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Modeling of performance enhancement of the TAIGA-IACT Cherenkov gamma-ray telescope equipped with semiconductor photomultipliers

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Abstract. We present modeling of effective area and count rates of a TAIGA-IACT Cherenkov gamma-ray telescope unit with an upgraded camera based on semiconductor photo detectors (SiPM) OnSemi MicroFJ-60035 and optical filters SL 290–590 and SL 280-390. In comparison with the current configuration of TAIGA-IACT where classic vacuum photomultipliers are employed, the threshold detection energy of cosmic gamma-quanta by a TAIGA-IACT unit equipped with a SIiPM-based camera and a wide-band optical filter SL 290590 would be reduced down to about 0.4 TeV, and with a narrower filter SL 280-390 down to about 0.7 TeV. Application of semiconductor photo detectors, which are stable against excess illumination, and optical filters of the near-UV band allows one to substantially increase the duty cycle of a Cherenkov gamma-ray telescopes due to the possibility to carry out observations during moonlit nights and at twilight even without a need to substantially increase the trigger threshold. Hence, one may conclude that a TAIGA-IACT unit with an upgraded camera with SiPM detectors will be an efficient instrument for studies of TeV-range emission from space gamma-ray objects.

Keywords: Cherenkov gamma-ray astronomy, silicon photomultipliers, TAIGA observatory

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Моделирование параметров черенковского гамма-телескопа TAIGA-IACT с камерой на полупроводниковых фотодетекторах

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Аннотация. В работе представлены результаты моделирования эффективной площади и скоростей счета черенковского телескопа TAIGA-IACT с модернизированной камерой, оснащенной полупроводниковыми фотодетекторами SiPM OnSemi MicroFJ-60035 и светофильтрами SL 290-590 и SL 280-390. Показано, что по сравнению текущей конфигурацией телескопа TAIGA-IACT, где используются классические вакуумные фотоэлектронные умножители, пороговая энергия регистрации космического гамма-излучения телескопом TAIGA-IACT с камерой на SiPM и широким фильтром SL 290–590 будет снижена и составит около 0.4 ТэВ, а с более узким фильтром SL 280–390 − около 0.7 ТэВ. Применение устойчивых к засветке полупроводниковых фотодетекторов и светофильтров УФ-диапазона позволяет существенно увеличить рабочий цикл черенковского гамма-телескопа за счет наблюдений в лунные ночи и в сумерках даже без значительного увеличения порога регистрации. Таким образом, можно сделать вывод, что телескоп TAIGA-IACT с модернизированной камерой на SiPM будет перспективным инструментом для исследования теравольтного излучения космических гамма-источников.

Ключевые слова: черенковская гамма-астрономия, полупроводниковые фотодетекторы, обсерватория TAIGA

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Introduction

The TAIGA-IACT gamma-ray telescope is an array of small-size imaging atmospheric Cherenkov gamma-ray telescopes (IACTs) operated as part of the multipurpose TAIGA observatory located in the Tunka valley of Republic of Buryatia [1–6]. Recently a new detector cluster (28 pixels) for a TAIGA-IACT unit was developed at the Ioffe Institute [7–11]. The new cluster is based on silicon photomultipliers (SiPM) OnSemi MicroFJ-60035. Development of the new hardware is accompanied by numerical modeling of its characteristics. Such modeling has been performed both for individual blocks of the new detector [12, 13] and for the telescope as a whole [14, 15]. Here we present the results of quantitative modeling of the effective area of the upgraded TAIGA-IACT unit, as well as of the count rate and of the threshold detection energy for various types of energetic primaries (gamma-quanta, cosmic ray protons).

Modeling and results

Formation and propagation of Cherenkov emission of extensive air showers (EASs) triggered by energetic primaries was modeled with the standard CORSIKA package [16]. We have modeled EASs induced by vertically incident gamma-quanta and protons at logarithmically scaled energies 0.32, 0.5, 0.7, 1.0, 3.2, 10.0, 32 TeV. A typical model spectrum of EAS Cherenkov emission is shown in Fig. 1. Modeling of optical night sky background was carried out with a Monte Carlo code TAIGA Soft [15], where a set of local parameters was adopted from [17–20] and the global integral intensity in the 300-600 nm band was normalized to $3 \cdot 10^{12}$ phot/m^2/s/srad. A typical night sky background spectrum is also shown in Fig. 1.

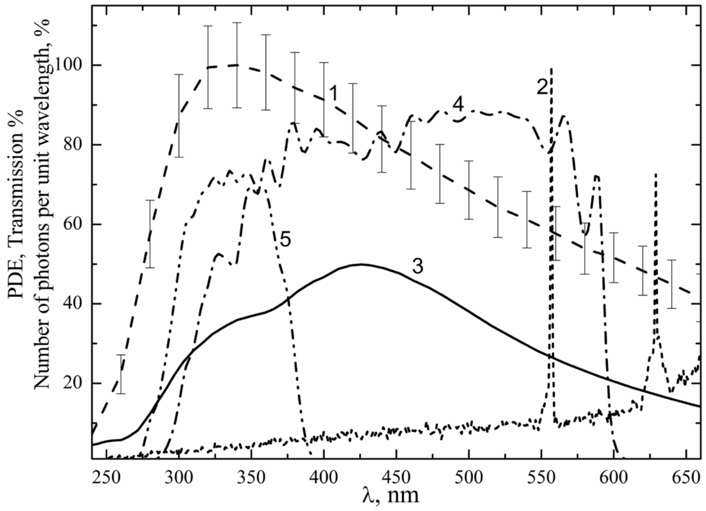

Fig. 1. Curve (1) corresponds to the averaged Cherenkov emission spectrum from and EAS induced by a 1 TeV gamma-quantum, normalized to 100% at its maximum at ~330 nm (long dash); (2) is an example of particular Monte-Carlo realization of the night sky background spectrum (normalized to 100% at its maximum at ~557 nm, short dash); curve (3) is the photon detection efficiency of the SiPM OnSemi MicroFJ-60035 photomultipliers (solid curve); curve (4) is the transmission of the SL 290-590 optical filter (dot-dashed curve); curve (5) is the transmission of the SL 280-390 optical filter (double dot-dashed curve)

With the TAIGA Soft package, we were also able to model the photon transport of the telescope and its registration within its camera. A significant difference from the algorithm described in [15] is the modification allowing a realistic approximation for the segmented mirror structure, where the effective camera mirror radius $R_T^{eff} = (S_m / \pi)^{1/2} = 1.75\,m$ (S_m is the reflecting area) was replaced by the real mirror radius value $R_T = 2.15m$ and the probability of a particular photon hitting the mirror segment was $\zeta \le S_m / (\pi R_T^2)$, where ζ is a random value evenly distributed over the [0; 1] interval. Within this modeling such data as wavelength dependencies of the filter transmission [22] and photon detection efficiency (PDE) of the SiPM detectors [23] were employed. The transmission of the Winston cones was conservatively set to 0.7 [13]. The triggering conditions were formulated as signal over the threshold in any three neighboring pixels; the threshold was set at the level of 10 photo electrons for the wideband filter SL 290-590 and 4 photo electrons for the medium band filter SL 280-390. Such a trigger choice reflected the balance between a relatively low false count rate ($\le 10^3$ Hz) required in order not to overload the read out chains and a relatively high percentage (~10%) of the triggered events caused by EAS emission.

The effective area of the telescope was defined as

$$S^{MC}(E) = 2\pi \int_0^\infty P(E,r)\,r\,dr,$$

where $P(E,r)$ is the probability to register emission of a cosmic primary of energy E at the distance r from the EAS axis, estimated within a Monte Carlo approach [15].

The results of effective area calculations and their approximations are shown in Fig. 2. There results show that effective areas in regards of gamma-quanta triggering are larger than those for the protons (for both filters), while the cutoff energy, where the areas begin to rapidly decline with energy, is about 2 times higher for the protons. For the highest considered energies (above 100 TeV), the modeled effective area for the protons was found to be about 0.9—1 km^2 and for the gamma-quanta 1.3—1.4 km^2. For the medium-band filter SL 280-390 the effective areas are expectedly lower. Once the effective areas are modeled with the already measured parameters of the cosmic ray spectrum [24] and typical parameters of some classes of space gamma-ray sources [25, 26], one may estimate the total count rates as integrals over energy of the product of the spectral flux (measured, e.g., in [phot m^{-2}s^{-1}TeV^{-1}]) and the effective area, and the threshold energies as the maxima of these products. The modeled values of a modified TAIGA-IACT camera triggering rate are ~212 Hz from proton-induced EASs and ≈ 0.13 Hz for gamma-ray induced EASs from a 1 Crab Unit object [25, 26]. The corresponding detection thresholds would be ~0.94 TeV for the protons and ~0.4 TeV for the gamma-quanta. With the medium-band filter SL 280-390 the triggering rates would decrease to ~106 Hz for the protons and to ~0.06 for the gamma-quanta, and the threshold energies increase to ~1.2 TeV and ~0.7 TeV, correspondingly.

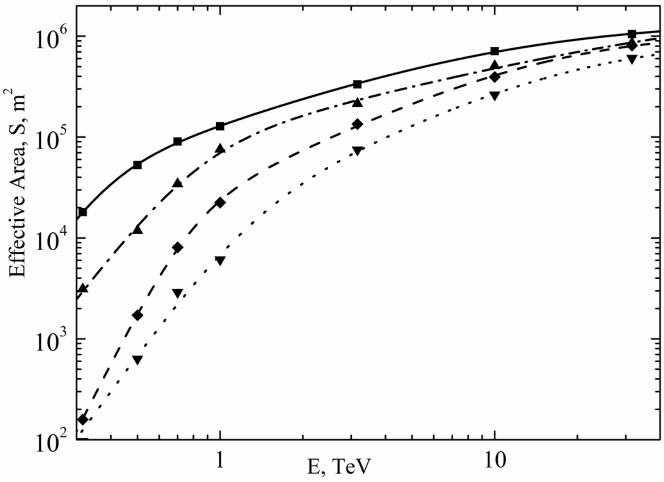

Fig. 2. Modeled effective areas of a TAIGA-IACT unit and their approximations (shown as separate symbols and curves) for various types of energetic primaries and various optical filters. The square symbols: gamma-quanta and the SL 290—590 filter; the rhomb symbols: cosmic ray protons and the SL 290—590 filter; the downward-directed triangles: gamma-quanta and the SL 280—390 filter; the upward-directed triangles: cosmic ray protons and the SL 280—390 filter.

Conclusions

The undertaken modeling has shown that at the chosen triggering conditions the count rates in an upgraded TAIGA-IACT camera would be low enough so that the read-out electronics would not be overloaded. With an SL 290–590 filter, the threshold triggering energy can be decreased down to ~0.4, which is somewhat lower than the currently obtained threshold of the TAIGA-IACT camera based on vacuum photo multipliers (0.5 TeV, [27]).

With a medium filter SL 280—390 the threshold would be ~0.7 TeV, which is quite acceptable for small-size (about 10 sq. m mirror) IACTs. At the same time, unlike vacuum photo multipliers, which are damaged by excess illumination, the SiPM detectors are stable and can operate normally during moonlit nights and at twilight. Hence, a simultaneous application of SiPM detectors and near-UV band filters would substantially (up to 30%) increase the duty cycle of an IACT without a dramatic increase of the detection threshold.

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