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Primary Gamma Ray Selection Technique in the Joint Operation of Imaging Atmospheric Cherenkov Telescopes (IACTs) and Wide-Angle Cherenkov Timing Detectors

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Abstract—A combined approach to distinguishing extensive atmospheric showers (EASes) from gamma rays, based on analyzing Imaging Atmospheric Cherenkov Telescope (IACT) images and shower parameters reconstructed using data from a nonimaging (timing) array, is investigated. The study is conducted with simulated data on the registration of Cherenkov radiation from an EAS. The optimum set of combined parameters, the efficiency of the multivariate approach, and the dependence of the background suppression factor on energy and distance are determined. The findings are compared to those from the operation of an isolated IACT. It is shown that in the >50 TeV range of energies, the background can be suppressed by a factor of 100 even at distances of up to 450 m from an IACT telescope.

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INTRODUCTION

Up to now, data on the TeV and sub-TeV regions of energy in gamma-ray astronomy have been obtained using imaging atmospheric Cherenkov telescopes (IACTs) [1] and stereoscopic systems of several such devices [2]. The TAIGA gamma observatory (Tunka Advanced Instrument for Cosmic-Ray Physics and Gamma-Ray Astronomy [3]) in the Tunka Valley will operate in the region of energies above 30 TeV. The observatory will combine an IACT and a network of relatively inexpensive wide-angle timing stations, allowing us to extend the area of the installation to several square km and substantially suppress the cosmic ray background due to very good angular resolution (~0.1° for energies above 100 TeV). With the combination of the two methods for distinguishing gamma-ray events, we can create an installation with a large area at comparatively low cost. This is the first time such a combination of an IACT and a timing array has been attempted.

DATA SIMULATION

The IACT data were simulated in two steps: EAS modeling using the CORSIKA software [4] and calculating the number of Cherenkov photons of a simulated shower reflected from a telescope's mirror and recorded in its focal plane by a camera of 547 photomultipliers. The parameters determined from the time delay of recording photons in different detectors were used as the data for the timing array: primary energy, angle of incidence, and the position of the EAS core. The direction of primary gamma-ray incidence (the point source) was fixed, and the proton shower's angle of incidence was randomized around this direction with an error of 0.4°, much worse than that of the real installation. The exact position of the EAS core was considered to be unknown and was randomly smeared with varying dispersion.

METHODOLOGY

From the data base we calculated different parameters of an IACT image for each EAS, along with the background suppression quality factor for each configuration of these parameters:

$$Q = \varepsilon_\gamma \Big/ \sqrt{\varepsilon_{\text{proton}}},$$

where ε_γ and $\varepsilon_{\text{proton}}$ are the fractions of events selected for gamma showers among true gamma showers and proton showers, respectively. The optimum algorithm was the one with the combination of parameters for which the Q factor reached its maximum under the condition $\varepsilon_\gamma \geq 0.5$. The background is in this case suppressed by a factor of $\varepsilon_{\text{proton}}^{-1} = (Q/\varepsilon_\gamma)^2$.

All calculations were performed with multiply simulated random night sky backgrounds, and the results were averaged over all simulations. The need for this procedure, which was not performed in earlier IACT experiments, was confirmed by the large fluctuations of Q from the average value, due to random noise

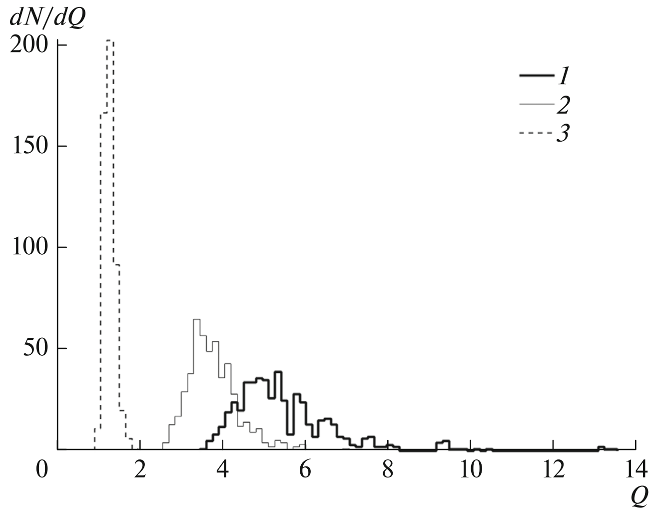

Fig. 1. Q factor distributions for three different night sky filtering thresholds. The threshold values in terms of μ and σ of the background distribution are (*1*) μ + 5.4σ (optimum filtering), (*2*) μ + 4σ, and (*3*) μ+ 3.6σ. The threshold values in terms of photoelectrons per pixel are 17, 14, and 13, respectively. The thresholds in neighboring pixels are μ – 0.4σ, μ, and μ (4, 5, 5 photoelectrons/pixel), respectively. The calculations were performed with a simulated EAS from gamma rays and protons with energies of 100 TeV at distances of 300–450 m from the IACT to the EAS core.

(Fig. 1). Repeating the procedure N times lengthened the time required for calculations, $t \sim N$, and reduced the error of the average Q factor, $dQ/Q \sim 1/N^{1/2}$.

To clean the image from the night sky background, we tried several filtering schemes and determined the one with the optimum parameters maximizing the Q factor. The optimum values differed from those in IACT experiments, in which the filtering threshold is μ + 2–3σ of the background distribution [5] (where μ is the average value of the background). They depend on the energy and distance from the EAS core, and their influence on the Q factor is considerable: in Fig. 1, the average is $Q > 5$ for threshold μ + 5.4σ and $Q < 2$ for threshold μ + 3.6σ. All of the results below were therefore obtained using the corresponding optimum image cleaning procedure. The procedure will be described in detail in a separate work.

RESULTS AND DISCUSSION

The optimum parameters of an IACT image are a width in the direction perpendicular to the one toward the camera's center (the azwidth [6], from "azimuthal width"), and a width in the direction perpendicular to a shower core (the azcorewidth, from "azimuthal core width," introduced in this work). The effectiveness of the second parameter depends on the accuracy of shower core determination; for an accuracy of ~10–15 m, the Q factor for this parameter exceeds the one for the parameter azwidth only for events at distances of more

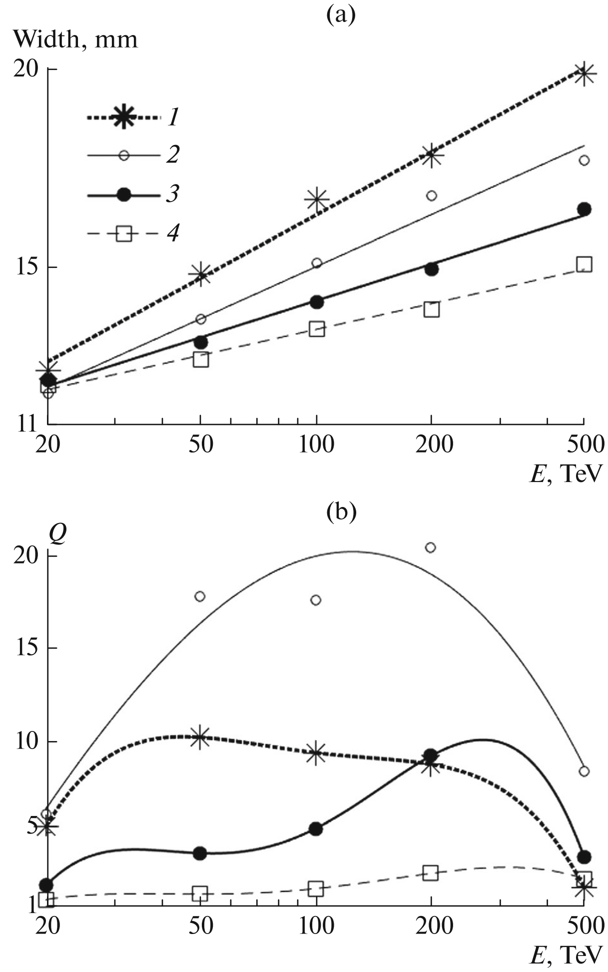

Fig. 2. (a) Optimum threshold image width and (b) Q factor for this threshold as functions of the primary EAS energy for different distances from the IACT to the EAS core: (*1*) 0–150, (*2*) 150–300, (*3*) 300–450, and (*4*) 450–600 m.

than 450 m from the EAS core. Efforts are now under way to increase the accuracy of core reconstruction using data from timing detectors, as a result of the more detailed approximation of the spatial distribution of Cherenkov light from EASes.

All three parameters considered above (the primary energy, the core position, and the EAS angle of incidence) are found optimal for combining with the IACT imaging parameters. The optimum method for combining these two groups of parameters (imaging and timing) is to include the dependence of the threshold values of parameters azwidth and azcorewidth on the energy and distance from the shower core in the procedure for distinguishing gamma showers (Fig. 2a). We then have $Q > 5$ for energies of 100–200 TeV and distances of up to 450 m (Fig. 2b).

The reduction in the Q factor when there are no data from a timing array (i.e., if the IACT is operating separately) is considerable: for unknown energies at distances of up to 150 m, Q falls from 10 to 3 at 50 TeV and from 9 to 5 at 100 TeV. It thus becomes difficult to distinguish gamma showers with axes close to the telescope at energies as low as 50 TeV. With an unknown distance (i.e., unknown position of the EAS axis) in the interval R = 300–450 m, Q falls from 4 to 2 at 50 TeV, from 5 to 2 at 100 TeV, and from 10 to 2 at 200 TeV. In the interval R = 150–300 m, it falls from 17 to 5 at 50 TeV, from 18 to 4 at 100 TeV, and from 20 to 6 at 200 TeV. This means it is difficult to distinguish gamma events over the interval R = 150–450 m even when E = 100 TeV.

The growth of the Q factor in distinguishing gamma showers when several image parameters are used simultaneously in quadratic discriminant analysis [7] (i.e., separating gamma and proton showers according to second order surfaces in the multidimensional space of several parameters) offers only slight improvement: if $Q = 4.8$ for one parameter, then $Q = 5.4$ for two and $Q = 5.6$ for three; this corresponds to background suppression by factors of 92, 117, and 125, respectively. For higher-quality suppression, we must use more complex types of separating surfaces or another set of decision rules, which is a subject for further analysis.

CONCLUSIONS

A methodical study of the combined operation of two types of Cherenkov installations, IACT + nonimaging (timing) detectors, was performed using simulated data. The optimum set of imaging and shower reconstruction parameters for combined operation was determined, along with the optimum procedures for background suppression and selecting gamma-ray events. Background suppression by a factor of 100 was achieved (suppression quality factor $Q = 5$) for showers with energies of 100 and 200 TeV at distances of up to 450 m, while an IACT operating separately without a timing array suppressed the background 75% less efficiently (the Q factor was halved). This work qualitatively proves the effectiveness of combining an IACT and a timing component at the TAIGA gamma observatory.

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