Performance of joint gamma-ray observations with MAGIC and LST-1 telescopes

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The prototype Large-Sized Telescope (LST-1) of the Cherenkov Telescope Array Observatory (CTAO) is in commissioning phase at the Observatorio del Roque de Los Muchachos at 2200 m a.s.l. in La Palma (Canary Islands, Spain). LST-1 is a 23-m diameter telescope and is the first of four that will compose the LST part of the CTAO Northern array. The LST subarray is optimized to provide the best sensitivity for gamma rays in the 20 GeV - 200 GeV energy range. The MAGIC telescopes, which are located approximately 100 m from the LST-1, is operating as a two 17-m telescope stereoscopic system for more than 14 years. LST-1 and MAGIC routinely perform joint observations of gamma-ray sources to exploit the potential of the three-telescope system. This contribution describes the analysis pipeline and evaluates the performance of the system using Monte Carlo simulations and data on the Crab Nebula. The sensitivity achieved during joint observations with MAGIC and LST-1 is about 30% higher than that of MAGIC alone.
1. Introduction

The study of very-high-energy ($\gtrsim 100$ GeV) gamma rays is a unique tool to unveil the origin of cosmic rays and shed light on extremely energetic processes. The Cherenkov Telescope Array Observatory (CTAO) is the upcoming next-generation gamma-ray facility [1] composed of two telescope arrays located in each of Earth’s hemispheres. In order to cover a broad energy range (from few tens of GeV up to a few hundreds of TeV) it will be composed of telescopes of three different sizes: Large-Sized Telescopes (LST), Medium-Sized Telescopes (MST) and Small-Sized Telescopes (SST). The LSTs, with mirror diameters of 23 m, will be the most sensitive to the lowest energy range of CTAO (tens of GeV). The construction of the first LST telescope, named LST-1, finished in October 2018 and since 2019 it is taking commissioning and engineering data [2].

LST-1 is located in Observatorio Roque de los Muchachos, La Palma (Spain), at the altitude of 2200 m a.s.l.. It is placed at a distance of only $\sim 100$ m from the MAGIC telescopes (Fig.1), a pair of 17 m diameter IACTs [3]. Both systems work independently, but accordingly to an MoU between the two collaborations they regularly perform joint observations of gamma-ray sources. An offline search of the same event seen by the two systems enables a joint LST-1+MAGIC analysis [4]. In this work we report the common analysis chain and the achieved performance, using both Monte Carlo (MC) simulations and observations of the Crab Nebula. This conference contribution summarizes results described in more details here [5].

2. MAGIC and LST-1

The main characteristics of the MAGIC telescopes and the LST-1 telescope are summarized in Table 1. In current scheme at trigger level the requirement is to have all three telescopes while at analysis level just two images are needed. The presence of LST-1 allows to recover 20% of the events that, considering only the MAGIC telescopes, would be discarded because only one image would survive the quality cut (image intensity > 50 p.e.), while thanks to the LST-1 image can be further processed. This results in a 15% lower energy threshold as shown in Fig.2.

<table>
<thead>
<tr>
<th></th>
<th>Diameter</th>
<th>Camera FoV</th>
<th>Pixel FoV</th>
<th># pixels</th>
<th>Peak QE</th>
<th>Trigger</th>
<th>Event rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>LST-1</td>
<td>23 m</td>
<td>4.5°</td>
<td>0.1°</td>
<td>1855</td>
<td>41%</td>
<td>mono</td>
<td>$10^4$ s$^{-1}$</td>
</tr>
<tr>
<td>MAGIC I/II</td>
<td>17 m</td>
<td>3.5°</td>
<td>0.1°</td>
<td>1039</td>
<td>32-34%</td>
<td>stereo</td>
<td>300 s$^{-1}$</td>
</tr>
</tbody>
</table>

Table 1: Summary of main LST-1 and MAGIC telescopes parameters.

3. The joint analysis pipeline

To analyze the joint observations, we developed a python-based analysis pipeline, named magic-cta-pipe\(^1\) (MCP), based on lstchain [6] and ctapipe [7] libraries. The MCP pipeline is composed of several scripts each one dedicated to a specific analysis step. The highest level analysis steps are done with scripts using methods from pyirf [8] and gammapy [9]. Concerning the analysis of real data, after the event matching based on event timestamps, the calibration step,  
\(^1\)https://github.com/cta-observatory/magic-cta-pipe
consisting in the extraction of the integrated charge in p.e. and the timing from the waveforms of each pixel, is done by MARS [10] for data from MAGIC and by lstchain for LST-1 data. Then the MAGIC data are converted into HDF5 format, compatible with the LST-1 data using the dedicated ctapipe_io_magic package\(^2\). The standard image cleaning and Hillas image parameterization is applied to all calibrated images. Starting from the individual telescope parameters stereoscopic parameters are reconstructed, the shower axis, from which the impact parameter for each telescope and the height of shower maximum. Then telescope-wise distinct Random Forests (RF) [11] are used to reconstruct the energy, the arrival direction (by means of the DISP method [12]) and to classify the nature of the primary, through a classification parameter named gammaness [13]. The implementation of the RFs is done using the scikit-learn package [14]. The telescope-wise reconstructed parameters are averaged, weighting on image intensities, to get a single value for each parameter. Finally, to estimate higher level scientific products, such as the source spectral energy distribution (SED), the light curve (LC), the skymap; data should pass gamma-selection cuts based on gammaness and theta (i.e.: the angular distance between the reconstructed event and the known source position) and should be interpreted by means of the Instrument Response Functions obtained using MC test samples.

4. The datasets: Crab Nebula observations and Monte Carlo simulations

We estimated the performance of joint MAGIC+LST-1 observations using real observations of the Crab Nebula and from Monte Carlo simulations.

The observations used for the presented analysis have been performed between October 2020 and March 2021, with a final selection of 4 hours of good quality data, taken in the 12°-53° zenith angle range.

\(^2\)https://github.com/cta-observatory/ctapipe_io_magic
As described in the previous section, to analyze the real observations we have to rely on Monte Carlo samples. The basic MC samples to perform the analysis are gamma and proton primaries, in addition to them, electron and helium samples have been used to evaluate the sensitivity from simulations. The common simulation software used to simulate the response of all telescopes to the same EAS is `sim_telarray` [15], the standard simulation program for CTA. The validation of the MC has been done through comparison of distributions of intermediate reconstructed parameters obtained from real data and from simulations. The MAGIC telescope implementation in `sim_telarray` was further validated by a direct comparison with results obtained with the MAGIC collaboration’s official simulation tool. As an end-to-end validation of the whole reconstruction process we report in Fig. 3 the energies reconstructed by the official MAGIC reconstruction + MC pipeline and our MCP + `sim_telarray` for the same real events.

In Fig. 4 the pointings of the real observations and of the training and test MC samples are reported. The MC training samples, simulated along the declination line of the source, are used to train the RFs. The MC test samples are used to derive the IRFs and the optimal quality cuts to analyze each individual data run, using interpolation among the closest nodes.

5. Performance of the joint MAGIC+LST-1 observations

A typical and robust check of the quality of an instrument and of its data analysis is the reconstruction of the spectrum of the Crab Nebula, commonly referred to as the standard candle of VHE gamma-rays. The Crab Nebula spectral energy distribution measured by MAGIC+LST-1, using 4h of data, taken mostly at medium zenith angles is shown in Fig. 5. The main applied image cuts are on intensity $> 50$ p.e. (MAGIC) and $> 80$ p.e. (LST-1), while the values of the

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure2.png}
\caption{True energy distribution obtained with MC simulations (weighted to a source spectrum of $-2.6$) of gamma rays for $Zd < 30^\circ$ at the reconstruction level (at least two images with intensity $> 50$). Vertical lines show the peak position for the joint analysis (blue) and MAGIC-only analysis (orange). Bottom panel shows the ratio of the two curves.}
\end{figure}
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**Figure 3:** Comparison of the reconstructed energy of the same MAGIC-only events by MARS and MCP chain. Only gamma-like events with MARS hadronness value of \(< 0.2\) and intensity of each image above 100 p.e. are used.

**Figure 4:** Simulated (Train and Test sample) and real data used in this analysis.

energy dependent *gammaness* and *theta* cuts are obtained requiring a 90\% gamma efficiency for the former and 80\% containment radius for the latter. The obtained SED is compatible with previous measurements by MAGIC reported in literature.

Comparing the reconstructed and the true energy of the MC samples it is possible to estimate the energy bias and resolution, defined as the mean of the \(E_{\text{rec}} - E_{\text{true}}\) and the interval corresponding to 68\% containment, respectively. Results are shown in Fig.6.

The angular resolution, defined as the angular distance from the source that corresponds to 68\% containment of the point spread function, has been estimated using MC and Crab Nebula observations, applying the standard 90\% efficiency cut in *gammaness*. Results, shown in Fig.7 for low and medium zenith angle, show a good agreement between MC and real data. At high energy (\(E > 10\) TeV) events far from the telescopes are included in the sample introducing an expected overall worsening of the angular resolution.

We finally show in Fig. 8 the estimated differential sensitivity of the MAGIC+LST-1 system,
Figure 5: Spectral energy distribution of Crab Nebula obtained with joint LST-1+MAGIC observations compared to reference measurement from MAGIC-alone [16]).

Figure 6: Left panel: Energy migration matrix, reconstructed energy vs true energy. Right panel: Energy bias and resolution.

from real Crab Nebula observations (blue) and from MC simulations (orange), compared to the MAGIC sensitivity estimated on the same data sample with the standard MAGIC analysis. We notice a rather good agreement between data and MC results, with still some discrepancies for \( E > 1 \, \text{TeV} \) that should be further investigated and will probably require an improvement of the telescope models in MC. The improvement in sensitivity of the MAGIC+LST-1 joint observations is of the order of 30% with respect to MAGIC only observations.

6. Conclusions

Thanks to the proximity of LST-1 and the MAGIC telescopes it is possible to perform joint observations of the same gamma-ray sources. We described how the events are first matched and then reconstructed. We have shown the good agreement between MC and real data and also the good agreement between the newly developed analysis pipeline and the standard MAGIC one. As a robust check we have shown that the Crab Nebula SED measured by the MAGIC+LST-1 system is in perfect agreement with measurements from other instruments. We have shown the achieved
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**Figure 7:** Angular resolution (68% containment radius), for low (left) and medium (right) zenith angles. Results for MC and Crab Nebula data are compared.

**Figure 8:** Differential sensitivity of the MAGIC+LST-1 joint observations. Estimation from Crab Nebula observations and MC are compared to MAGIC-only sensitivity estimated with the standard MAGIC analysis on real data.

Angular and energy resolutions and an improvement in sensitivity of around 30% with respect to MAGIC only, making the three-telescopes system already a very powerful instrument.

**References**


