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# Simulation of the ASTRI two-mirrors small-size telescope prototype for the Cherenkov Telescope Array

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## Abstract.

The Cherenkov Telescope Array (CTA) is a world-wide project to build a new generation ground-based gamma-ray instrument operating in the energy range from some tens of GeV to above 100 TeV. To ensure full sky coverage CTA will consist of two arrays of Imaging Atmospheric Cherenkov Telescopes (IACTs), one in the southern hemisphere and another one in the northern hemisphere. CTA has just completed the design phase and it is entering in the pre-production one that includes the development of telescope precursor mini-arrays. ASTRI is an ongoing project, to develop and install at the southern CTA site one of such mini-arrays composed by nine dual-mirror small size telescopes equipped with an innovative camera based on silicon photomultiplier sensors. The end-to-end telescope prototype, named ASTRI SST-2M, has been recently inaugurated at the Serra La Nave observing station, on Mount Etna, Italy. ASTRI SST-2M expected performance has been carefully studied using a full Monte Carlo simulation of the shower development in the atmosphere and detector response. Simulated data have been analyzed using the traditional Hillas moment analysis to obtain the expected angular and energy resolution. Simulation results, together with the comparison with the available experimental measurements, are shown.

## 1. Introduction

The Cherenkov Telescope Array (CTA) [1] is an international initiative to develop a third generation facility for ground-based gamma-ray astronomy. In the last decade, thanks to the current arrays of Cherenkov telescopes, Very High Energy ( $30 \text{ GeV} \leq E \leq 30 \text{ TeV}$ ) gamma-ray astrophysics has grown into a mature branch of astronomy. The spectacular results from the current Cherenkov instruments have generated considerable interest in both the astrophysics and particle physics communities stimulating the desire for a next-generation, more sensitive and more flexible facility, able to serve a larger community of users.

The CTA project intends to fulfill such wish by building a gamma-ray observatory featuring a flux sensitivity at least an order of magnitude better than current IACT arrays, a much larger





	Gammas	Protons
Minimum Energy	100 GeV	100 GeV
Maximum Energy	330 TeV	600 TeV
Spectral Slope	-2.0	-2.0
Zenith angle	20.0°	20.0°
Azimuth angle	0.0°	0.0°
Maximum off-axis angle	0.0	6.0°
Maximum impact point distance	800 m	1200 m
Samples	10	20
Events	$11 \cdot 10^6$	$550 \cdot 10^6$

**Figure 1:** The ASTRI SST-2M is zero for particles coming from North and increases clockwise. Each telescope prototype at Serra La atmospheric shower has been sampled 10-20 times, respectively for Nave observing station.

**Table 1:** Main characteristics of simulated samples. Azimuth angle for gammas and protons, randomizing their impact point on the ground.

operational energy range extending from few tens of GeV to 100 TeV and improved angular and energy resolution. Detailed Monte Carlo simulations demonstrated that such performance goals can be achieved by an IACT array comprising three different size telescopes: some Large Size Telescopes (LST) for the low energy range ( $\sim 20$  GeV  $\sim 1$  TeV), several Medium Size Telescopes (MST) for the core energy range ( $\sim 100$  GeV -  $\sim 10$  TeV) and many Small Size Telescope (SST) for the high energy range ( $E \geq 1$  TeV). CTA will actually consist of two arrays one in the Northern hemisphere and one in the Southern hemisphere for full sky coverage. Mini-arrays composed by a handful of telescopes will be installed at both site during the pre-production phase, to test the chosen technological solutions and pave the way for the full deployment. ASTRI (Astrofisica con Specchi a Tecnologia Replicante Italiana) [2] is a flagship project of the Italian Ministry of Education, University, and Research (MIUR), led by Italian National Institute of Astrophysics (INAF) in cooperation with the Universidade de Sao Paulo (Brazil) and the North-West University (South Africa), to develop and install a mini-array of 9 SSTs at CTA southern site [3]. The first step toward the fulfillment of such project is the development of a SST prototype to be extensively tested on field in realistic environmental conditions.

## 2. ASTRI SST-2M telescope prototype

ASTRI collaboration has developed an end-to-end prototype of the CTA small size telescope, named ASTRI SST-2M, which has been installed at Serra La Nave observing station on Mount Etna (Italy) in September 2014, see figure 1. ASTRI SST-2M is characterized by two innovative technological solutions, for the first time adopted together in the design of Cherenkov telescopes: the optical system is arranged in a dual-mirror aplanatic Schwarzschild-Couder (SC) [4] configuration and the camera at the focal plane is composed by a matrix of multi-pixel silicon photon-multipliers (SiPMs). The optical system of the Schwarzschild-Couder telescope is not affected by spherical or comatic aberrations which affect traditional Davies-Cotton [5] and parabolic IACTs. Moreover its secondary mirror de-magnifies the image allowing a wide field of view and reduced plate scale enabling the use of novel SiPM photo-sensors. ASTRI SST-2M optical design has an f-number  $f/0.5$  and an equivalent focal length of 2.150 m resulting in a plate scale of 37.5 mm/deg. The light is focused on a compact camera [6], composed of 37 photon detection modules (PDM), which covers a  $9.6^\circ$  full field of view. Each PDM is a flat array of  $8 \times 8$  logical pixels appropriately tilted with respect to the optical axis of the telescope to fit the curvature of the focal surface. Logical pixels are obtained by coupling 4 monolithic Hamamatsu

SiPMs S11828-3344M to cover a  $6.2 \text{ mm} \times 6.2 \text{ mm}$  area, that is an angular size of  $0.17^\circ$ . There are many advantages in using SiPMs compared to the traditional photo-multiplier tubes: excellent single photon resolution, high photon detection efficiency, low bias voltage, no damage when exposed to ambient light. The SiPM signals are processed by a front-end electronics based on the CITIROC ASIC [7] which continuously integrates the input signal over a predefined time-window and saves only the integrated signal when triggered. Conversely, current IACTs and other CTA telescope prototypes are based on ASICs that sample the input signal at typical rates of 1 GHz.

### 3. Monte Carlo Simulation

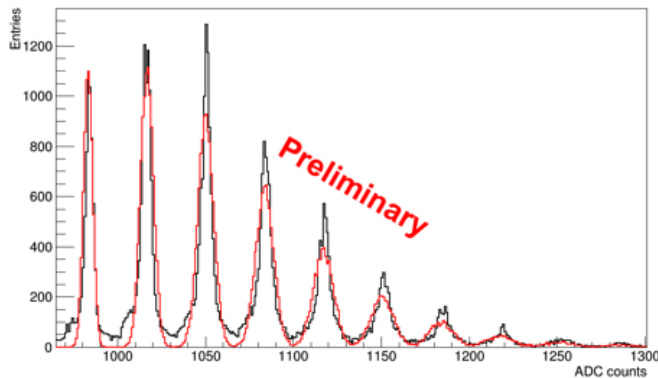
ASTRI SST-2M expected performance has been carefully studied using a full Monte Carlo simulation of the shower development in the atmosphere for both gammas and hadronic background, followed by a detailed simulation of the atmospheric extinction and detector response. The official CTA simulation pipeline has been used to obtain results comparable with other prototypes and reliably scalable to a higher number of telescopes. Shower development in the atmosphere has been simulated with CORSIKA version 6.99 [8] while atmospheric extinction and detector response have been simulated using the `sim_telarray` package [9]. The main characteristics of the simulated samples are summarized in table 1. Showers produced by gamma primaries from a point-like source at  $20^\circ$  zenith angle and diffused protons within a cone with  $6^\circ$  radius around the same direction have been simulated. Only events with at least 4 adjacent pixels inside a PDM with signal above 5 photo-electrons have been selected to simulate the telescope trigger condition. The electronic chain of the ASTRI SST-2M prototype is quite different from the one commonly used by Cherenkov telescopes which usually make use of photo-multiplier tubes and high frequency FADCs that save the full signal pulse shape. The `sim_telarray` package has been modified to properly simulate ASTRI front end electronics which instead save only the amplitude of pixel signal, as explained in the previous section.

### 4. Crosschecks of electronic simulation

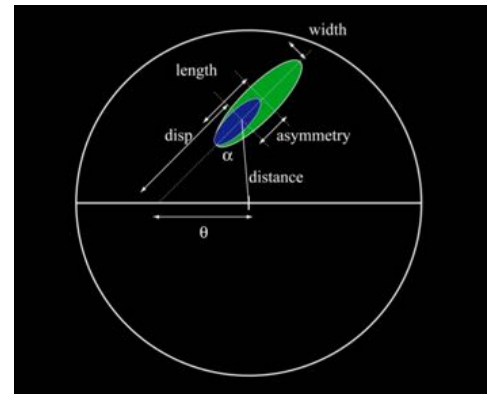
To verify that the ASTRI SST-2M electronic chain is properly simulated we compared the signal of one pixel when illuminated by a pulsed LED, as measured in our laboratory, with the simulated signal, see figure 2. The LED emission has been dimmed until the average number of photons hitting the pixel is very low in order to have a handful of well defined peaks in the pixel signal distribution. The shape of such distribution is determined by the baseline of the electronic signal, the average number of photo-electrons per pulse, the optical cross-talk probability, the average number of ADC counts per photo-electron and the fluctuation of such conversion factor. We used the modified `sim_telarray` package to simulate the camera response when illuminated by a pulsed light source. We produced many samples changing all the above listed steering parameters over a wide range and compared the signal distribution obtained with the experimental one. A smaller region in the parameter space centered on the input parameters of the sample which best fit real data has been considered for a second step. This procedure has been iterated until a very good agreement has been reached, as shown in figure 2. The residual differences between data and MC are due to the Gaussian parametrization of the signal peaks which clearly doesn't reproduce the inter-peak regions. Tests with an improved parametrization of the peak signal are ongoing. Nevertheless the very good agreement already achieved clearly demonstrates that `sim_telarray` package can properly simulate ASTRI front-end electronics.

### 5. Analysis of simulated data

The simulated data have been analyzed with the `Eventdisplay` package [10]. Shower images have been cleaned with the robust two fixed levels cleaning algorithm with thresholds set at 12/6 photoelectrons. The resulting images have been selected requiring at least 5 pixels and



**Figure 2:** Comparison between laboratory measurements (solid black line) of pixel signal when illuminated by a pulsed LED and simulated data (solid red line).

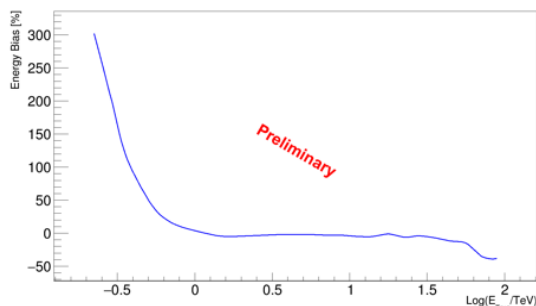


**Figure 3:** Schematic Cherenkov image and definition of Hillas parameters.

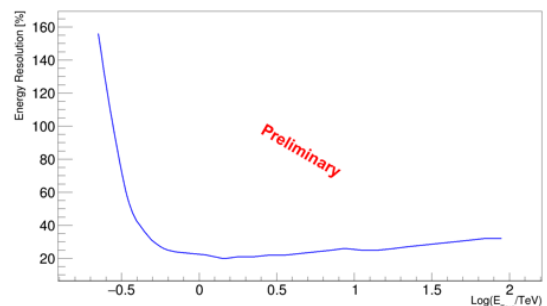
an overall signal, the so-called size, greater than 100 photoelectrons. Images surviving to these preliminary cuts have been parameterized using the standard second moment Hillas analysis [11], see figure 3 for their definition. Cuts on width and length has been optimized as a function of distance and logarithm of the size to remove as many background events as possible while retaining a sizable fraction of gamma events.

## 6. Energy resolution

The energy of primaries has been estimated using a three dimensional lookup table which depends on the image distance, logarithm of the size and eccentricity, that is the ratio width/length. The reconstructed energy, see figure 4, shows a bias, that is a difference between the mean reconstructed energy and the true energy, at the lower end of the energy range due to a threshold effect. A bias at highest energies due to pixel saturation and image truncation effect is clearly visible too. The energy resolution is about 20% at 1TeV slowly increasing with energy, see figure 5. The reason for this unexpected behavior is under investigation.



**Figure 4:** Energy bias, that is the mean of  $(E_{Rec} - E_{True})/E_{True}$ , as a function of true energy.

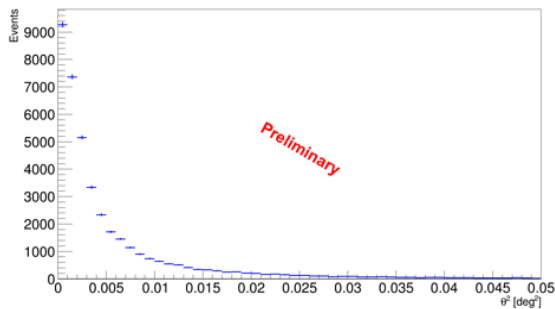


**Figure 5:** Energy resolution, defined as the 68% containment radius, as a function of true energy.

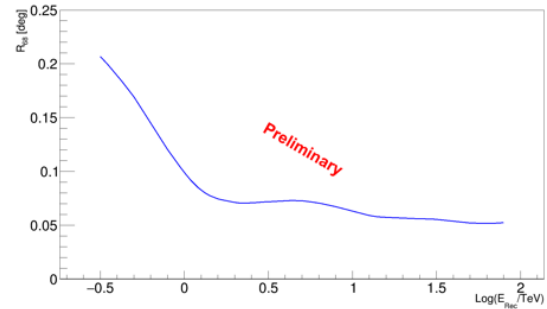
## 7. Angular resolution

The direction of primaries has been determined using the Disp method, as described in [12]: the point on the focal plane corresponding to the primary direction lies on the major axis of the

image in the direction indicated by the asymmetry of the image itself. The distance of this point from the image centroid, the so-called Disp, has been determined using a three dimensional LUT which depends on the image distance, logarithm of the size and eccentricity. The distribution of the squared angular distance between the reconstructed primary direction and the nominal source position  $\theta^2$  is shown in figure 6 as well as the angular resolution  $R_{68}$  (the radius of the circle containing 68% of the events), see figure 7.



**Figure 6:**  $\theta^2$  distribution for gamma ray events.



**Figure 7:** Angular resolution as a function of energy.

## 8. Conclusions

Preliminary estimations of angular and energy resolution of the ASTRI SST-2M telescope confirm expected performance, about  $0.1^\circ$  and 20% respectively at  $E > 1$  TeV.

## Acknowledgments

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