

Expected performance of the ASTRI mini-array in the framework of the Cherenkov Telescope Array

F Di Pierro, C Bigongiari, A Stamerra and P Vallania for the ASTRI Collaboration and the CTA Consortium.

INAF Osservatorio Astrofisico di Torino, Via P. Giuria 1, 10125 Torino (To), Italy

E-mail: dipierro@oato.inaf.it

Abstract. The Cherenkov Telescope Array (CTA) Observatory is a world-wide project for the ground-based study of the sources of the highest energy photons. By adopting telescopes of three different size categories it will cover the wide energy range from tens of GeV up to hundreds of TeV, limited only by the source physical properties and the gamma absorption by the extragalactic background light. The full sky coverage will be assured by two arrays, one in each hemisphere. An array of small size telescopes (SSTs), covering the highest energy region (3-100 TeV), the region most flux limited for current imaging atmospheric Cherenkov telescopes, is planned to be deployed at the southern CTA site in the first phase of the CTA project. The ASTRI collaboration has developed a prototype of a dual mirror SST equipped with a SiPM-based focal plane (ASTRI SST-2M) and has proposed to install a mini-array of nine of such telescopes at the CTA southern site (the ASTRI mini-array). In order to study the expected performance and the scientific capabilities of different telescope configurations, full Monte Carlo (MC) simulations of the shower development in the atmosphere for both gammas and hadronic background have been performed, followed by detailed simulations of the telescopes. In this work the expected performance of the ASTRI mini-array in terms of sensitivity, angular and energy resolution are presented and discussed.

1. Introduction

The Cherenkov Telescope Array (CTA) [1] Observatory will study the highest energy photons (from few tens of GeV up to hundreds of TeV) with unprecedented sensitivity, angular and energy resolutions [2]. Since the Cherenkov photon yield is directly proportional to the primary photon energy, the four orders of magnitude energy range of CTA means that three different size categories of telescope will be adopted. At low energy the photon density is very low, so very large reflective surfaces are needed to collect enough photons to correctly reconstruct the Cherenkov images requiring a minimum number of 50-100 photoelectrons (p.e.). On the other hand, the higher incoming flux at lower energies reduces the need of large effective collection areas. In this energy region a small number (3-4) of Large Size Telescopes (LSTs ~ 24 m diameter) is envisaged. In the medium energy regime, the drop of incoming flux due to the slopes of the source spectra requires a larger collection area, built up with ~ 30 Medium Size Telescopes of intermediate aperture (MSTs, ~ 12 m diameter). In the highest energy range the photon density on the ground is very high even for large core distances, while the source flux becomes very low. An effective area of $1 - 10 \text{ km}^2$ is thus necessary, and it can be obtained by placing ~ 70 Small Size Telescopes (SSTs, ~ 4 m diameter) on a grid with ~ 250 m spacing.



With one site in each hemisphere CTA will cover the full sky. The southern site will address the bulk of the Galactic physics cases and will host all 3 kinds of telescopes whereas the northern site is proposed to host only LSTs and MSTs. The ASTRI Collaboration has developed a dual mirror 4m-class telescope equipped with a SiPM-based focal plane (ASTRI SST-2M) and has proposed to install a mini-array of nine of such telescopes at the CTA southern site (the ASTRI mini-array) [3]. This array of precursors will be used for technical purposes but also for the first scientific studies. The ASTRI mini-array will already have the sensitivity to outperform current generations of instruments in the region > 10 TeV and so may yield exciting and unexpected discoveries.

2. The simulation

The study of the expected performance and the layout optimization of an array of Imaging Atmospheric Cherenkov Telescopes (IACT) requires a relevant Monte Carlo (MC) simulation effort in terms of computing and storage resources [2]. The MC simulations are composed of two main steps: the first one is the simulation of the extensive air shower and Cherenkov light emission (performed here by means of the *corsika* package [4]), while the second one is the telescope simulation, including optics, photo-sensors and electronics (performed by means of the *sim_telarray* package [5]). The ASTRI SST-2M telescope [6, 7] is a dual mirror telescope equipped with an innovative SiPM-based camera. The photo-sensors will be the Hamamatsu MPPC LCT5 75 μm [8] and the front-end electronics will be based on the CITIROC ASIC [9]. The detailed telescope simulation includes the optical design (fig. 1), the camera geometry (fig. 2), the photo-sensors photon detection efficiency (fig. 3) and the electronics response (fig. 4).

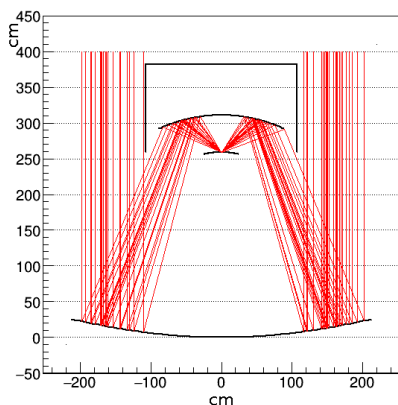


Figure 1. ASTRI SST-2M optical design.

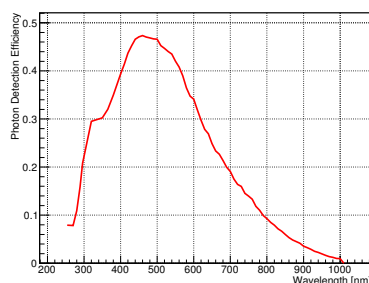


Figure 3. Photon Detection Efficiency of the Hamamatsu MPPC LCT5 75 μm .

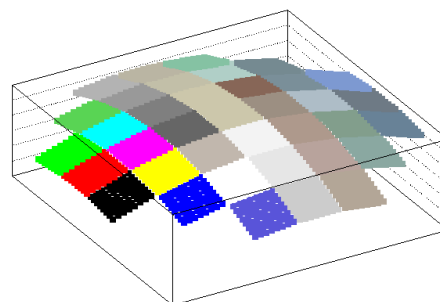


Figure 2. ASTRI SST-2M focal plane geometry, with the 37 Photon Detection Modules identified by different colors.

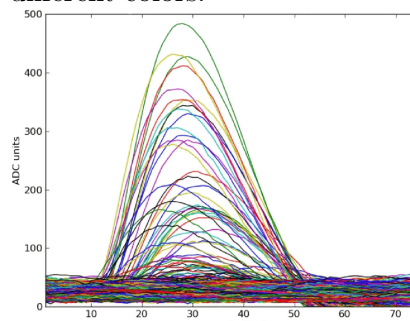


Figure 4. Examples of signals shaped and integrated by CITIROC.

The detailed simulation of the ASTRI SST-2M telescope has been included in the third large scale CTA MC production, which has not yet concluded. The preliminary results shown here have been obtained from the second large scale MC production [10] performed using the CTA virtual organization (VO) GRID resources [11]. The main characteristics of the ASTRI SST-2M simulated in the second production (left column) and foreseen for the telescopes which will be deployed at the CTA site (right column) are summarized in table 1.

Table 1. The ASTRI SST-2M main characteristics in the CTA MC productions.

	Production 2	Production 3
Primary Mirror	Monolithic (4300 mm diameter)	18 hexagonal tiles (849 mm face-to-face)
Secondary Mirror	Monolithic (1800 mm diameter)	
Equivalent focal length	2150 mm	2150 mm
Field of view	9.6 deg	11.2 deg
Number of pixels	1984	2368
Pixel size	0.18 deg	0.19 deg

The simulation of the events needed for the characterization of a site on average required 10^7 HS06 CPU hours and 20 TB. Table 2 shows the number of events generated for different primaries with E^{-2} spectra.

Table 2. Event statistics.

Primary	Energy [TeV]	Events [10^9]
Gamma point	0.003 - 330	5
Gamma diffuse	0.003 - 330	20
Protons	0.004 - 600	100
Electrons	0.003 - 330	5.3

The ASTRI mini-array is expected to be formed of 9 telescopes therefore we focused on square 3 by 3 telescope layouts (fig. 5) placed at a South American site (El Leoncito) at 1650 m a.s.l.

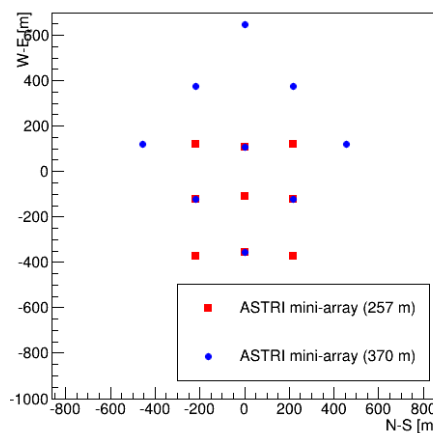


Figure 5. The considered ASTRI mini-array layouts.

3. Mini-array performance

The simulated events are reconstructed with standard IACT stereo methods: individual pixel signal extraction, image cleaning, Hillas parameterization, geometric shower reconstruction, lookup tables for energy reconstruction and gamma-hadron discrimination. Here we show the results obtained with the *eventdisplay* software [12]. The applied image cleaning, to reduce the NSB noise, is the two-levels cut described in [13]. Hadronic background discrimination is performed through an energy-binned multivariate procedure using Boosted Decision Trees implemented in the TMVA (*Toolkit for Multivariate Analysis*) framework [14]. The data selection cuts were not optimized for this analysis therefore the results can be considered as conservative. The expected angular resolution (68% containment radius) and the energy resolution (defined such that 68% of gamma rays will have true energy within ΔE of their reconstructed energy) are shown in figs. 6 and 7, respectively, while the differential flux sensitivity is shown in fig. 8, and compared to current and next generation observatories.

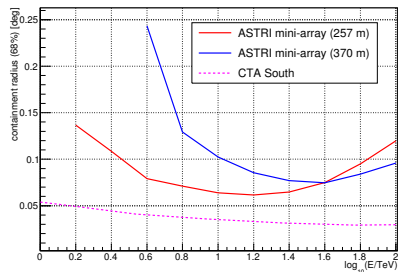


Figure 6. ASTRI mini-array angular resolution.

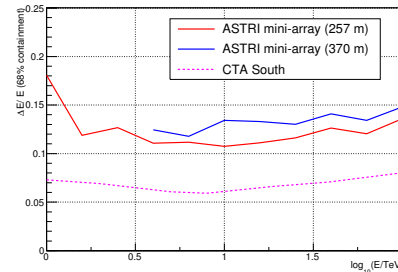


Figure 7. ASTRI mini-array energy resolution.

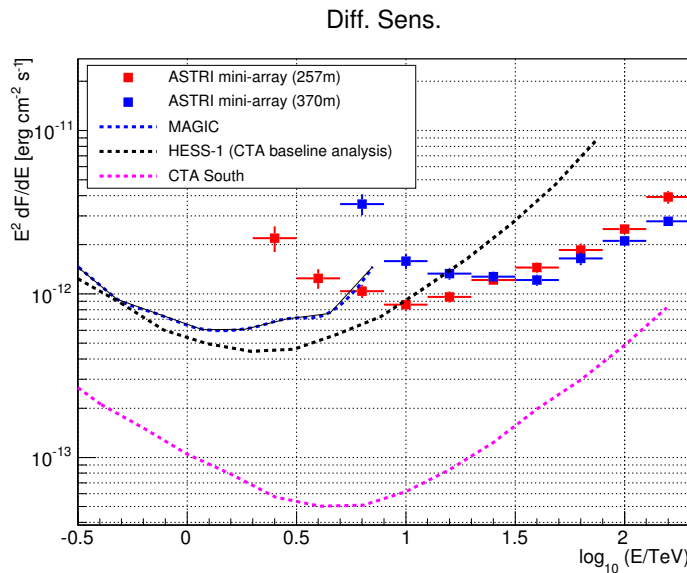


Figure 8. The ASTRI mini-array expected differential flux sensitivity compared to HESS [15], MAGIC [16] and CTA [17] ones.

4. Conclusions

We have discussed the results of a large-scale and detailed set of simulations of a mini-array composed of 9 telescopes with different spacing. The simulated data have been analyzed with standard software used by currently operating IACTs. The expected sensitivity of the ASTRI mini-array is better than the HESS one above 10 TeV. Therefore, it will be possible to address several science cases during the CTA pre-production phase [18]. This study has also pointed out the expected effects of the telescope distance and its optimization has to consider also the CTA Medium Size Telescopes (MST) array. The trade-off between the increased sensitivity at the highest energies and good performance over the full energy range seems to suggest that the most effective distance between SST units is of the order of 250m.

Acknowledgment

This work was partially supported by the ASTRI “Flagship Project” financed by the Italian Ministry of Education, University, and Research (MIUR) and led by the Italian National Institute of Astrophysics (INAF). We acknowledge partial support by the MIUR Bando PRIN 2009 and TeChe.it 2014 Special Grants. We also 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. We gratefully acknowledge support from the agencies and organizations listed in this page: <http://www.cta-observatory.org/?q=node/22>.

References

- [1] CTA Consortium 2011 Design concepts for the Cherenkov Telescope Array, *Exp. Astr.* **32** 193
- [2] Bernlöhner K *et al* 2013 *Astroparticle Physics* **43** 171
- [3] Pareschi G *et al* 2016 this conference proceedings
- [4] Heck D *et al* 1998 Report FZKA 6019, Forschungszentrum Karlsruhe.
- [5] Bernlöhner K 2008 *Astroparticle Phys.* **30** 149
- [6] Canestrari R *et al* 2015 *Proc. of the SPIE* Vol. **8861** id. 886102-1
- [7] Catalano O *et al* 2014 *Proc. of the SPIE* Vol. **9147** id. 91470D
- [8] Bonanno G *et al* 2016 *Nuclear Instruments and Methods in Physics Research A* **806** 383
- [9] Fleury J *et al* 2014 *Journal of Instrumentation* **9** 1
- [10] Hassan T *et al* 2015 *Proceedings of the 34th ICRC*
- [11] Arrabito L *et al* 2014 *Journal of Physics: Conference Series* **513** 032003
- [12] <https://znwiki3.ifh.de/CTA/Eventdisplay%20Software>
- [13] Holder J *et al* 2006 *Astroparticle Physics* **25** 391
- [14] <http://tmva.sourceforge.net>
- [15] <https://www.mpi-hd.mpg.de/hfm/HESS/>
- [16] Aleksic J *et al* 2015 *Astroparticle Physics* **72** 76
- [17] <https://portal.cta-observatory.org/Pages/CTA-Performance.aspx>
- [18] Vercellone S 2015 *RICAP 2014 Proceedings Preprint* arXiv:1508.00799