma, Italy*
[c] *INAF – Istituto di Astrofisica Spaziale e Fisica Cosmica, Via U. La Malfa 153, I-90146 Palermo, Italy*
[d] *INAF – Osservatorio Astronomico di Brera, Via E. Bianchi 46, I-23807 Merate (LC), Italy*
[e] *http://www.astri.inaf.it/en/library/*

E-mail: francesco.saturni@inaf.it, ciro.bigongiari@inaf.it

The ASTRI Mini-Array is an INAF project aimed at observing astronomical objects that emit photons in the TeV and multi-TeV spectral bands. It consists of an array of nine innovative imaging atmospheric Cherenkov telescopes under deployment at the *Observatorio del Teide* (Tenerife, Spain). Detailed simulations of atmospheric showers of Cherenkov events using Monte Carlo methods are needed to estimate the expected performance of the ASTRI Mini-Array under different observing conditions, to validate the Monte Carlo simulation chain, for calibration purposes and for the development of ancillary instruments, and finally to allow the reconstruction of the real data collected by the array. The production of events detected by Cherenkov telescopes comprises the simulation of the development of particle cascade in the atmosphere with the associated emission of Cherenkov light and the simulation of the response of telescopes to the impinging light; the first task is carried out with the CoRSiKa software (which also simulates the emission of Cherenkov light), while the second is achieved with the `sim_telarray` package by simulating the transmission of Cherenkov light from the emission point to the telescope and the response of the telescope itself. In this contribution, we present the ASTRI Mini-Array simulation system, describing in detail the software pipeline adopted for the generation of Monte Carlo events, the hardware facilities dedicated to run the simulations at the offsite ASTRI Data Center, and the final products delivered for the Cherenkov data analysis.

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[*] Speaker

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1. Introduction

The study of very-high energy (VHE) sources, i.e. the most energetic phenomena in the Universe emitting photons of energy $E_\gamma > \mathcal{O}(0.1\ \mathrm{TeV})$, is one of the main topics of the current and future γ-ray astronomy [1, 2]. Sources such as γ-ray bursts (GRBs), jets originating from active galactic nuclei (AGN), pulsars and supernova remnants (SNRs) produce VHE photons through particle acceleration mechanisms around compact objects; the production of such photons is also possible in larger environments (e.g., ionised winds in starburst galaxies), through the interaction of cosmic rays (CRs) and by elusive processes expected from dark matter (DM) particles. Huge steps forward in the VHE astronomy have been done in the last years thanks to current ground-based instruments, in particular the imaging atmospheric Cherenkov telescopes (IACTs) like VERITAS [3], H.E.S.S. [4] and MAGIC [5]. Furthermore, the next-generation IACTs, especially the ASTRI Mini-Array [6, 7] and the Cherenkov Telescope Array Observatory (CTAO; [8]), are close to starting their data-taking operations. Their unprecedented sensitivity and angular resolution in the VHE band will be greatly beneficial to clarify the nature of the γ-ray emission from already detected sources, and discover new ones [9, 10].

The ASTRI Project was born as an INAF flagship project [11] aimed at developing an end-to-end prototype of the CTAO small-sized telescope (SST; [12]) in dual-mirror configuration. Such a prototype, the ASTRI-*Horn* telescope [13], is currently operative at the INAF "M. C. Fracastoro" observing station in Serra La Nave (Mt. Etna, Italy). The further step of this project is related to the installation of the ASTRI Mini-Array, an array of nine ASTRI-like telescopes, at the *Observatorio del Teide* in Tenerife (Canary Islands, Spain). The first three telescopes will be ready to take data for both the stereoscopic system verification and the first scientific observations of astrophysical targets in 2024. The ASTRI Mini-Array will be able to study relatively bright sources ($E_\gamma^2 \times dF/dE_\gamma \sim 10^{-12}$ erg s^{-1} cm^{-2} at 10 TeV) in deep detail, with an angular resolution of ~3 arcmin and an energy resolution of around 10% at energies of ~10 TeV that suffer a rather little degradation up to 100 TeV [14].

Beside the major efforts that are underway for the on-site deployment of the hardware components, the ASTRI team is working as well on the development of the software tools needed to pre-process, reduce and analyse the upcoming data collected with the Mini-Array. A consistent part of such software is included in the ASTRI simulation system, which is the main topic of this contribution. In particular, the software chain for the simulation of Cherenkov atmospheric showers and their detection from an array of telescopes is installed at the ASTRI Data Center [15], a new facility for high-performance calculus located in Rome (Italy).

2. The ASTRI simulation system software chain

The ASTRI Mini-Array simulation system is a collection of software components that are in charge of generating all of the simulated data needed for the ASTRI Project. Detailed Monte Carlo (MC) simulations are indeed fundamental in all of the project phases:

- in the design and development phase, MC simulations are used for (i) optimising the telescope positions in the array, (ii) fully characterising the scientific performance of the system, (iii) defining and testing data analysis methods that are eventually exploited for the processing of real data, (iv) calibration purposes and (v) the development of ancillary instrumentation;

- in the commissioning and operation phase, MC simulations are used to (i) provide auxiliary inputs for the reconstruction of real Cherenkov events through the generation and application of suitable reconstruction models, and (ii) obtain the response of the system to γ-ray astrophysical observations by means of the generation of appropriate instrument response functions (IRFs; [16]).

The simulation of the Cherenkov events recorded by IACTs is composed by two steps: (i) the generation of the development of particle cascades in the atmosphere with the associated emission of Cherenkov light, and (ii) the reproduction of the telescope response to the impinging light. The first step is carried out with the CoRSiKa software package[1], a program for detailed simulation of extensive air showers initiated by high-energy CRs. 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 [17]. 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 [18], which can be flexibly configured at run-time depending on the telescope system.

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 computational needs. Furthermore, since the Cherenkov imaging technique achieves a very high background rejection, huge numbers of hadronic events need to be simulated in order to properly estimate the instrumental performances. To cope with such requirements, massive productions of simulated events are usually carried out using distributed computing frameworks like `DIRAC` [19]. Although such systems have been commonly used for ASTRI MC productions generated to date, an extensive use of the resources of the upcoming ASTRI Data Center is starting in view of the commissioning and operation phases of the ASTRI Mini-Array (see Sect. 1).

3. The ASTRI MC productions

The first massive production of MC simulations for the ASTRI Mini-Array at the *Observatorio del Teide* site, called “ASTRI-MA Prod1”, was carried out in spring 2020 and released in fall 2020. For this production, we simulated γ-rays coming from a point-like source at a zenith angle (ZA) of 20° and an azimuth angle (Az) of 180°, along with diffuse γ-rays, electrons, and protons with incoming directions uniformly distributed in a cone of 10° radius centered on the point-like source direction. The energy of all primary particles was cast according to a power-law energy spectrum with a 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 was fully reduced and analyzed with the `A-SciSoft` software package [20], in order to provide the first evaluation of the system performance and to generate suitable IRFs for scientific studies related to the ASTRI Mini-Array science program [10, 21, 22].

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[1] Available at https://www.iap.kit.edu/corsika/.

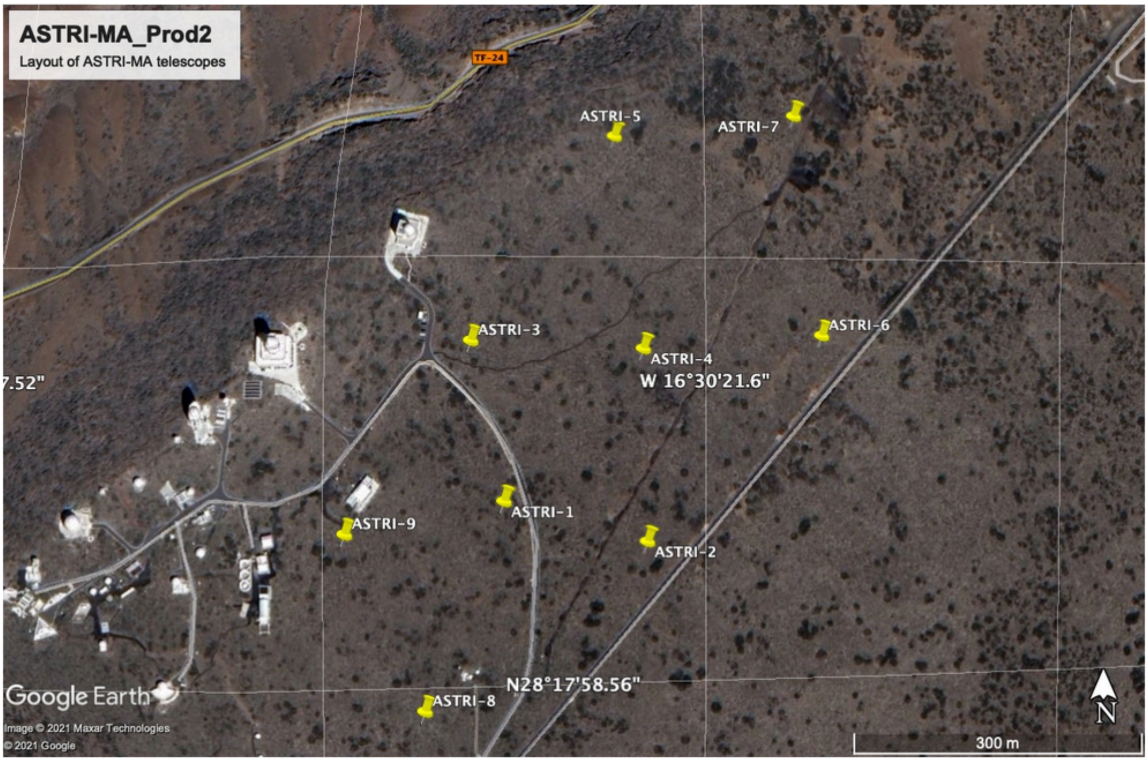

Figure 1: Layout of the ASTRI Mini-Array telescopes simulated in the ASTRI-MA Prod2.

A new massive production, called "ASTRI-MA Prod2", started in the fall of 2020 and is still underway. Since the performance of any IACT system significantly depends on the actual zenith pointing directions, the purpose of this new production is to characterize the performance of the system at different sets of ZA and Az. In addition, since the final layout of the ASTRI Mini-Array is quite elongated (see Fig. 1), its performance is expected to show non-trivial dependencies with respect to the Az pointing direction, particularly for medium and high ZAs. Furthermore, compared with the previous MC production, the ASTRI-MA Prod2 takes into account the final positions of the ASTRI Mini-Array telescopes at the *Observatorio del Teide* site, officially approved[2] in the fall of 2020.

The first sub-production of the ASTRI-MA Prod2, called "ASTRI-MA Prod2_20deg" (simulations at ZA = 20°) was launched in late 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 the ASTRI-MA Prod1, the new production increased the number of generated events along two different Az orientations of 0 and 180°. This sub-production has been fully reduced and analyzed with `A-SciSoft` in order to update the the assessment of the system performance [14].

After the ASTRI-MA Prod2_20deg sub-production, the so-called ASTRI-MA Prod2_60deg (simulations at ZA = 60°) has been generated, and its analysis is currently underway; in this way,

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

Particle type	Spectral slope	Energy range [TeV]	View-cone radius [deg]	Scatter radius [m]	Az [deg]	ZA [deg]	No. of simulated showers
ASTRI-MA Prod1							
Photons (point-like)	−1.5	0.1 – 330	0	2000	180	20	10^7
Photons (diffuse)	−1.5	0.1 – 330	10	2400	180	20	10^8
Electrons	−1.5	0.1 – 330	10	2400	180	20	10^8
Protons	−1.5	0.1 – 600	10	2400	180	20	10^9
ASTRI-MA Prod2_20deg							
Photons (point-like)	−1.5	0.1 – 330	0	2000	0/180	20	4×10^7
Photons (diffuse)	−1.5	0.1 – 330	10	2400	0/180	20	4×10^8
Electrons	−1.5	0.1 – 330	10	2400	0/180	20	2×10^8
Protons	−1.5	0.1 – 600	10	2400	0/180	20	2×10^9
ASTRI-MA Prod2_60deg							
Photons (point-like)	−1.5	0.1 – 330	0	2000	0/90/180/270	60	8×10^7
Photons (diffuse)	−1.5	0.1 – 330	10	2400	0/90/180/270	60	8×10^8
Electrons	−1.5	0.1 – 330	10	2400	0/90/180/270	60	4×10^8
Protons	−1.5	0.1 – 600	10	2400	0/90/180/270	60	4×10^9

Table 1: Main parameters describing the MC air shower simulations in the so-called ASTRI-MA Prod1, ASTRI-MA Prod2_20deg and ASTRI-MA Prod2_60deg productions generated so far for the ASTRI Mini-Array at the *Observatorio del Teide* site.

it will be possible to provide the ASTRI Mini-Array performance and IRFs at the two edges of the expected ZA range of nominal observations, while a sub-production at the intermediate ZA of 40° will follow. We report the main parameters adopted to produce each particle data set of the ASTRI-MA productions in Tab. 1.

4. The ASTRI simulation plan

As described in Sect. 3, the MC simulations produced by the ASTRI simulation team for which a complete analysis has been carried out so far 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 *Observatorio del Teide* 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 to increase the overall duty cycle of the system, as already shown for existing IACTs [23]. For these reasons, the full ASTRI-MA Prod2 will cover different zenith and azimuth pointing directions – namely, ZA = $\{20°, 40°, 60°\}$ and Az = $\{0°, 90°, 180°, 270°\}$ – with different levels of the NSB [24].

In addition to such massive productions of atmospheric shower events induced by cosmic primary particles interacting with atmospheric nuclei, we also need to simulate different types of events acquired during calibration procedures, as well as specific events needed to optimize the ancillary instruments and algorithms. The main ancillary simulations encompass the generation of:

- events for camera calibration (dark, LED and pedestal), needed to analyse the simulated events exactly in the same way that will be used for the scientific data acquired by the ASTRI Mini-Array;
- muon-initiated events for the analysis of muon rings acquired by the ASTRI cameras, that may be used to estimate and monitor the overall optical throughput of the ASTRI telescopes and also their optical point-spread function;
- atmospheric showers induced by γ-ray primaries coming from many different combinations of Az and ZAs to optimize the algorithm of the offline stereo trigger;
- light emission by an illuminator that will serve as a cross-calibration device for the ASTRI telescopes.

This simulation plan 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 *Observatorio del Teide* site, we will continue the validation process of the simulation chain, which started in December 2018 with the real data taken with the ASTRI-*Horn* telescope [13]. Such a process will require many iterative comparisons between both calibration and scientific data acquired with the first camera(s) – first at a pixel level, and then at the image level for each available camera – and data simulated with different sets of input parameters. 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.

Since this process will involve the simulation of many different samples of calibration and scientific data with different sets of steering parameters, whose large number can quickly lead to the need for a considerable amount of computing and storage resources, we rely on the capabilities of the newborn ASTRI Data Center to properly produce and store the MC runs. The ASTRI Data Center is the main data processing and archiving off-site infrastructure for the entire ASTRI Project, hosted at the Astronomical Observatory of Rome (OAR) and composed of 12 nodes that are managed via a virtualized environment with I/O speedup. The storage capabilities are ensured by a redundant 3-PB cluster, backuped by a fiber-channel tape library containing up to 15 PB of cold-storage data space (expandable up to hundreds) [25]. Such a hardware setup guarantees that the available computing and storage resources are properly sized to take into account the MC requirements.

5. Summary and outlook

The expected performances of the ASTRI Mini-Array in the framework of the ASTRI-MA Prod1 and Prod2_20deg productions have already been studied in detail, and have been collected into a set of publicly available ASTRI IRFs[3]. In the future, thanks to the ASTRI Data Center computing and storage capabilities, the production and analysis of MC simulation samples for different pointing directions of the ASTRI Mini-Array will allow the detailed study of the instrument's performances

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[3] Available at `https://doi.org/10.5281/zenodo.6827882`.

up to 60° in ZA and over the whole Az range, thus ensuring a complete overview of the ASTRI Mini-Array scientific prospects in the VHE γ-ray domain.

In parallel, the ASTRI Mini-Array is expected to start its scientific operations at the *Observatorio del Teide* site within 2023, with the installation of the first Cherenkov camera on the ASTRI-1 structure that will be immediately operated to take data for the verification and validation of the acquisition and analysis chain. Then, the completion of a working stereo subarray of three telescopes (ASTRI-1, ASTRI-8 and ASTRI-9; see Fig. 1) is planned within the first half of 2024; such a subsystem will perform the scientific observations that will be used in turn for both the validation of the stereo data analysis chain and the delivery of the preliminary science products. The production of valid sets of MC atmospheric shower simulations covering the range of hardware parameters, telescope pointings and site conditions that will hold during the observations will be therefore a crucial task in the next months in order to properly analyse the first forthcoming real data sets.

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