PROCEEDINGS OF SCIENCE

The Stereo Event Builder of the ASTRI Mini-Array

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The ASTRI Mini-Array is an international project led by the Italian National Institute for Astrophysics (INAF) which is in the process of deploying nine Imaging Atmospheric Cherenkov Telescopes (IACTs) of the 4-m class at the Observatorio del Teide in Tenerife (Spain). The project is designed to detect very high-energy gamma rays up to the multi-TeV scale. Upon completion it will be for some time the largest IACT array in operation both in terms of number of telescopes and of ground surface area. The first telescope of the array, named ASTRI-1, is now in its commissioning phase; the second telescope is being installed at the site, and by the end of 2025 a sub-array of three telescopes should become operational. The ASTRI Mini-Array operation concept is based on the stereoscopic technique, i.e. the detection of the same atmospheric shower event with two or more telescopes; all single-telescope events data are acquired independently and stored for off-line processing. The Stereo Event Builder (SEB) software system, i.e. the part of the off-line data processing chain that is responsible for identifying single and stereo Cherenkov events, will become of fundamental importance as soon as multiple telescopes will be operational. In this contribution we present the SEB design and expected performance; simulation results will be interpreted considering the data acquired during the commissioning phase.

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1. Introduction

Gamma-ray astronomy is a continuosly evolving field where the detection technique needs to be adapted to the energy range under study.
The ASTRI project [1] is related to the development of Imaging Atmospheric Cherenkov Telescopes (IACTs) particularly suitable for the multi-TeV energy range. The ASTRI Mini-Array is an international project led by INAF aimed at the construction and operation of an array of nine IACTs at the Observatorio del Teide in Tenerife (Spain) [2].
The design and expected performance of the ASTRI Mini-Array [3] are based on the stereoscopic technique which requires the detection of the same atmospheric shower event by two or more telescopes. The stereoscopic technique improves both the measurement resolution of the gamma-ray parameters and the background rejection. The correct identification of the single-telescope triggers participating to the same stereo event is therefore a fundamental step. At the same time each single telescope must be able to observe cosmic muon events to allow for calibrations with adequate precision [4].
In the ASTRI Mini-Array operation concept, all the single-telescope Cherenkov events are acquired independently and stored for off-line processing. The off-line reconstruction pipeline [5] will run at the ASTRI Data Center in Rome; the Stereo Event Builder software system is the step that will provide the identification of either single or stereo events.

2. Monte Carlo Based Performance

The SEB algorithm development and expected performance [6] are based on Monte Carlo simulations. For the purpose of optimising the stereo events identification algorithm, proton events have to be considered because of their much higher rate and larger time dispersion among the single-telescope triggers. Signal events will be diluted in the dominant flux of protons and will be correctly identified by the same algorithm developed for background events.
The SEB algorithm is based on the fact that single-telescope triggers from the same stereo event are clustered in time and follow a predictable time pattern depending on the telescope pointing direction. The algorithm uses the time differences between single-telescope trigger as the main input data together with the information of the telescope Alt-Azimuth pointing direction as a function of time to infer the average shower propagation direction. The pointing direction at the exact time of the event is interpolated.
Considering an event as well identified only if it matches the Monte Carlo truth in terms of multiplicity, telescope identity and timestamp of the single-telescope triggers, we can define N_{true} as the number of stereo events according to the Monte Carlo truth, N_{reco} as the number of stereo events as identified by the SEB, independently of their correspondence with the Monte Carlo truth and N_{good} as the number of reconstructed events that are well identified. We can define the SEB algorithm efficiency ε_{SEB} (the fraction of the true events that are correctly reconstructed) and the purity p_{SEB} (the fraction of reconstructed events which match the Monte Carlo truth):

$$\varepsilon_{SEB} = \frac{N_{good}}{N_{true}}, \qquad p_{SEB} = \frac{N_{good}}{N_{reco}}.$$

Previous studies based on [6] have shown that the SEB algorithm can achieve both efficiency and purity above 99 %.

3. Array Status

The ASTRI Mini-Array as a whole is in the construction phase [1], in particular the first telescope (ASTRI-1) is now fully operational and is undergoing an extensive phase of commissioning, calibration [4, 7] and performance evaluation [8] based also on the observation of astrophysical sources like the Crab Nebula [9].
As of today, other telescopes are in their commissioning or construction phase; by the end of 2025 more than one telescope should become fully operational and array observation should be started. The Stereo Event Builder software system will start to be a necessary part of the reconstruction pipeline; verifying its capabilities to cope with the ASTRI Mini-Array real data as soon as possible is of paramount importance.

4. Data Driven Studies

In order to test the SEB system with real data as soon as possible, ASTRI-1 data has been used to emulate the full array with a data driven approach.
As mentioned in 2, gamma-ray events correspond to only a small fraction of the observed trigger rate, but the SEB must correctly identify all the events types, including the background ones. Therefore for a realistic emulation of the full array data ASTRI-1 triggers can be used without any event selection.
For the present study two types of observation runs are used:

- fixed telescope pointing (20 deg Zentih Angle, 180 deg Azimuth) similar to the Monte Carlo data used to develop the SEB algorithm;
- Crab Nebula tracked pointing, with the source at a fixed offset position.

Figure 1 shows the time distance between two consecutive trigger for run with fixed telescope pointing, as predicted by the Monte Carlo simulation, even if different events are typically quite far apart in time (0.1 ms) they can be as close as a few hundreds of ns.
Figure 3 shows the telescope Alt-Azimuth pointing direction as a function of time for the observing run used to emulate array tracking conditions for this study.
In order to perform a data-driven array emulation, for each ASTRI-1 trigger a stereo event is generated assuming a telescope multiplicity derived from the Monte Carlo 2 according to the following steps:

- the event multiplicity is randomly assigned following the multiplicity probability distribution;
- the identity of the telescopes triggered by the event is randomly assigned;
- the expected time delay between the different telescopes is computed assuming the shower propagation direction is the same as the telescope pointing direction;

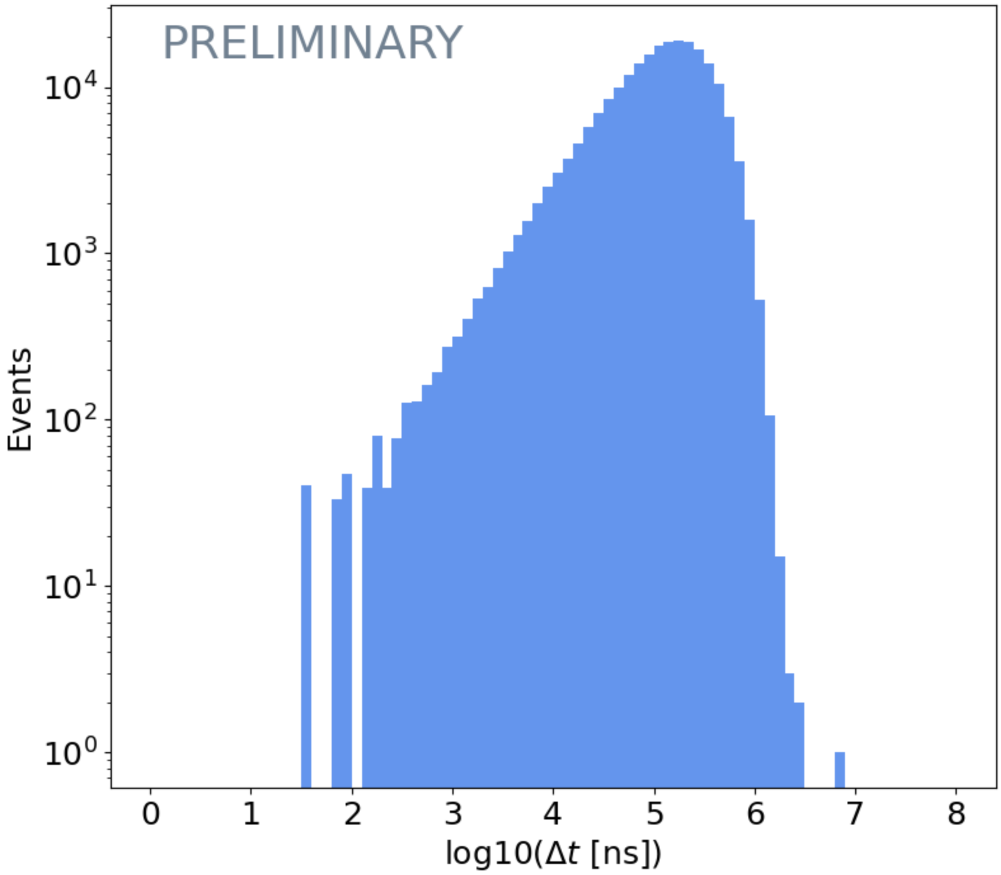

Figure 1: ASTRI-1 time difference (Δt) between consecutive triggers, with the telescope pointing at 20 deg Zentih Angle and 180 deg Azimuth.

- for each telescope the assigned trigger time is randomly fluctuated according to a Gauss distribution whose width is derived from the Monte Carlo simulations;
- for each telescope a fits file with the expected format is saved;
- in order to evaluate the SEB performance a separate file containing the truth about the emulated events is saved.

The emulated array data are then processed with the SEB system generating a SEB output with the same format expected for real data. Comparisons between generated and reconstructed events show performance comparable with the one derived from full Monte Carlo studies.
Even if the emulated data cannot replicate all the complexities and challenges of real data, this study verified that the SEB can cope with realistic conditions, and particularly important is the use of data in real tracking conditions which has been tested for the first time.

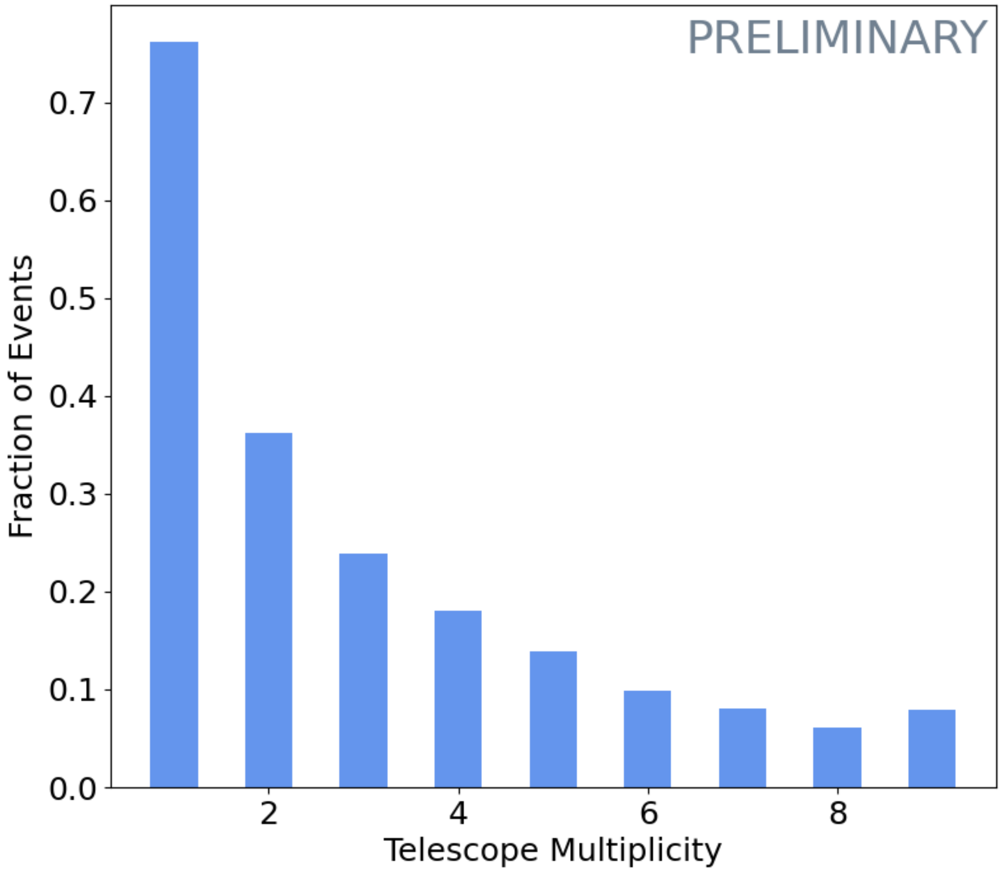

Figure 2: Events Telescope Multiplicity for Data Driven studies.

5. Conclusions

The ASTRI Mini-Array is under construction at the Observatorio del Teide in Tenerife (Spain) with the aim of studying gamma-ray astrophysical sources at the TeV and multi-TeV energy scale, and it is expected to be for some time the largest IACT array in operation. The stereo events identification is a fundamental step which will be performed off-line, as part of the reconstruction chain, by the Stereo Event Builder software system.

The SEB algorithm is based on a time window applied to consecutive single-telescope trigger times with respect to the pattern expected from the shower propagation direction. Real data from a single telescope has been used to emulate the full array in realistic observing conditions; preliminary results confirm that stereo events can be identified with efficiency and purity of the order of 99 %.

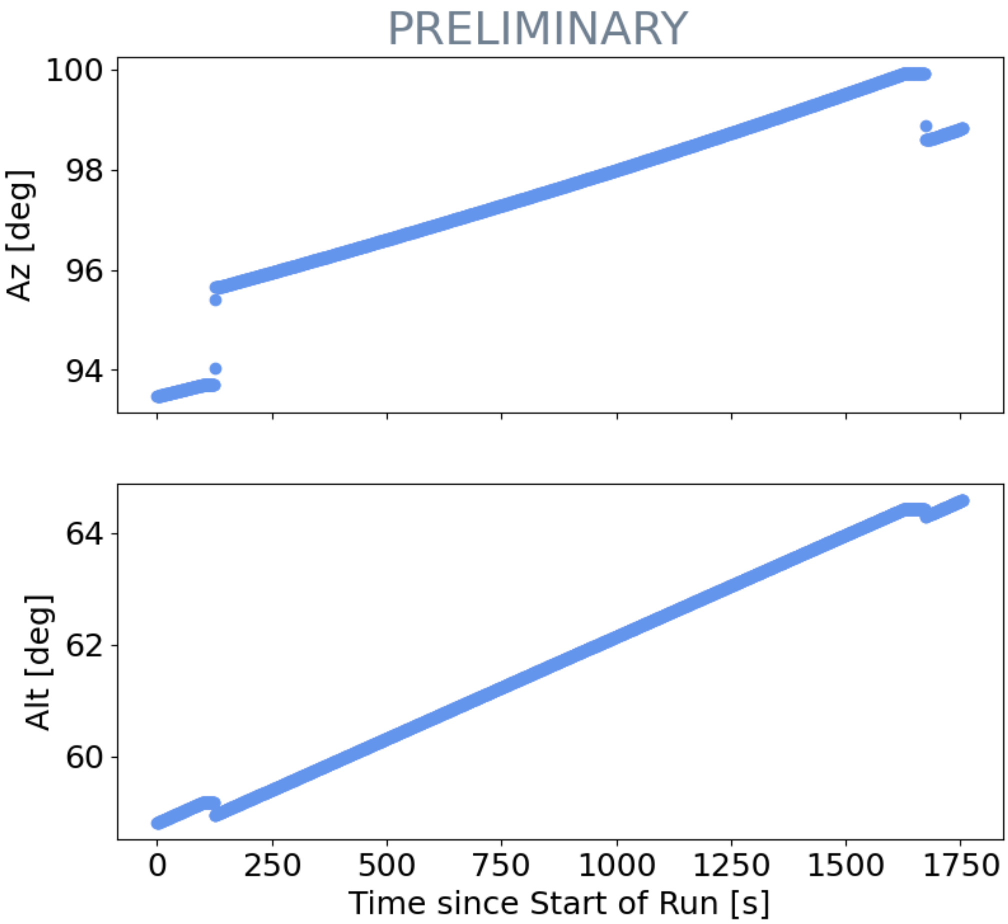

Figure 3: Telescope Alt-Azimuth pointing direction vs. time since the start of the run.

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References

[1] G. Pareschi et al., *Status of the astri mini-array gamma-ray experiment*, vol. Proc. 39th ICRC, Geneva, Switzerland, PoS(ICRC2025), 2025.

[2] S. Scuderi, A. Giuliani, G. Pareschi, G. Tosti, O. Catalano, E. Amato et al., *The astri mini-array of cherenkov telescopes at the observatorio del teide*, *Journal of High Energy Astrophysics* **35** (2022) 52.

[3] F. Pintore et al., *Renewed performance of the astri mini-array at the observatorio del teide*, vol. Proc. 39th ICRC, Geneva, Switzerland, PoS(ICRC2025), 2025.

[4] T. Mineo et al., *Using muon rings for the optical calibration of astri-1 telescope: preliminary results*, vol. Proc. 39th ICRC, Geneva, Switzerland, PoS(ICRC2025), 2025.

[5] S. Lombardi et al., *The data processing system of the astri mini-array project*, vol. Proc. 38th ICRC, Nagoya, Japan, PoS(ICRC2023)682, 2023.

[6] S. Germani et al., *The stereo event builder software system of the astri mini-array*, vol. Proc. 38th ICRC, Nagoya, Japan, PoS(ICRC2023)597, 2023.

[7] D. Mollica et al., *Calibration of the astri-1 cherenkov camera*, vol. Proc. 39th ICRC, Geneva, Switzerland, PoS(ICRC2025), 2025.

[8] S. Iovenitti et al., *Measurement and monitoring of the astri mini-array pointing accuracy*, vol. Proc. 39th ICRC, Geneva, Switzerland, PoS(ICRC2025), 2025.

[9] S. Crestan et al., *Astri-1: Early data and performance highlights*, vol. Proc. 39th ICRC, Geneva, Switzerland, PoS(ICRC2025), 2025.