Low energy performance boost through a hardware stereoscopic trigger between CTA LST-1 and MAGIC

J. Baxter, a,∗ J. A. Barrio, b M. Bitossi, c A. Donini, d D. Mazin, a,e R. Paoletti, c,f A. Pérez Aguilera b and L. Á. Tejedor Álvarez b on Behalf of the CTA-LST Project and MAGIC collaboration

a Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba 277-8582, Japan
b IPARCOS Institute and EMFTEL Department, Universidad Complutense de Madrid, Spain
c Istituto Nazionale di Fisica Nucleare (INFN) Sezione di Pisa, 56127 Pisa, Italy
d Istituto Nazionale di Astrofisica (INAF), Osservatorio Astronomico di Roma, Italy
e Max-Planck-Institut für Physik, Föhringer Ring 6, 80805 München, Germany
f Università degli Studi di Siena, via Roma 56, 53100 Siena

E-mail: joshua28@icrr.u-tokyo.ac.jp, joshuaicrr@gmail.com

The next generation facility for gamma-ray ground-based observations is the Cherenkov Telescope Array (CTA) observatory, which comprises three types of imaging atmospheric Cherenkov telescopes (IACTs). The Large-Sized Telescopes (LSTs) of CTA are the largest telescope type with a mirror dish of 23 m diameter. They cover the low energy end of the accessible gamma-ray energies for IACTs, starting from about 20 GeV up to a few TeV. The first LST prototype, known as LST-1, was officially inaugurated at the Observatorio del Roque de los Muchachos in La Palma (Canary Islands, Spain) in 2018 and has since performed calibration observations of various known gamma-ray sources. Additionally, the site houses the MAGIC telescopes, two 17 m IACTs situated approximately 100 m away from LST-1, which have been performing stereo observations since 2009. Currently, joint observations between LST-1 and MAGIC are being carried on, and the data taken independently by the two IACT systems is analyzed by combining events via software. However, this method increases the energy threshold, as it discards all but the relatively high-energy events triggered by all three telescopes. To address this issue, we have developed a novel hardware stereo trigger system between LST-1 and MAGIC, which is capable of handling events triggered by any-two out of the three telescopes. In this contribution, we will report on the performance estimation of joint LST-1 and MAGIC observations using the hardware trigger.
1. Introduction

The Cherenkov Telescope Array (CTA) is the forthcoming generation of terrestrial gamma-ray observatories, sensitive to an extensive energy bandwidth from 20 GeV to 300 TeV [1]. Designed to observe the entire sky, the observatory will be constructed in both the Northern and Southern Hemispheres. The Northern Hemisphere site, situated at the Observatorio Roque de los Muchachos in La Palma, Spain, at an altitude of 2200 m.a.s.l, comprises 4 Large-Sized Telescopes (LSTs) and 15 Medium Size Telescopes (MSTs). Of these, the inaugural Large-Sized Telescope, LST-1, was completed in 2018 and has embarked on scientific observations since 2019. Boasting its substantial 23-meter diameter reflector, LST-1 possesses the highest sensitivity within the lowest energy domain of the CTA [2, 3].

The MAGIC telescopes, a pair of current generation IACT with a 17 m aperture mirror situated approximately 100 m from LST-1 (Figure 1), has been observing in stereoscopic mode since 2009. For sources with a spectral index of -2.6 at low zenith angles (zd < 35 deg), MAGIC is estimated to have an energy threshold (characterized by the peak resulting from a Gaussian fit to the differential true energy distribution of triggered events) of about 50 GeV for the standard trigger [4]. MAGIC is generally operated to record only stereo events that trigger both telescopes, and operates independently of LST-1.

LST-1 and MAGIC can trigger identical Cherenkov shower events due to their proximity, and joint observations have been performed by searching for independently triggered events offline [8]. Joint observations with this approach can only handle events triggered by all three telescopes, as there is no physical trigger exchange between LST-1 and MAGIC. To overcome this, we have implemented a Hardware Stereo Trigger (HaST) between LST-1 and MAGIC, constructing a system capable of recording relatively faint low-energy shower events triggered by any-two telescopes amongst LST-1 and MAGIC, thereby enhancing the performance of joint observations.

Figure 1: Photograph of LST-1 and MAGIC in La Palma (credit: Akira Okumura). From left to right: LST-1, MAGIC-II, MAGIC-I. The longest distance between LST-1 and MAGIC-I is 156 m apart.
2. Implementation of the hardware stereo trigger system

Both the LST-1 and MAGIC telescopes have a multilevel trigger architecture to acknowledge the occurrence of a potentially interesting event. Once there is a positive result from the trigger system for a given event, the digitizing and the data acquisition systems are triggered. This multilevel trigger architecture is structured hierarchically as: the pixel level trigger (L0), the telescope camera level trigger (L1) and the array, or the stereo [5], level trigger (the temporal coincidence of several camera level triggers from different telescopes). In the case of LST-1, all the trigger system components are integrated inside the telescope camera, while the trigger system of MAGIC is centralized in a building called the Counting House (CH).

The implementation schematic of the HaST system is illustrated in Figure 2. To facilitate the transmission of trigger signals, we implemented a new optical fiber cable between LST-1 and the MAGIC CH. After the trigger signal enters the MAGIC CH via this optical fiber, the LST-1 L1 signal is converted into a digital signal by a newly fabricated Electro-Optical Transceiver (EOT). To ensure compatibility with subsequent signal standards, the signal is then converted from differential (LVDS) to single-ended (CMOS). The topological (TOPO) trigger [6] subsystem, originally crafted to enable the rejection of events based on the positions of the images in the cameras and relative position of the two MAGIC telescopes, was reprogrammed to enable coincidence of LST-1 L1 trigger signals with the L1 signals of MAGIC-I and MAGIC-II. This reconfigured system was then deployed in the MAGIC CH. On the LST-1 side, no further changes are necessary, as the telescope camera, equipped with a Trigger Interface board (TIB) [7], is ready to receive L1 trigger signals from neighboring telescopes.

3. Performance estimation

Extensive Monte Carlo (MC) simulations underpin the expected performance of an IACT system. First, we provide a concise explanation of the MC simulations setup and the analysis pipeline used for the performance evaluation of the HaST system. We re-utilize the same MC simulation productions of gamma rays, along with background noise events such as protons and helium, and electrons as in [8]. The simulation from the emission of Cherenkov light to the instrumental response of MAGIC and LST-1 is performed with CORSIKA [9] and sim_telarray [10]. From the low-level information like the waveforms signals of each simulated PMT pixel, the magic_cta_pipe ¹ was used to reconstruct high-level information such as the physical quantities of primary particles entering the atmosphere, including their arrival direction, energy, and particle species. Since the HaST approach allows us to capture any-two events that are triggered only by MAGIC-I and LST-1 or MAGIC-II and LST-1, which would be discarded by the software coincidence method, we kept these events until the final phase of the analysis.

The distribution of MC gamma-ray events incident from zd = 20 deg at the trigger level segregated by true energy is presented in Figure 3. Due to its extensive effective area, the majority of events across all energy bands are triggered by LST-1. Aside from LST-1-mono events, as the energy increases, brighter showers are more likely to form, resulting in an increase of LST-1+M1+M2 events. Conversely, at lower energies (< 0.12 TeV), roughly 1-2 times more LST-1+M1

¹https://github.com/cta-observatory/magic-cta-pipe
events and 2-3 times more LST-1+M2 events are triggered compared to LST-1+M1+M2 events. The higher occurrence of LST-1+M2 events compared to LST-1+M1 events is attributed to their geometric proximity.

Subsequently, using MC gamma rays with zd < 30 deg, we estimated the energy thresholds for three different approaches; HaST-system approach, Software Coincidence (SC) approach, and MAGIC-only approach (Figure 4). MAGIC-only approach here refers to the method of mimicking the performance of the MAGIC by processing the events triggered by MAGIC stereo with magic_cta_pipe, without involving event information from LST-1. To enhance the production efficiency, MCs are initially generated with a spectral index of -2.0; however, when deriving the energy threshold from the event distribution, they are reweighted to a spectral index of -2.6, which resembles that of the standard gamma-ray candle, the Crab Nebula. The respective energy thresholds are estimated to be $\sim 39$ GeV for HaST, $\sim 49$ GeV for SC, and $\sim 56$ GeV for MAGIC-only, namely, HaST system presents an improvement of about 20% over SC, and roughly 30% over MAGIC-only. The ratio of triggered events clearly shows the effect of effective area expansion by the HaST system, as seen in the fact that the HaST system increases the number of triggered events by another 3-4 times more than the SC method, which itself enhances the event count by up to twice that achieved solely with MAGIC.

Lastly, we estimated the sensitivity based on the widely used definition for steady point source observations in the IACT community. Specifically, we assume an observation time of 50 hours

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2For example, see [4]
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Figure 3: MC gamma-rays true energy distribution of events by telescope triggered. For example, LST-1 + M2 represents events triggered by LST-1 and MAGIC-II (M2) but not by MAGIC-I (M1).

Figure 4: Left: the distribution of the true energy derived from MC simulations for gamma rays at $\theta_d < 30$ deg, reweighted for a source spectral index of -2.6. MAGIC+LST events by the HaST system is colored blue, MAGIC+LST events by the Software-Coincidence (SC) approach is green, and MAGIC-only events is orange. The dotted line indicates the peak of the distribution, i.e., the energy threshold of the corresponding system. Right: The ratio of the number of events over MAGIC-only events.

and divide the dataset into 5 bins per decade in reconstructed energy. We then seek the minimal flux that satisfies a trifold criteria: (1) detection of more than 10 events attributed to gamma rays, (2) a S/N surpassing 5 %, and (3) Li&Ma significance \cite{11} exceeds $5\sigma$. To avoid bias in the selection of the dataset during cut optimization, we divided the dataset into four subsamples and conducted k-fold cross-validation. The result of our estimation is given in Figure 5. The improvements in the effective area and energy threshold provided by the HaST system result in an overall sensitivity enhancement of more than 1.1 times against the software-coincidence method across the majority of energy bands. Particularly in the lowest energies ($\lesssim 100$ GeV), both sensitivity of HaST system
demonstrate a improvement of about 1.1 to 1.5 times, indicating that the HaST system contributes to the performance boost in the lowest energy band. On the other hand, given the scarcity of statistic in the highest energies, generating an accurate estimate with the present production poses a challenge, marking it as an area for future investigation.

Figure 5: Differential sensitivity in Crab flux Unit (%C.U.) based on low zd (zd < 30 deg) and mid zd (30 deg < zd < 45 deg) MC simulations for a 50 hour observation of a steady point source. The above curves compare the sensitivity of the HaST system, which handles events triggered by any-two or more telescopes, with the sensitivity of the Software-Coincidence method, which deals with events triggered by all three telescopes. Below the each plot, the mean ratio of the HaST system’s sensitivity to that of the Software Coincidence is given.

4. Conclusion and Outlook

We have reported on the current status of the HaST system’s implementation between MAGIC and LST-1, and its expected performance using Monte Carlo simulations. The introduction of the HaST system has made it possible to record events triggered between any-two of the three telescopes, which was previously unattainable with the offline joint analysis methods. We showed that the system contributes to lowering the energy threshold, further improving the sensitivity of the IACT system.

We have recently conducted test observations of the HaST system by pointing the telescopes towards known galactic and extragalactic sources, including the Crab Nebula. The data obtained from the observations are currently being analyzed. The amplification of triggered events as expected in the MC study has actually been confirmed. Once the optimization of the system is completed through commissioning, joint observations by MAGIC and LST-1 using the HaST system are expected to become feasible within this year. Moreover, through the additional integration of the optical fiber cables, coupled with a envisaged firmware/software updates, the HaST methodology could potentially enable the joint observations amongst the forthcoming LST-2, 3, 4, and MAGIC.
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