PROCEEDINGS OF SCIENCE

ONLINE ICRC 2021
THE ASTROPARTICLE PHYSICS CONFERENCE
Berlin | Germany
37th International Cosmic Ray Conference
12–23 July 2021

Performance of the Cherenkov Telescope Array in the presence of clouds

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The Cherenkov Telescope Array (CTA) is the future ground-based observatory for gamma-ray astronomy at very high energies. The atmosphere is an integral part of every Cherenkov telescope. Different atmospheric conditions, such as clouds, can reduce the fraction of Cherenkov photons produced in air showers that reach ground-based telescopes, which may affect the performance. Decreased sensitivity of the telescopes may lead to misconstructed energies and spectra. This study presents the impact of various atmospheric conditions on CTA performance. The atmospheric transmission in a cloudy atmosphere in the wavelength range from 203 nm to 1000 nm was simulated for different cloud bases and different optical depths using the MODerate resolution atmospheric TRANsmission (MODTRAN) code. MODTRAN output files were used as inputs for generic Monte Carlo simulations. The analysis was performed using the MAGIC Analysis and Reconstruction Software (MARS) adapted for CTA. As expected, the effects of clouds are most evident at low energies, near the energy threshold. Even in the presence of dense clouds, high-energy gamma rays may still trigger the telescopes if the first interaction occurs lower in the atmosphere, below the cloud base. A method to analyze very high-energy data obtained in the presence of clouds is presented. The systematic uncertainties of the method are evaluated. These studies help to gain more precise knowledge about the CTA response to cloudy conditions and give insights on how to proceed with data obtained in such conditions. This may prove crucial for alert-based observations and time-critical studies of transient phenomena.

37th International Cosmic Ray Conference (ICRC 2021)
July 12th – 23rd, 2021
Online – Berlin, Germany

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1. Introduction

Gamma rays entering the atmosphere interact with the atmospheric nuclei producing cascades of secondary particles, the so-called extensive air showers (EAS). The ultra-relativistic secondary particles in the air shower produce Cherenkov radiation, short flashes of light with the peak at ~ 300 nm in wavelength, that can be recorded using Imaging Air Cherenkov Telescopes (IACT) [1].

Cherenkov Telescope Array (CTA) is the future ground-based observatory for very-high-energy gamma-ray astronomy that will be sensitive in the energy range from 20 GeV to 300 TeV [2, 3]. CTA will consist of large arrays of IACTs located in the Northern (CTA-N, La Palma, Spain,) and Southern (CTA-S, Atacama Desert, Chile) hemispheres. There will be three different types of telescopes, each type covering different energy range: the Large-Sized Telescopes (LST) will provide the low-energy sensitivity; the Medium-Sized Telescopes (MST) will provide the bulk of the sensitivity in the core energy range; and the Small-Sized Telescopes (SST) will provide the high-energy sensitivity.

The atmosphere is an integral part of every IACT and it affects measured Cherenkov light in several ways. First, the number of Cherenkov photons produced in the EAS depends on the refraction index and air density, while the lateral distribution of Cherenkov light depends on the atmospheric profile [4]. Second, Cherenkov photons are scattered and absorbed along the way from the emission point to the detector. The latter is particularly noticeable in the presence of dense clouds and aerosols, which results in a decrease in the number of events near the energy threshold that would otherwise trigger the telescope. Also, the effects of the clouds are not only evident near the energy threshold, but across the entire energy range, reducing an overall trigger yield and biasing events towards lower energies [5].

The impact of the atmospheric conditions on the IACTs has been studied in [6, 7]. An approach to atmospheric corrections for IACTs has been already studied in MAGIC [8] and H.E.S.S. [5, 9] collaborations. In [8] it is shown that for layers of low and moderate optical depths a straightforward correction to the reconstructed energy is possible. The corrected energy is simply obtained as a reconstructed (estimated) energy, E_{est}, scaled with the inverse of the average optical depth. In the presence of clouds event reconstruction using simulations based on cloudless atmospheric models [5, 9] yields a bias in the reconstructed energy, therefore the analysis should be performed using simulations that include proper atmospheric conditions.

2. Simulation chain

The development of EAS was simulated using `CORSIKA` code version 7.7 [10] with the hadronic interaction model `QGSJET-II`. Simulations have been performed in such a way that they cover low-energy range (4 LSTs, CTA-N), core energy range (15 MSTs, CTA-N), and high-energy range (5 1M-SSTs, CTA-S) for directions of primaries of 20 degrees in Zenith, 180 degrees in Azimuth for CTA-N, and 20 degrees in Zenith, 0 degrees in Azimuth for CTA-S layout (the most favorable directions due to the influence of the geomagnetic field [11]). To simulate the telescope response, CTA Monte Carlo (MC) code, `sim_telarray` with Prod3b settings has been used [12]. The layouts of the telescope systems used are presented in Figure 1.

Because the number of emitted Cherenkov photons is roughly proportional to the primary energy, in an EAS initiated by low-energy gamma rays a smaller number of Cherenkov photons is emitted, which complicates event reconstruction itself and therefore requires more precise and detailed simulations of atmospheric conditions. Hence, the atmospheric transmission in the presence of 1 km thick altostratus clouds, with their bases at 3 and 9 km a.g.l. was simulated for the Northern site (ground altitude at 2174 m a.s.l) using the MODerate resolution atmospheric TRANsmission (`MODTRAN`) code [13]. Two sets of data have been simulated in total, each set differing by the total atmospheric transmission ($T = 0.6, T = 0.8$), in the wavelength range from 200 nm to 1000 nm. `MODTRAN` output was used as an input for `sim_telarray` instead of the default atmospheric file for cloudless conditions.

The atmospheric conditions simulations for the Southern site (ground altitude at 2500 m a.s.l) have also been included within the `sim_telarray`. However, at higher primary energies a significantly larger number of Cherenkov photons is emitted, therefore very precise simulations with `MODTRAN` are not mandatory and the whole process of simulating atmospheric conditions can be simplified. The additional extinction due to cloud presence has been included in the default cloudless atmospheric file for Armazones site using equation (3.11) presented in [14]. Different concentrations of water in cloudy media were used to obtain the total transmissions of $T = 0.8, T = 0.6, T = 0.4$, and $T = 0.2$ in the wavelength range from 250 nm to 700 nm. The clouds at 2.5 and 4.5 km a.g.l. with a thickness of 0.5 km were simulated.

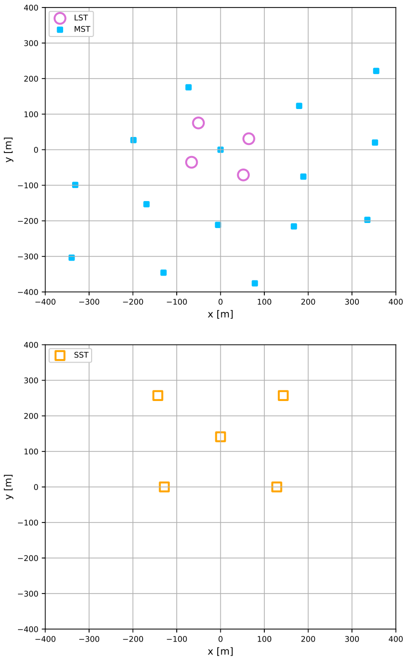

Figure 1: Telescope layouts for the Northern (top panel) and Southern (bottom panel) site of the observatory. Note that the layout of the two sites is the one implemented in Prod3.

3. Analysis chain

The analysis of the simulated data was performed with MAGIC Analysis and Reconstruction Software (`MARS`) adapted for the CTA use [15, 16]. The full Monte Carlo sample consists of gamma, proton, and electron primary `sim_telarray` subsamples. Before the higher-level analysis, `sim_telarray` files are converted to `ROOT` format using the Convert Hessio Into MARS inPut (`chimp`) package, which performs signal extraction by a *two-pass sliding window* algorithm, image cleaning using the *absolute image cleaning* method and image parametrization. Next, about 5% of the gamma subsample is used to obtain a direction look-up table and to train the telescope-wise energy reconstruction using Random Forest (RF) algorithm [17]. The event direction is obtained as the point in the camera which minimizes the sum of squares of distances to the main axis of the image. Then, another 5% of gamma subsample and 5% of the total proton subsample are used to train gamma/hadron separation using RF, once those subsamples have been processed to the level of stereoscopic reconstruction and energy reconstruction. The rest of the gamma and proton

MC data set, and the full electron subsample are used as a test sample, processed through trained energy and gamma/hadron separation RFs. The final reconstructed energy for each event, E_{est} is calculated as a weighted average of the reconstructed energies of all telescopes, where 1/RMS^2 is used as a weight. The global *hadronness*[1] is calculated as a weighted average of the *hadronnesses* calculated by each telescope, where $size_i^{0.54}$ (the $size_i$ is a total number of Cherenkov photons in the camera of the i-th telescope) is used as a weight[2]. Finally, gamma-ray selection cuts, θ^2 cut, where θ is the parameter that specifies the angular distance between the reconstructed and the real source direction, and $hadronness$ cut, are optimized and applied to obtain the instrument response functions in means of differential sensitivity, angular resolution, and energy resolution.

4. Results and discussion

4.1 Differential sensitivity

The differential sensitivity is the minimum flux that can be detected with a statistical significance of 5σ, in this study calculated for 50 hours of observations. The differential sensitivity is calculated in non-overlapping logarithmic energy bins (five per decade), with a minimal number of 10 gamma-ray counts per energy bin, and of signal counts above 5% of the residual background counts.

In Figure 2, the influence of the clouds with $T = 0.6$ and $T = 0.8$ and cloud bases at 3 and 9 km a.g.l. on the differential sensitivity compared to the clear atmosphere ($T = 1.0$) is presented.

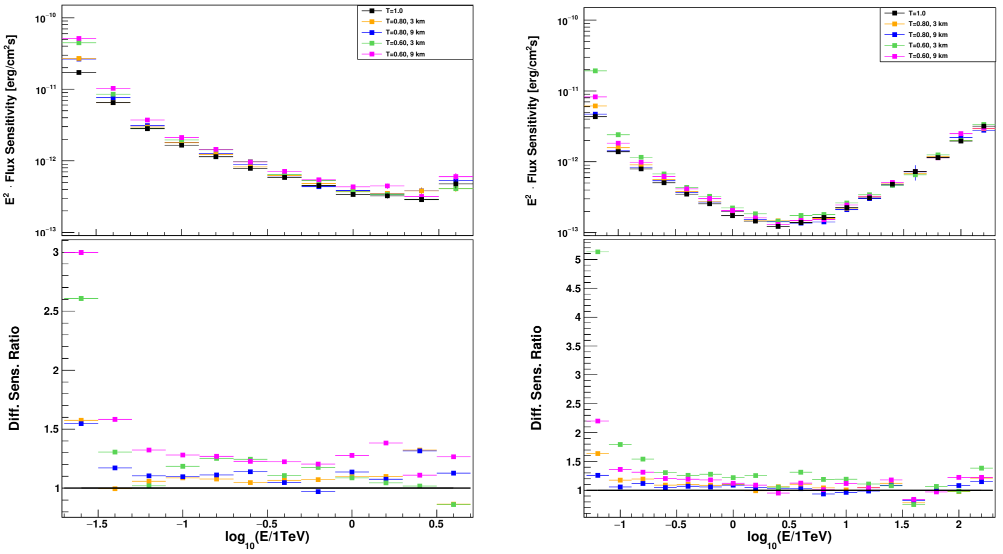

Figure 2: The differential sensitivity (**upper panel**) and ratio of differential sensitivities (**bottom panel**) versus E_{est} for the layout of 4 LSTs (**left side**) and 15 MSTs (**right side**).

In the case of 4 LSTs, the most significant impact on the performance of the telescopes have the clouds with the higher cloud base at 9 km a.g.l. and $T = 0.6$, reducing the sensitivity by a factor

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[1] The *hadronness* is a value ranging between 0 and 1 describing how likely the event is initiated by the gamma primary. The closer the *hadronness* is to 0, the event is more gamma-like.

[2] The value of the exponent 0.54 is obtained empirically.

of ~ 3 at the energy threshold, with the average reduction of 1.42 in the LSTs sensitivity range. In the case of 15 MSTs, the most prominent impact on the sensitivity of the telescopes have clouds with the lower cloud base at 3 km a.g.l. and the same $T = 0.6$, reducing the sensitivity in the lowest energy bin by a factor of ~ 5, with the average reduction of 1.44 in the MSTs sensitivity range. An explanation of unexpected behavior that higher clouds of the same T have a greater impact on the sensitivity of the LSTs than lower clouds (which is not observed for MSTs) might be due to the fact that low-energy showers (sensitivity range of LSTs) reach the maximum of development higher in the atmosphere (closer to higher clouds). In the common energy range from 0.1 TeV to 4 TeV for the cloud at 3 km a.g.l. with $T = 0.6$, the average reductions for 4 LSTs and 15 MSTs are, respectively, 1.11 and 1.33. To draw more accurate conclusions further studies are required and planned.

4.2 Energy resolution

The assessment of energy reconstruction is obtained by calculating the energy resolution using MC simulations. The energy resolution describes how accurately the instrument can determine the real energy of gamma primary, E_{true}, and it is calculated bin-wise as a half width of the interval which contains 68% of the distribution in a respective bin, symmetric around $E_{est}/E_{true} = 1$.

For the layouts of 4 LSTs and 15 MSTs (Figure 3, left and middle panel, respectively), the worst-case scenario appears in the lowest energy bin in the case of clouds with $T = 0.6$, with a reduction in the energy resolution by a factor of ~ 1.20 for 4 LSTs, and ~ 1.03 for 15 MSTs.

For large biases in the presence of clouds, the standard definition of the energy resolution is not a useful metric, therefore in the case of 5 SSTs the corrected energy, E_{cor} is used instead of E_{est} (see Section 4.4 or [7] for details). For the layout of 5 SSTs (Figure 3, right panel), the energy resolution reaches its plateau at a value of ~ 13% in the case of $T \geq 0.6$ and $E_{cor} > 2$ TeV. For lower E_{cor}, the energy resolution is poor due to threshold effects.

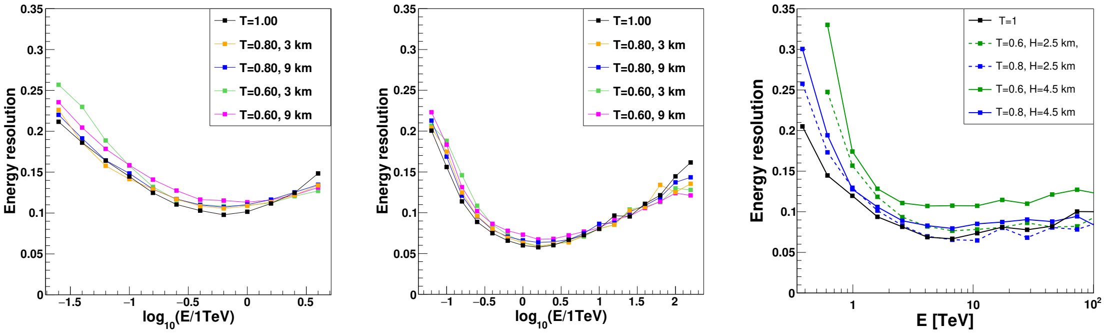

Figure 3: Left: The energy resolution versus E_{est} for the layout of 4 LSTs. **Middle:** The energy resolution versus E_{est} for the layout of 15 MSTs. **Right:** The energy resolution versus E_{cor} for the layout of 5 SSTs (taken from [7]).

4.3 Angular resolution

The assessment of direction reconstruction is obtained by calculating the angular resolution. The angular resolution is determined from the θ distribution, and it is represented by the value which contains 68% of all reconstructed gamma-like events in a given energy bin.

In the case of 4 LSTs (Figure 4, left panel), the impact of clouds on the angular resolution is negligible, with largest differences up to ∼ 5%. For the layout of 15 MSTs (Figure 4, middle panel), the angular resolution reaches its plateau for $E_{est} > 2.5$ TeV. In that region even in the worst simulated case ($T = 0.6$, 3 km a.g.l.) it amounts to only 0.05 degrees, while the largest difference is ∼ 15%. For the layout of 5 SSTs (Figure 4, right panel), the angular resolution is obtained from the MC simulations of the cloudless conditions in such a way that E_{est} is folded with the corrected total atmospheric transmission τ_A (see Section 4.4 or [7] for details):

$$\sigma_\theta(E_{cor}, T, H) = \sigma_\theta(E_{est} \cdot \tau_A(E_{true}, T, H), 1, 0), \tag{1}$$

where H represent the altitude of the cloud base. In the presence of clouds with $T \geq 0.4$, the angular resolution decreases at $E_{cor} < 4$ TeV, whereupon a plateau is reached. In the case of clouds with $T = 0.2$, the plateau is reached only for $E_{cor} > 10$ TeV.

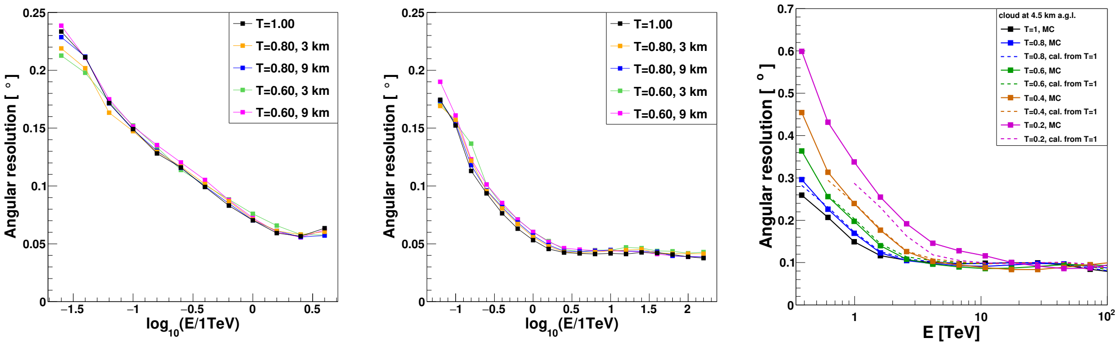

Figure 4: Left: The angular resolution versus E_{est} for the layout of 4 LSTs. **Middle:** The angular resolution versus E_{est} for the layout of 15 MSTs. **Right:** The angular resolution versus E_{cor} for the layout of 5 SSTs (note different vertical scale compared to 4 LSTs and 15 MSTs). Dashed lines represent approximation equation (1), while points present the results of the MC simulations. Figure is taken from [7].

4.4 Data analysis method for very high energies

To avoid time-consuming MC simulations, a method to analyze high-energy data taken in the presence of clouds ($T < 1.0$) is proposed [7]. The method requires simulations for the cloudless conditions ($T = 0$) and the total atmospheric transmission:

$$\tau(E_{true}, T, H) = 1 - (1 - T) \cdot F_{ab}(E_{true}, H), \tag{2}$$

where $F_{ab}(E_{true}, H)$ is the fraction of Cherenkov photons created above the cloud compared to all photons produced in the EAS, obtained from `CORSIKA` simulations for given energy. To improve the agreement between MC data and this method, a phenomenological correction parameter $A = 1.2$ is introduced [7]:

$$\tau_A(E_{true}, T, H) = 1 - A \cdot \tau(E_{true}, T, H). \tag{3}$$

Relative difference between E_{est} and E_{true} is generally called energy bias. In the presence of clouds, high-energy shower images resemble low-energy events, meaning that E_{est} obtained with standard reconstruction should be corrected [8]. The correction method is based on the energy bias calculated for clear atmosphere, to take into account the energy threshold effects, and $\tau_A(E_{true}, T, H)$. In Figure 5, the results of the method (dashed lines) and energy biases calculated from MC simulations (solid points) are presented. For clouds with cloud bases at 2.5 km and 4.5 km a.g.l., and $T > 0.4$, the bias approximation as proposed in the method [7] may be used to get the corrected energy of reconstructed events. $\tau_A(E_{true}, T, H)$ can be used to reproduce the energy and angular resolutions from MC simulations of cloudless conditions (as shown in previous sections), but also for the assessment of the effective collection area [7].

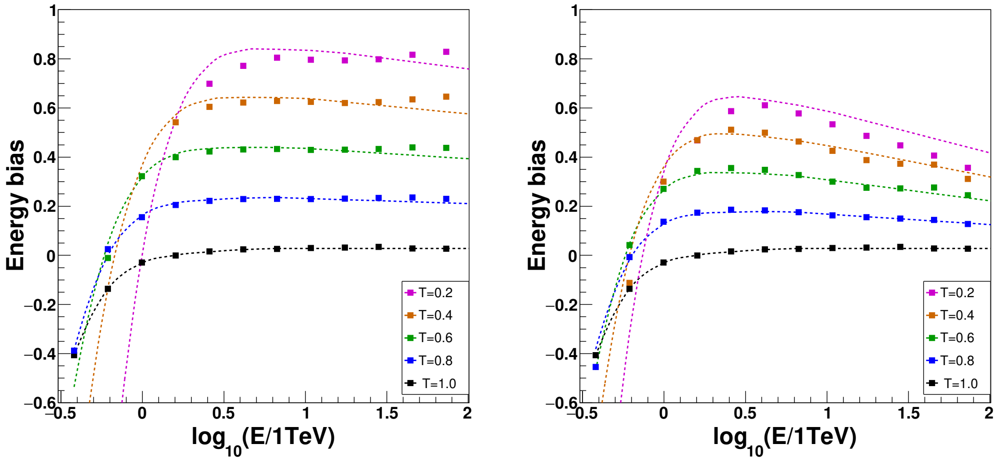

Figure 5: The energy bias versus E_{cor} for clouds with cloud bases at 2.5 km a.g.l. (**left panel**) and 4.5 km a.g.l. (**right panel**). Figures are taken from [7].

The spectrum of the potential source can be estimated from the events classified as gamma-like. In the presence of clouds, gamma/hadron separation based on the *hadronness* and θ^2 cuts optimized for clear sky simulations was performed. The reconstructed energy of gamma-like classified events is corrected using the aforementioned method. Then, the flux is calculated in the standard way, but using corrected effective collection area and E_{cor} [7, 8]. In Figure 6, the ratio between the flux reconstructed in the proposed way and the flux obtained from MC simulation for the cloudless conditions (solid and dashed lines, respectively) is presented. In the energy range between 2 TeV and 30 TeV, the expected spectra are underestimated by less than 20% for $T \geq 0.6$. For $E_{cor} > 30$ TeV, the flux underestimation is increased mainly due to the fast degradation of the hadronness cut efficiency. When no corrections are applied (long dashed lines), the underestimation of the spectra is much higher.

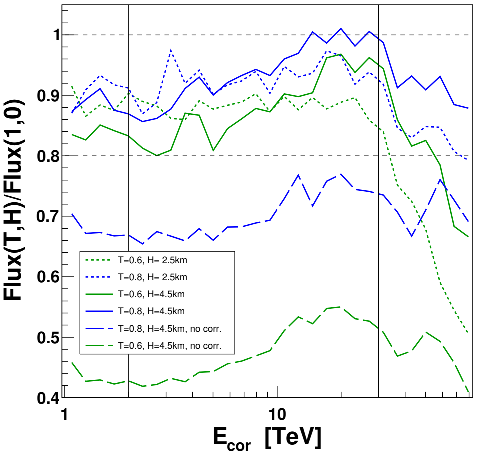

Figure 6: The ratio between the reconstructed fluxes. Taken from [7].

5. Conclusion

In the presence of high-density clouds with low transmissions through the atmosphere, it is shown that the performance of all three types of CTA telescopes (LSTs, MSTs and SSTs) degrades. Although the degradation effects are most prominent at the energy thresholds, the effects of the clouds are evident across the entire energy range for each telescope type and if not taken into account, they might result in additional systematic errors affecting the measurement.

The effect of the presence of clouds is primarily observed through the reduced number of emitted Cherenkov photons in the shower development, which for low and middle energies (LSTs and MSTs, respectively) leads to the necessity of detailed MC simulations to properly assess the telescope response in the given atmospheric conditions. This may prove crucial for alert-based observations and time-critical studies of transient phenomena at the CTA-N site.

On the other hand, for the high energy range (SSTs foreseen to be built at the CTA-S site) extremely time-consuming MC simulations can be avoided by using a correction method. In this way, the gamma-ray source spectra in the presence of various clouds in the energy range between 2 and 30 TeV have been reconstructed with a systematic uncertainty smaller than $\sim 20\%$ for $T \geq 0.6$. For the lower and upper energy edge of the SSTs sensitivity range, the uncertainty of the method is worse due to threshold effects and the *hadronness* cut efficiency, respectively.

Acknowledgements

The work performed at the University of Łódź was supported by the Narodowe Centrum Nauki grant No. UMO-2016/22/M/ST9/00583. The work at the University of Rijeka was performed using the supercomputer "Bura" within the Center for Advanced Computing and Modelling. The authors would like to thank CTA Consortium and MAGIC Collaboration for the permission to use their software.

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