PROCEEDINGS OF SCIENCE

The Stereo Event Builder software system of the ASTRI Mini-Array

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The Stereo Event Builder (SEB) software system of the ASTRI Mini-Array is the part of the off-line data processing chain that is responsible for identifying single and stereo Cherenkov events. 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. In the ASTRI Mini-Array operation concept, the expected performance is based on the stereoscopic technique, i.e. the detection of the same atmospheric shower event with two or more telescopes. However all single-telescope events are acquired independently and stored for off-line processing. This strong requirement must meet the need to observe muon events with each single telescope to allow for calibrations. In this scenario, the correct identification of the single telescope triggers participating to the same stereo event is of fundamental importance. In this contribution we present the SEB constraints, design, and expected performance.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

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1. Introduction

The study of astrophysical sources emitting gamma rays is continuously evolving thanks to new observatories and experiments exploiting technological innovations. Imaging Atmospheric Cherenkov Telescopes (IACTs) can be used to detect gamma-ray induced particle showers in the atmosphere through their Cherenkov light emission from an energy of few tens of GeV to the multi-TeV scale.

The ASTRI project [1] is related to the development of telescopes intended to cover the high-end of the IACTs 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] rely on the stereoscopic technique which is based on 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, therefore the correct identification of the single-telescope triggers participating to the same stereo event is fundamental. At the same time each single telescope must be able to observe cosmic muon events to allow for calibrations with adequate precision.

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 [4] 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. The Array

The telescopes design is based on the Schwarzschild-Couder two mirror configuration with Silicon Photomultipliers sensors and it features a very wide field of view (FoV) of 10.5 degrees [5].

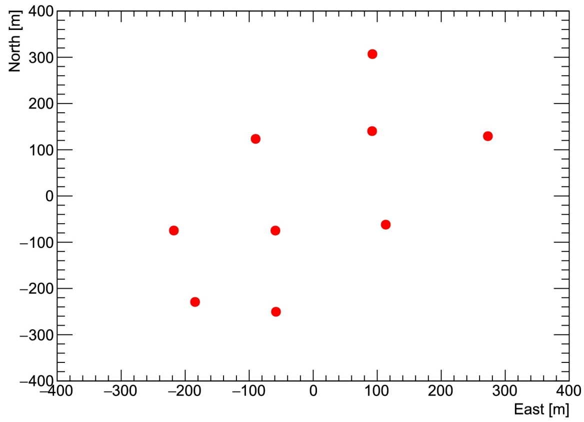

Figure 1: ASTRI Mini-Array telescope positions.

Thanks to the large FoV the array can operate with an average inter-telescope distance of about 160 m and cover a large ground surface. The telescope positions (Fig. 1) have been chosen on the basis of a trade-off between scientific performance requirements and site constraints, resulting in an asymmetric shape of the array. Upon completion, the ASTRI Mini-Array will be for some time the largest IACT array in operation below 2500 m a.s.l. both in terms of number of telescopes and of ground surface area, with the primary goal of investigating gamma-ray emission from celestial sources.

3. Stereo Events

Cherenkov events have been characterised on the basis of Monte Carlo simulations [6] for gamma rays and protons representing the signal and background respectively. Air showers were simulated using the `CORSIKA` package [7] and the response of the array telescopes was simulated using the `sim_telarray` package [8].

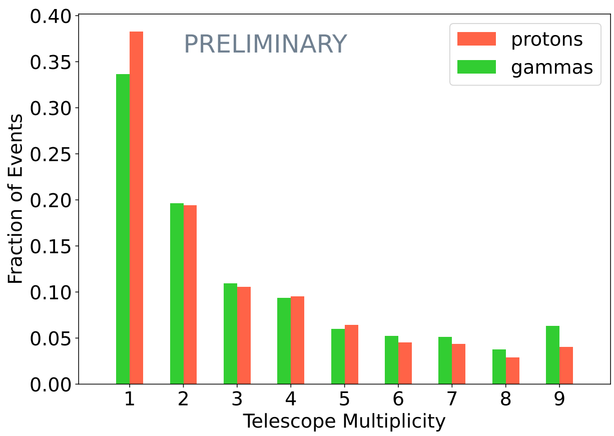

Figure 2: Telescope multiplicity for simulated gamma and proton events triggered by the ASTRI Mini-Array.

Fig. 2 shows the telescope multiplicity (number of single-telescope triggers in the stereo event) for simulated events at 20 degree Zenith angle. The simulated energy spectrum is a power law with -1.5 spectral index: $\frac{dN}{dt} \propto E^{-1.5}$. The simulated particle rate is representative of the expected flux values for both protons and photons with (0.1-330 TeV) and (0.1-600 TeV) energy range respectively. The multiplicity behaviour for protons and gamma rays show similar traits with a decreasing probability for an increasing number of triggered telescopes. We can note the non-zero probability to have all the nine telescope triggering on the same event. The slight probability increase for stereo events with 9 telescopes with respect to the ones with 8 telescopes can be explained with the fact that, contrary to the lower multiplicity values, there is no upper bound to the surface area an event can cover to trigger 9 telescopes, only a lower bound.

The event duration can be defined as the time difference between the latest and earliest single-telescope trigger times in the event. Figure 3 shows the event duration as a function of the multiplicity for simulated protons and photons. The events with a multiplicity of one are assigned a duration of zero. We can note how there is a correlation between the event duration and the multiplicity both for signal and background events. This can be explained with the travel time of the Cherenkov light front at a given angle with respect to the telescope positions. Two telescopes which

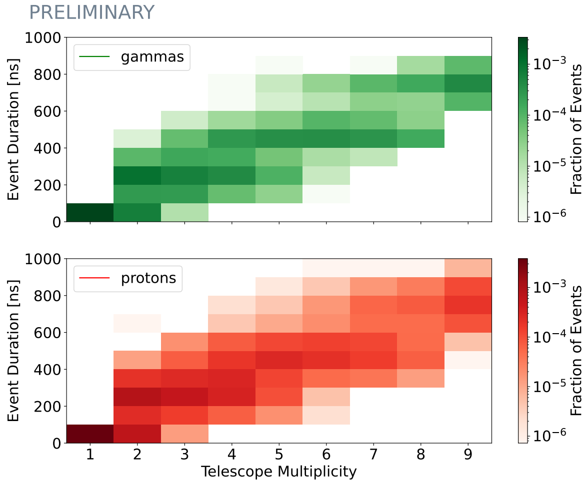

Figure 3: Event duration as a function of the event multiplicity for simulated gamma-ray and proton events.

are aligned parallel to the Cherenkov light front will trigger approximately at the same time, while the longer their projected distance along the Cherenkov light propagation direction the larger the time difference in the trigger times. The total event duration, for the simulated configuration, can range between 0 ns and 1 μs, while, for a given multiplicity, the duration spread is approximately constant. We can also note that, for a given multiplicity, time duration for proton events has a slightly larger spread. The simulated photon rate is 0.8 Hz, while the simulated proton rate is 1.6 kHz, corresponding to an average time difference between consecutive events of about 0.6 ms.

4. Identification Algorithm

For the purpose of developing and 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 to identify stereo events 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 difference between single-telescope triggers and the concepts of projected distance and projected time difference.

The first step in the SEB algorithm is to merge all single-telescope triggers in a time ordered fashion. The left side of Fig. 4 shows the time difference between consecutive single-telescope triggers (Δt). We can note that single-telescope triggers pertaining to the same stereo event typically cluster at Δt which are three order of magnitude smaller than the average time separation between two stereo events. Even if there is a small overlap between the two distributions, a simple cut to the maximum allowed Δt would correctly identify the majority of the stereo events. The cut would necessarily be dependent on the pointing direction though.

If $\bar{d}$ is the vector representing the displacement between two telescope positions and $\hat{p}$ is the unit vector indicating the propagation direction of the shower, assumed to be the opposite of the telescopes pointing direction, we can define the projected distance as the scalar product between $\bar{d}$ and $\hat{p}$:

$$d_p = \bar{d} \cdot \hat{p}.$$

The right side of Fig. 4 shows the time difference between consecutive single-telescope triggers as a function of the projected distance d_p. The time separation for triggers relative to different events does not show any correlation with the projected distance. The dashed green line represents the expected time pattern assuming the shower front moves at the speed of light, which, as we can see in the plot, is approximately followed by single-telescope triggers pertaining to the same event. We can define the projected time difference as the difference between the measured and expected Δt, which corresponds to the vertical distance between the points and the dashed line on the right side of Fig. 4. The distributions of projected time differences for triggers within the same event and from separate events are shown in Fig. 5. The SEB algorithm applies a selection window to the projected time difference in order to assign two single-telescope triggers to the same stereo event. The solid green lines in Fig. 4 and Fig. 5 represent a time window of 300 ns.

To summarise the SEB algorithm goes through the following steps:

1. merge all single-telescope triggers in a time ordered fashion;
2. compute the projected time differences between consecutive single-telescope triggers;
3. assign the single-telescope triggers within a predefined window of projected time difference to the same stereo event.

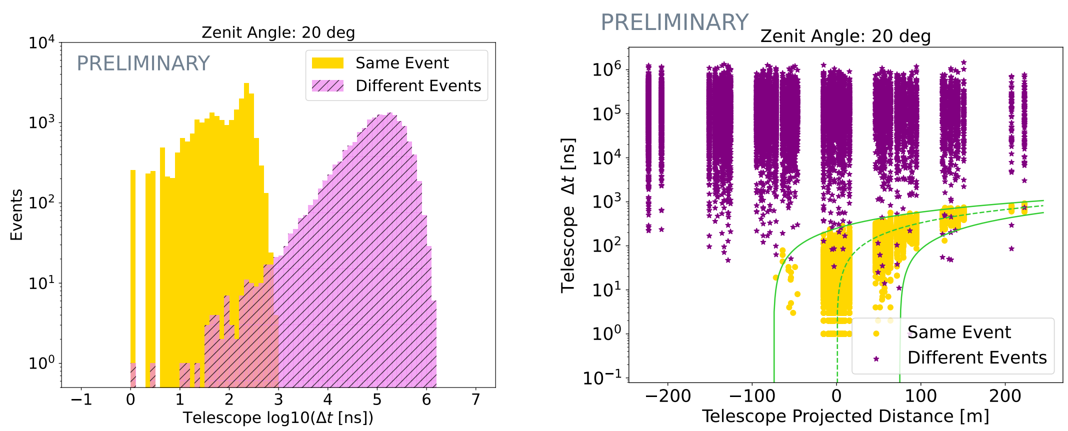

Figure 4: Left: time difference between two consecutive single-telescope triggers; the shaded yellow histogram represents triggers from the same stereo event while the violet histogram with the pattern fill corresponds to triggers from different events. Right: time difference between two consecutive single-telescope triggers as a function of the telescopes projected distance; yellow dots and purple stars represent triggers from the same stereo event and from different events respectively. The dashed green line shows the expected time pattern for stereo events while the solid green lines represents the selection window.

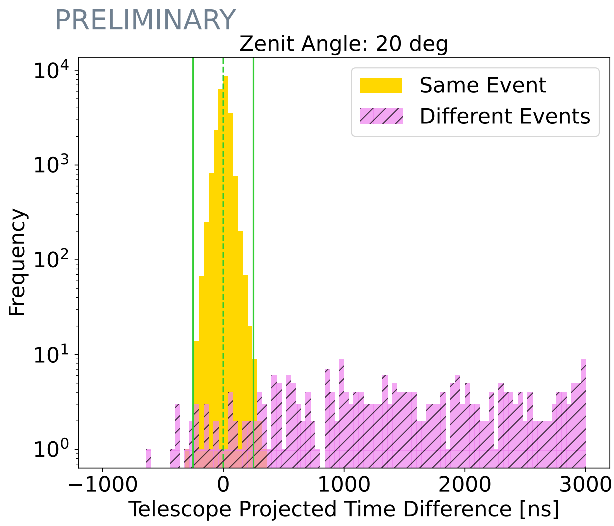

Figure 5: The distribution of the projected time difference for consecutive single-telescope triggers from the same stereo event (yellow shaded area) and from different events (violet with pattern fill). The dashed green line shows the expected time pattern for ideal stereo events while the solid green lines represents the selection window (±300 *ns*).

In order to evaluate the performance of the SEB algorithm in terms of the correct identification of the stereo events, we can define the following quantities:

N_{true}: the number of stereo events according to the Monte Carlo truth;

N_{reco}: the number of stereo events as identified by the SEB, independently of their correspondence with the Monte Carlo truth;

N_{good}: the number of reconstructed events perfectly matching the Monte Carlo truth in terms of multiplicity, telescope identity and timestamp of the single-telescope triggers.

A reconstructed event which only partially overlaps with the Monte Carlo truth expectations is not considered among the N_{good}.

Starting from the quantities introduced above, we can define the SEB algorithm efficiency (ε_{SEB}) as the fraction of the true events that are correctly reconstructed and the SEB algorithm purity p_{SEB} as the fraction of reconstructed events which match the Monte Carlo truth:

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

The resulting efficiency and purity as a function of the selection windows on the projected time difference are shown in Fig. 6 for different Zenith angles. The minimum considered window is 25 *ns* while the largest window for this study corresponds to 400 *ns*. We can note that all pointing directions show a similar behaviour. Both purity and efficiency start from low values for the smallest windows, since many true events are split into two or more reconstructed events, and reach values above 99 % for windows between 200 and 400 *ns*. Even if the results shown here are related to a

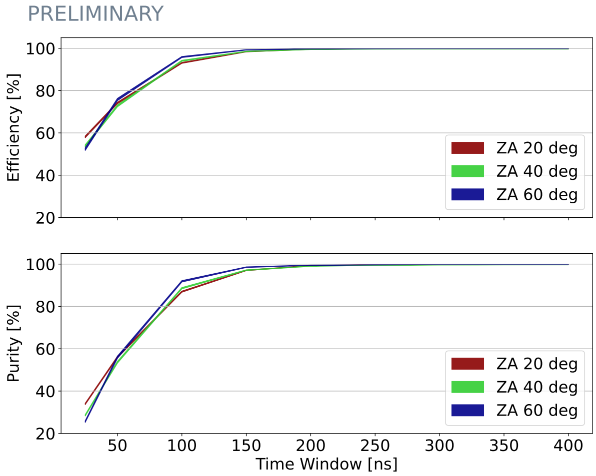

Figure 6: The SEB algorithm efficiency (top) and purity (bottom) for different projected time windows. The statistical errors are negligible compared to the plot scale, the colors represents different Zenith angles.

single Azimuth direction the conclusions can be generalised, therefore a single time window on the projected time difference can be applied for all the telescopes pointing directions.

Concerning the SEB output, it is important to note that all events are considered and their information is stored for subsequent use, independently of their multiplicity. Events resulting with a multiplicity of 1 are not considered proper stereo events but can be used for calibration purposes when they correspond to muon events. Events with a multiplicity of 2 or more can be considered as stereo even if a higher multiplicity threshold could be set during the reconstruction or the analysis.

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 stereo Cherenkov events observed by the ASTRI Mini-Array have been characterised through Monte Carlo simulations. 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. A single time window can be used independently of the pointing direction of the telescopes. The preliminary results show that stereo events can be identified with efficiency and purity above 99 %.

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. 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 Ministero dell'Istruzione dell'Universitaá e della Ricerca (MUR) is acknowledged for financial support through the program "Dipartimenti di Eccellenza 2018-2022" (Grant SUPER-C). The ASTRI project is becoming a reality thanks to Giovanni "Nanni" Bignami, 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.

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