

Studies of the Influence of Moonlight on Observations with the MAGIC Telescope

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Abstract. The ground-based imaging atmospheric Cherenkov technique is currently the most powerful observation method for very high energy gamma rays. With its specially designed camera and readout system, the MAGIC Telescope is capable of observing also during nights with a comparatively high level of night-sky background light. This allows to extend the MAGIC duty cycle by 30% compared to dark-night observations without moon. Here we investigate the impact of increased background light on single-pixel level and show the performance of observations in the presence of moonlight conditions to be consistent with dark night observations.

Keywords: Imaging Atmospheric Cherenkov Technique, MAGIC telescope, moonlight

I. INTRODUCTION

MAGIC-I is an Imaging Atmospheric Cherenkov Telescope (IACT) located on the Canary Island of La Palma at 2200m a.s.l. [1]. The IACT technique is a very successful observation method for very high energy cosmic-ray particles, particularly gamma rays with energies ranging from ≈ 100 GeV up to 10 TeV. The underlying background from single photons from the night sky (night-sky background; NSB) as measured with MAGIC-I is at 0.12 phe/ns/pixel (photoelectrons per nanosecond per 0.1° diameter photomultiplier [PMT] pixel) for an extragalactic field of view and around 0.18 phe/ns/pixel for a galactic area. Here we define an NSB unit as the background level which MAGIC-I records while pointing to a galactic celestial field comparable to the Crab Nebula region. It is directly proportional to 0.18 phe/ns/pixel and to the anode current at $\sim 1.0\mu\text{A}$, or with a square-root proportion to the pedestal RMS at 0.8 phe/pixel/event.

Under moonlight (or twilight) conditions, which seem still feasible for observations with MAGIC, the background increases by up to a factor of 6, i.e., to above 1.0 phe/ns/pixel.

A first study had been performed for the initial MAGIC-I telescope setup with 300 MHz readout [9]. It could be shown that the noise induced by the moonlight itself

contributes only in a negligible way. The distributions of the Hillas parameters (parameters that describe the air shower images [13]) are in good agreement with that of dark night observations. This makes the analysis of data taken under moonlight conditions straightforward, as no special treatment is required for calibration. The energy threshold of the telescope was shown to be only marginally affected by increased light levels due to moonlight. Since the initial study [9], several substantial improvements in the hardware and analysis were implemented. The readout system was upgraded to a 2-GSamples/s Flash-ADC system [15] along with new signal receivers, allowing for a substantially improved air shower image cleaning that now also takes the air shower timing into account [11], reducing the NSB included in the pixel signal. The study presented in this paper is based on data taken with the new readout and subsequent analysis refinements, but also accounts for the now-standard observation mode in MAGIC, the *wobble* mode [14], which allows to record on-source and off-source (background control) data simultaneously. In this paper we analyze a large sample of Crab Nebula data taken under vastly different moonlight conditions with the above mentioned system. As done in [9], we focus on the relevant physics analysis quantities – the resulting differential energy spectrum and flux of the Crab Nebula as well as the achieved sensitivity for a Crab-like source. We investigate the telescope performance with the MAGIC standard analysis [17], employing two exemplarily chosen image cleanings (see below). The results are compared with expectations from Monte Carlo (MC) simulations.

II. CONSIDERATIONS FOR OBSERVATIONS UNDER MOONLIGHT

The MAGIC-I camera was designed to allow for observations under moonlight conditions. It consists of an inner hexagon with 396 PMTs with a field of view (FOV) of 0.1° each, and an outer region with 180 PMTs of 0.2° FOV. The PMTs have a low gain amplification of 3×10^4 . This prevents the last PMT dynode from too high damage by frequent pulses from diffuse background

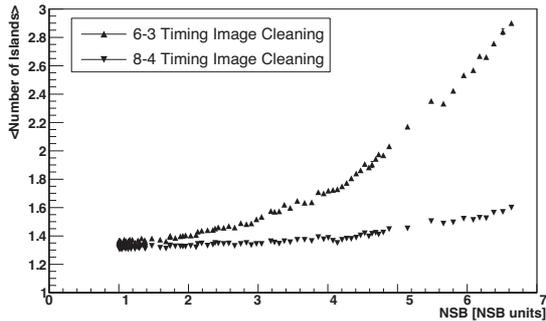


Fig. 1: Mean number of islands depending on NSB (and $\text{Size} > 100$ phe) for two different time image cleanings applied to the same data.

light, like moonlight.

The illumination from moonlight depends on the lunar phase, the distance of the moon from earth, the altitude of the moon, and the separation angle between the observed source and the moon. For IACT, particularly small lunar phases, low lunar altitudes and separation angles between 25° - 110° are relevant: within 80% of moontime observations the altitude of the moon does not exceed 30° . The first/last-quarter moon has only $\sim 10\%$ of the full-moon brightness [2]. For estimating the brightness of moonlight in the MAGIC-I telescope camera, a model has been developed [7] similar to [4], [6], which holds for those special conditions. It incorporates differences to previous predictions (e.g. [2], [4], [5]), particularly for early lunar phases and small moon altitudes. It is presented in [7] in detail and can be used for automated MC simulations as well as for observation scheduling.

The main motivation for observing under moonlight (or twilight) is the gain in observation time. This is particularly relevant for long-term source monitoring, for the coverage of multiwavelength observations, or to increase the probability to detect gamma-ray bursts and to follow-up flares, e.g., in active galactic nuclei. MAGIC has a dark night observation time of 1600 h per year, dark time being defined as astronomical night (sun below -18° altitude) and the moon being below horizon. Conservatively assuming a twice higher NSB, additional 300 h per year are accessible. This assumption corresponds to a 30% illuminated moon and a separation angle above 50° . More ambitiously allowing for an increased background of $6 \times \text{NSB}$ extends the observation time by 550 h per year. This is equivalent to a 70% illuminated moon at a separation angle more than 50° .

III. OBSERVATIONS PERFORMED UNDER MOONLIGHT

More than 42 hours of Crab Nebula data were recorded under moonlight conditions. After the hardware upgrade of the DAQ system, dedicated data was taken within 27 days from February 2007 to February 2008 under very different moon phases. The moon phase ranges up to 53% at 55° altitude and to 80% at low altitudes, respectively. The separation angle ranges from 25° to

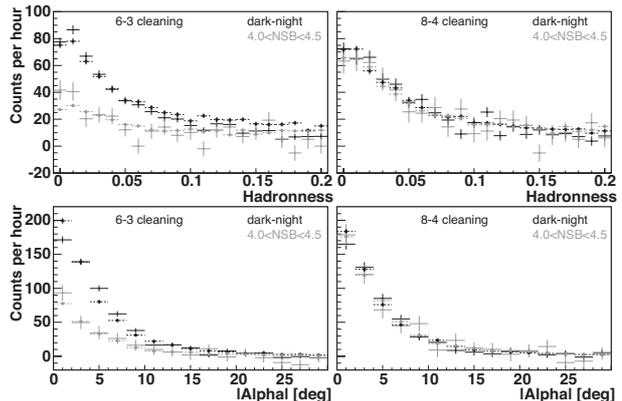


Fig. 2: Hadronness-excess (upper plots) and $|\text{Alpha}|$ -excess (lower plots) for two different cleaning parameters (left: 6-3; right: 8-4). Black markers indicate dark night data, while the grey markers are for $4.0 < \text{NSB} < 4.5$. Dotted markers are corresponding MC simulations. A size cut of 220 phe was applied.

130° . The Crab Nebula zenith angle was between 5° and 30° . The moonlight increases the background from 1 up to 6.5 NSB in the data. The level-0 trigger thresholds for each pixel were adjusted with an automatic individual pixel control system as to achieve an almost constant trigger rate. (Splitters divide the signal before the trigger level, so the recorded images are not affected by these changing trigger thresholds.) We record the anode direct currents (DC) for each inner PMT using an ADC with an integration window of a few μs sampled with 3 Hz frequency. The median and mean values of the DCs are calculated in bins of one minute size. The DCs are therefore proportional to the NSB.

IV. THE IMPACT OF MOONLIGHT ON MAGIC OBSERVATIONS

The basic problem of observations under moonlight conditions is given by the increased background fluctuations in each individual pixel. During moonlight observations, the recorded phe rate rises to $< \text{geq} 1.0$ phe/ns/pixel. A 300 GeV gamma-ray induced shower produces a signal of 2–20 phe/pixel in ~ 30 pixels, typically arriving within 3 ns; a resulting pedestal RMS of 3.2 phe/pixel/event is therefore comparatively high.

Accidental triggers from those fluctuations are suppressed by the automatically increased discriminator thresholds and are removed due to their small sizes. However, when “cleaning” the images, so-called islands remain as artifacts in the air shower images. An island is defined as a group of pixels detached from another group after image cleaning. This feature affects the analysis of the shower images.

Here we use the MAGIC standard analysis [17], [10], which additionally applies an image cleaning with timing constraints as presented in [11]. The standard image cleaning for non-moon observations (referred to as 6-3)

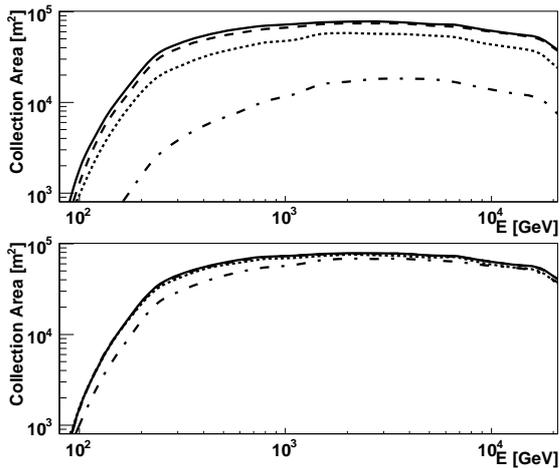


Fig. 3: Effective collection area after cuts for (a) 6-3 and (b) 8-4 timing image cleaning for four simulated background levels. Solid lines represent for dark night MCs (1.0 NSB), dashed lines correspond to 2.0 NSB, dotted lines to 3.75 NSB, and dash-dotted lines to 5.5 NSB.

keeps core pixels with charge >6 phe and a maximum spread of 4.5 ns plus boundary pixels with charge >3 phe and a maximum of 1.5 ns delay from the neighboring core pixel. Pixels not fulfilling these constraints are ignored in the image parametrization. With increasing NSB, the mean number of islands increases dramatically (Fig. 1). Besides the standard cleaning levels 6-3, we investigated exemplarily a higher cleaning level, applying the same timing constraints, but requires 8 phe for core pixels and 4 phe for boundary pixels (called 8-4 cleaning).

The choice of image cleaning parameters leaves its traces throughout the analysis chain. The mean number of islands can be used as a quality parameter, in the sense that with increasing NSB the mean number of islands stays constant until a certain NSB level, while it increases for higher background (cf. Fig. 1). We recognize a significant deviation from the dark night level at $2.0 \times \text{NSB}$ for the 6-3 cleaning, and around $4.5 \times \text{NSB}$ for the 8-4 cleaning. In the further analysis, we apply a cut on the number of islands ≤ 2 .

Within the MAGIC standard analysis the discrimination of hadronic background events (“ γ /hadron separation”) is performed using a decision tree algorithm [12]. For training of the *random forest*, we used dark-night MC simulations for γ -like events and real data for hadron-like events. Two individual *random forests* were generated for the different cleanings. The same decision trees are used for the complete data set, i.e., also for bright moonlight data, since the Hillas parameters [13] were found to be constant on average during moonlight observations (see e.g [9]).

Fig. 2 illustrates the effect of moonlight on the γ /hadron separation for the investigated data set. During dark night observations (black counts) the hadronness-excess

(classification parameter of the decision tree) indicates high excess for gamma-like particles. While for NSB between 4.0 and 4.5 (grey counts) the separation capability for 8-4 cleaned data is almost dark-like, there is a decreased hadronness excess for 6-3 cleaned data (upper-left plot). The solid lines represent the hadronness of MC simulations (black: dark like, grey: $3.75 \times \text{NSB}$). Those are in good agreement with the data.

The $|\text{ALPHA}|$ -excess plots are mainly affected by the decreased γ /hadron-separation power under strong moon conditions as also Fig. 2 indicates, since only events with hadronness < 0.1 are taken into account. Therefore, the $|\text{ALPHA}|$ -excess plot for 6-3 cleaning shows a less significant peak under high NSB levels. Again, the MC simulations are in good agreement with the data.

For energy reconstruction, also performed using a *random forest* method [12], we employed again only the “dark night” decision tree for all NSB levels. We checked that this results in correct energy estimates, showing again that the quality of the images is not affected by the increased NSB. Also the analysis energy threshold was checked to be constant at ~ 190 GeV for the applied size cut of 220 phe for all NSB levels.

A. Sensitivity

We apply cuts in Hadronness (< 0.05), size (>400 phe), and $|\text{ALPHA}|$ ($< 6^\circ$) and calculate the ON and OFF-events. The resulting sensitivity of MAGIC-I above an energy of 250 GeV for different NSB levels is presented in Fig. 5 in Crab units. The sensitivity is computed applying the standard MAGIC analysis and using the standard dark-night MC. We conclude that the sensitivity remains constant up to 3.5 NSB for the MAGIC standard 6-3 cleaning (grey counts). If higher cleaning parameters are applied, the sensitivity is constant for even higher NSB.

B. Spectrum under moonlight conditions

We performed MC simulations for four different NSB levels: 1.0, 2.5, 3.75, and 5.5 NSB. We crosschecked that the resulting pedestal RMS of the pixel calibration is the same as in real data. The simulated trigger threshold (DT) was also adjusted in MC with values from data. We apply cuts on Hadronness < 0.1 , size < 220 phe and $|\text{ALPHA}| < 8^\circ$. Fig. 3 shows the resulting effective collection area (A_{eff}). While for 6-3 cleaning parameters, A_{eff} already decreases around $\text{NSB} > 2.0$, it is still compatible with dark night until 3.75 NSB for 8-4. This shows that the dark-night MC can be used with the MAGIC standard analysis (6-3 cleaning) is stable until $\sim 2.5 \times \text{NSB}$ and $\sim 3.75 \times \text{NSB}$ with the 8-4 cleaning.

We used the estimated A_{eff} from Fig. 3 to obtain NSB-corrected differential energy spectra for Crab under different moonlight conditions. The resulting spectra for four different NSB levels are shown in Fig. 4. An exponential spectrum is assumed and fitted from 200 GeV to 2 TeV. For the 6-3 cleaning, the Crab spectrum remains stable up to 2.5 NSB and it can be

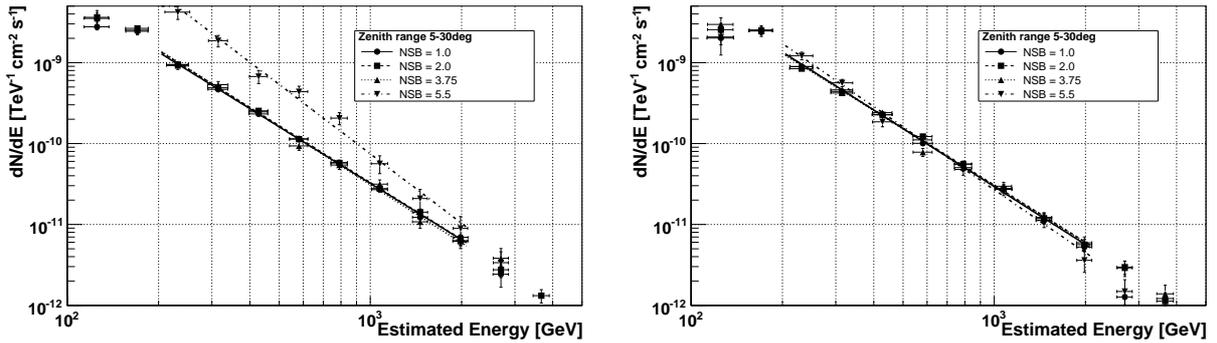


Fig. 4: Differential energy spectrum of Crab Nebula (left: 6-3, right: 8-4 image cleaning) for four different moonlight illuminations. The continuous line represents to the dark night spectrum derived from $t_{\text{eff}}=26$ h effective observation time. The dashed curve is derived for $2.0 < \text{NSB} < 3.0$ ($t_{\text{eff}} = 7.5$ h), the dotted curve for $3.0 < \text{NSB} < 4.5$ ($t_{\text{eff}} = 3.8$ h), and the dash-dotted line for $4.5 < \text{NSB} < 6.0$ ($t_{\text{eff}} = 2.3$ h).

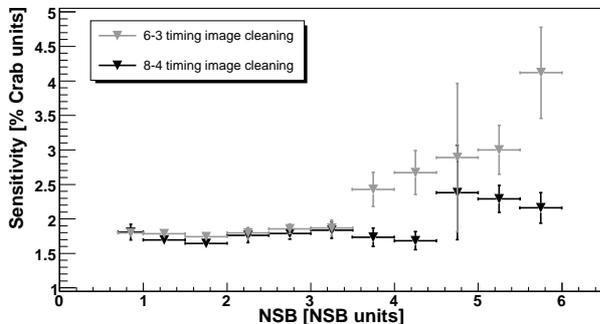


Fig. 5: Sensitivity in *Crab units* of MAGIC-I for the standard analysis (grey) and for an exemplarily applied 8-4 timing image cleaning depending on the NSB.

recovered by using A_{eff} computed from MC with the corresponding NSB up to about 4.0 NSB. For the 8-4 cleaning, no correction is needed up to even 6.0 NSB; With an appropriate correction one could control even higher NSB levels.

V. CONCLUSIONS

We performed a study of the effect of moonlight on MAGIC observations after the changes introduced in the DAQ, software and observation mode during the past years. As shown in previous studies [9], data quality is not affected by increased NSB levels. For observations under moonlight the MAGIC standard analysis (6-3 cleaning) is robust up to 2.5 NSB. Using dedicated moonlight simulations, the dark-like spectrum and flux can be recovered for even higher NSB levels.

If a higher image cleaning is applied, observations under more intense moonlight are possible with MAGIC. The investigated 8-4 timing image cleaning is robust until 4.5 times the galactic NSB with dark night Monte Carlo simulations. This is comparable to a first/third-quarter moon (50% illuminated; altitude on La Palma $< 60^\circ$) at a small separation angle of 30° . Dedicated moonlight simulations give the possibility to perform a correct analysis even for higher NSB levels.

The sensitivity of MAGIC-I is darktime-like up to 3.5 times increased NSB.

For a moon illumination of 70%, and assuming a source can be found at a separation angle > 50 degrees, the NSB is below 6 NSB. This allows us to add about 550 hours (additional 30%) of observation time per year, without any significant change in the analysis.

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