Proceedings of ICRC 2001: 2835 © Copernicus Gesellschaft 2001

ICRC 2001

On the application of differences in the intrinsic fluctuations of Cherenkov light images for rejection of the cosmic ray background

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Abstract. The sensitivity of Cherenkov telescopes critically depends on the rejection of cosmic ray background events. We have exploited a new method which improves the traditional background suppression technique by accounting for the intrinsically larger fluctuations of light intensity in the images of hadronic atmospheric cascades. The χ^2-criterion is employed to develop an event identification scheme.

Optimization of the method has been conducted using the database of simulated events for the VERITAS project. The same set has been used to evaluate the efficiency of the suggested technique for both stereoscopic and single telescope observation modes.

We have demonstrated that the application of the new technique yields an additional background rejection efficiency of a factor of $1.5 \div 2$ and at the same time it retains $\simeq 70\%$ of the genuine γ-ray initiated events. The discrimination efficiency increases rapidly with the energy of the primary photon.

1 Introduction

Gamma-ray astronomy in the energy range above 100 GeV has made dramatic progress in the last decade due to rapid development of the atmospheric Cherenkov technique at a number of ground-based γ-ray observatories. Only recently, however, has it become possible to overcome the main factor limiting the sensitivities of ground-based observatories which utilize this method. This is the high rate of the cosmic ray (CR) background events. Methods for the efficient discrimination of photon and hadron initiated events have been derived from the differences in the intrinsic properties of the Cherenkov radiation from purely electromagnetic and hadronic cascades. The most prominent of these is the substantially wider distribution of the arrival directions of photons in hadronic showers due to an additional angular scattering of the secondary products during hadronic interactions. This effect has been extensively studied in Monte-Carlo simulations of the cascade development in the atmosphere (Aharonian et al., 1991; Hillas, 1985), and the rejection criteria for the cosmic ray background has been derived in the form of the so-called "shape cut" (Fegan, 1993; Aharonian et al., 1997). Increased angular resolution of ground-based γ-ray observatories together with this means of identification of the primary photon are the most important components of the recent discoveries and advances made in the highest energy γ-ray astronomy.

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The confidence of discovery of a γ-ray source in the case of a background dominated data sample is defined as

$$R = \frac{N_{\rm on} - N_{\rm off}}{\sqrt{2N_{\rm off}}}, \qquad (1)$$

where $N_{\rm on}$ is the number of detected events produced by a hypothetic source for a given exposure, and $N_{\rm off}$ is the number of background events for the same observation time. This quantity reflects an excess of events due to the presence of a source measured in units of background standard deviation shown in the denominator for a Poisson distribution. It is generally accepted that the existence of a source is established if $R \geq 5$.

By application of the background rejection procedure one increases the confidence of the source discovery due to elimination of the signal fluctuations connected with the background. The efficiency of the discrimination technique used to identify primary photons and reject cosmic ray events is expressed then as

$$\eta = \frac{\kappa_\gamma}{\sqrt{\kappa_{\rm p}}}, \qquad (2)$$

where κ_γ and $\kappa_{\rm p}$ are the probabilities of acceptance of photon and background events after the application of selection criteria. Thus the η factor is an enhancement of R indicating that η^2 times less exposure is required for a source discovery when a new discrimination technique is applied.

In this paper we explore a new discrimination technique that is characterized by efficiency $\eta = 1.5 - 2$ in addition to the already existing methods of background suppression achieved by imposing shape and orientation cuts. This technique is based on the differences in intrinsic fluctuations of Cherenkov radiation produced in the pure electromagnetic and hadronic cascades. We adapt the maximum likelihood approach based on an analysis of the χ^2 functional to establish discrimination criteria to distinguish showers initiated by γ-rays from those initiated by CR nuclei. This idea was induced originally by the study of the mass composition of primary cosmic radiation (Plyasheshnikov et al., 1998) where similar methods were proved to be very successful.

2 The intrinsic fluctuations of the image

The imaging atmospheric Cherenkov telescope (IACT) consists of a set of mirrors on a single mount with a two-dimensional array of close-packed hexagonal photomultiplier tubes (pixels) in the focal plane. Therefore information about an event is recorded in the form of a two-dimensional image describing the distribution of the light intensity in the focal plane. Ultimately, the Cherenkov light image is a set of ADC counts corresponding to all pixels. But for simplicity we deal with the number of photoelectrons emitted from the pixels' photocathodes. Hence the Cherenkov light intensity in the focal plane is characterized by the continuous two dimensional distribution of photoelectron density, $\rho(x,y)$. Each point (x,y) on the focal plane corresponds to a certain arrival direction of photons relative to the pointing of the telescope mount. The total number of photoelectrons (pes) in the Cherenkov light image, $SIZE$, is given by

$$SIZE = \int \rho(x,y)\, dxdy.$$

In our further calculations we make frequent use of the normalized to unity distribution of photoelectrons

$$f(x,y) = SIZE^{-1}\rho(x,y)\,, \tag{3}$$

which is equivalent to the probability density function (pdf). Let us denote also the marginal distributions in the coordinate system with the origin in the centroid of the image and with the axes orientated along the major and minor axes.

$$\begin{aligned} f_L(x) &= \int f(x,y)\, dy, \\ f_W(y) &= \int f(x,y)\, dx, \end{aligned}$$

where indices L and W correspond to the major and minor axes of the image respectively. We estimate $f_L(x)$ and $f_W(y)$ by the grid functions

$$\begin{aligned} N_{L,k} &= \int_{x_k}^{x_{k+1}} f_L(x)\, dx, \qquad x_{k+1} = x_k + \Delta x; \\ N_{W,k} &= \int_{y_k}^{y_{k+1}} f_W(y)\, dy, \qquad y_{k+1} = y_k + \Delta y; \end{aligned}$$

defined at $\{x_k, y_k; k = 1, \ldots, K\}$.

Suppose that we have two sets of shower images, initiated by photons and cosmic rays, for which the mean values, $\bar{N}_{t,k}^{(\gamma)}$, $\bar{N}_{t,k}^{(\mathrm{p})}$, and variances, $\sigma^2_{N_{t,k}^{(\gamma)}}$, $\sigma^2_{N_{t,k}^{(\mathrm{p})}}$ of the grid functions are found for each k,$t \in \{L, W\}$. For each image we construct a pair of functionals χ_t^2

$$\chi_t^2 = \frac{1}{K}\sum_{k=1}^{K} \frac{\left(N_{t,k} - \bar{N}_{t,k}^{(\gamma)}\right)^2}{\sigma^2_{N_{t,k}^{(\gamma)}}} \tag{4}$$

so that the mean values of χ_t^2 for γ-showers and background events are equal to:

$$\begin{gathered} \overline{\chi_t^{2(\gamma)}} = 1; \\ \overline{\chi_t^{2(\mathrm{p})}} = \frac{1}{K}\sum_{k=1}^{K}\left[\frac{\sigma_{N_{t,k}^{(\mathrm{p})}}}{\sigma_{N_{t,k}^{(\gamma)}}}\right]^2 + \frac{1}{K}\sum_{k=1}^{K}\left[\frac{\bar{N}_{t,k}^{(\gamma)} - \bar{N}_{t,k}^{(\mathrm{p})}}{\sigma_{N_{t,k}^{(\gamma)}}}\right]^2. \end{gathered} \tag{5}$$

The $\overline{\chi_t^{2(\mathrm{p})}}$ consists of two terms. The first term reflects the differences in the fluctuations of the light intensity of images initiated by γ-rays and those initiated by CR particles. The second one characterizes the differences between the average shapes of distributions of the photoelectron density in the images of the two data sets.

Strickly speaking, two different effects influence the value of the "fluctuation" term of $\overline{\chi_t^{2(\mathrm{p})}}$. The first of them is connected with random variations of the angular size of the image described, for example, by WIDTH and LENGTH parameters. The second effect is the irregularity of the light distribution inside the image itself. Even in the case of γ-ray and proton induced images having the same angular size the first of them has a more smooth and regular structure and, therefore, a smaller value of intrinsic fluctuations. Large fluctuations in the number of secondary particles created during the hadron multi-particle production is the main reason of difference in intrinsic fluctuations of γ- and p-induced images.

In this work we attempt to make use of the contribution to $\overline{\chi_t^{2(\mathrm{p})}}$ from the first ("fluctuation") term because we expect that the second term (as well as the fluctuations connected with variations of the angular size of the image) is rather small for images which passed the image shape selection criteria.

Keeping in mind the argumentation presented above, one can hope to use selection criteria of the form

$$\chi_L^2 < \tilde{\chi}_L^2, \qquad \chi_W^2 < \tilde{\chi}_W^2 \tag{6}$$

to reject CR-induced events and retain genuine photon-initiated showers. For a single telescope, two constants $\tilde{\chi}_L^2$ and $\tilde{\chi}_W^2$ should be optimized to maximize the signal to noise ratio (see formula (1)). For a system of telescopes we consider the following background rejection criterion

$$\frac{1}{N_{\mathrm{trig}}}\sum_{i=1}^{N_{\mathrm{trig}}} \chi_{L,i}^2 < \tilde{\chi}_L^2, \qquad \frac{1}{N_{\mathrm{trig}}}\sum_{i=1}^{N_{\mathrm{trig}}} \chi_{W,i}^2 < \tilde{\chi}_W^2 \tag{7}$$

In the case of a single telescope, both criteria (6) and (7) are identical.

In order to increase the selection efficiency one should consider the smaller regions of the primary photon parameter phase space and formulate selection criteria for each of them. We expect that the shower parameters which affect background rejection most strongly are the primary energy, E and the impact parameter, r. In order to make the $\chi^{2(\gamma)}$ distribution narrower and thus improve the discrimination ability of the method, we will evaluate the dependence of the grid functions of photoelectron density on these parameters

$$N_{t,k} = N_{t,k}\left(E,r\right), \quad \bar{N}^{(\gamma)}_{t,k} = \bar{N}^{(\gamma)}_{t,k}\left(E,r\right), \quad \sigma_{N^{(\gamma)}_{t,k}} = \sigma_{N^{(\gamma)}_{t,k}}\left(E,r\right). \tag{8}$$

We would like to denote that the χ^2-based method has been used in the past to deduce parameters of the primary particle (Ulrich et al., 1998; Le Bohec et al., 1998). In our work, however, we do not explicitly assume that the fluctuations in the images of γ-rays are of a Poissonian nature.

3 Determination of the impact parameter

The efficiency factor, η, of the discrimination technique increases if the dependence of the image photoelectron density on the energy and the impact parameter of a shower is accounted for (formula (8)). Therefore, it is necessary to have some method of determining these quantities. In this work we have investigated three possibilities for estimating impact parameter of the primary particle:

- VERITAS operates as a system of telescopes. The impact parameter is determined by a simple geometrical event reconstruction method (see, e.g., Aharonian et al., 1997).
- VERITAS operates in a single telescope mode.
  - The impact parameter is determined on the basis of the $DIST$ (distance) parameter of the image.
  - The impact parameter is determined by means of the $ELLIPT$ (ellipticity) parameter of the image.

For a single telescope, determination of the impact parameter utilizes its correlation with such characteristics of the image, as $ELLIPT$ or $DIST$ (Plyasheshnikov and Konopelko, 1989) defined as

$$ELLIPT = \frac{LENGTH}{WIDTH} - 1, \quad DIST = \sqrt{x_{\rm c}^2 + y_{\rm c}^2} \tag{9}$$

where $x_{\rm c}$ and $y_{\rm c}$ are coordinates of the image centre of gravity in the reference frame with an origin at the source location. Unlike the $DIST$ parameter, $ELLIPT$ provides an opportunity for determining the impact parameter not only for a point-like, but also for an extended γ-ray sources when the arrival direction of a photon is not known. The summary on the accuracy of the impact parameter determination for γ-s is summarized in Table 1

In the case of the photon primary the method of impact parameter determination based on the $DIST$ parameter is substantially more accurate than the one where the ellipticity is in use. This is due to the weaker correlation of $ELLIPT$ with shower core location. For isotropically distributed cosmic rays one should not expect any correlation between the impact parameter of the showers and the $DIST$ value. The error on the determination of the shower core is finite because of the limited telescope field of view and the high directionality of the distribution of Cherenkov photons from atmospheric cascades.

4 Application of the discrimination technique

To estimate the discrimination efficiency of this new technique, we applied a preliminary event selection on the basis of the shape parameters using the scaled width $W_{\rm sc}$ (Aharonian et al., 1997) thereby excluding any possible correlation between the traditional and proposed event classification methods. We have simulated two data bases of photon and proton initiated showers for the VERITAS array of telescopes. This task has been accomplished by utilizing ALTAI computation code (Konopelko and Plyasheshnikov, 2000). Although, both proton and photon induced cascades were simulated as vertical showers, images of cosmic rays were also sampled isotropically on the focal planes of the telescopes near the vertical direction. A power law differential energy spectra of primary particles was assumed with exponent -2.6 for photons and -2.75 for protons. Photons were sampled from the energy interval $0.05 - 10$ TeV and protons were distributed between $0.1 - 20$TeV. The possibility of the application of the fluctuations can be seen from Fig. 1. Figure 1 depicts two histograms: the ratio of the mean photoelectron density along the major axis $(t = L)$ for images initiated by photons and protons (1), and the ratio of their standard deviations (2). The $SIZE$ parameter was limited within interval from 100 to 200 photoelectrons, and the actual shower impact parameter was restricted to the $50 - 75$ m interval. It can be seen that for the given conditions, the contribution to the χ^2 functional (Eq. 5) from the first, "fluctuation", term exceeds the second, "mean difference", term by almost a factor of ten.

The bin sizes, $\Delta x = 0.2°$ and $\Delta y = 0.06°$, used to construct the grid photoelectron density functions, were optimized to achieve the highest discrimination efficiencies. They are chosen as a balance between the necessity to resolve features in the shower images on the scales smaller than $LENGTH$ and $WIDTH$ and, at the same time, not to make

Table 1. The value of the impact parameter determination error [m]. 50% of showers have an error smaller than the value presented in the table. The $SIZE$ of the images is larger than 150 pes.

System of telescopes	5
Single telescope ($DIST$)	11
Single telescope ($ELLIPT$)	27

fluctuations in the bins dominated by Poisson statistics. In addition, a special analysis has shown that the χ^2-technique exhibits no essential sensitivity to the bin size if the value of this size does not exceed considerably the pixel size (0.15^o) of the VERITAS telescopes.

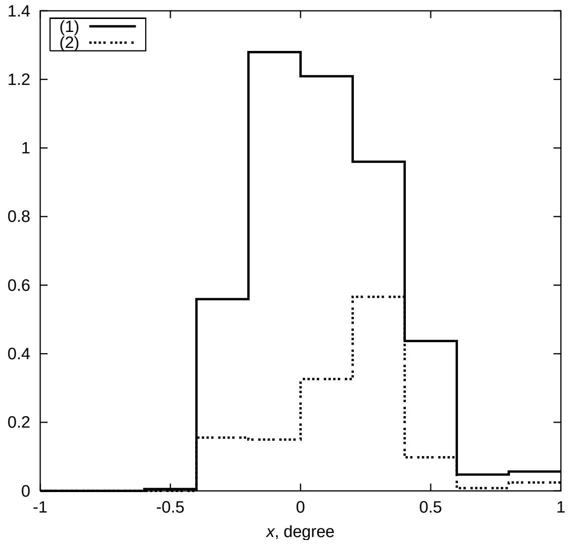

Fig. 1. $\bar{N}^{(\gamma)}_{L,k}/\bar{N}^{(\mathrm{p})}_{L,k}$ (1) and $\sigma_{N^{(\gamma)}_{L,k}}/\sigma_{N^{(\mathrm{p})}_{L,k}}$ (2) for events surviving the scaled width cut ($W_{\rm sc} = 1.4$, $DIST$-approach). A single VERITAS telescope is considered. Bin size $\Delta x = 0.2°$.

The largest value of the total efficiency factor, $\eta_{\rm tot}$, is achieved for $\tilde{W}_{\rm sc}$ larger than the value which provides maximum discrimination power of photon selection based solely on the scaled width cut. This is also correct for event reconstruction using a single telescope. Selection criterion utilizing only the χ^2_L cut demonstrates a discrimination efficiency factor $\simeq 80-90\%$ of the one obtained with the use of both χ^2 cuts. An increase of $\tilde{W}_{\rm sc}$ provides a moderate growth of photon discrimination efficiency when χ^2_W is sequentially applied, while the effect of a χ^2_L selection depends very weakly on the scaled width cut.

In Table 2 we present the true photon classification probability and discrimination efficiency of the χ^2 technique when various lower bounds on image $SIZE$ are included in the analysis. The dependence of these quantities on the lower limit of the estimated energy of the primary particle is shown in the Table 3. For both tables we tuned the scaled width cut to optimize the total efficiency factor. Primary energy was estimated by backward interpolation with respect to image $SIZE$ and estimated impact parameter, r, using simulated data base of photon induced showers.

5 Conclusion

In this work we have examined the feasibility of improving photon selection using differences in the fluctuations of the Cherenkov light distribution between the images of γ and p - initiated showers. Three different event reconstruction methods which are likely be utilized in the next generation of ground-based γ-ray observatories, such as VERITAS, have been studied. Two of them are applicable to observations with a single telescope and one uses the stereoscopic capability of VERITAS array.

Table 2. Discrimination efficiency of χ^2 photon selection technique ($\tilde{W}_{\rm sc}$ cut is tuned to maximize $\eta_{\rm tot}$). Different image $SIZE$ lower bound for analyzed events is shown.

	System		$DIST$		$ELLIPT$	
S	100	300	100	300	100	300
κ_γ	0.75	0.71	0.73	0.70	0.79	0.70
η_{χ^2}	1.50	2.14	1.43	4.11	1.22	1.95

Optimization of our technique indicates that the proposed method provides an additional increase of the total discrimination efficiency by a factor $\geq 1.5-2.0$ retaining the survival probability of γ-ray initiated events at the level larger than 0.7. That is true for both the telescope array and the single telescope (with estimation of impact parameter by the $DIST$-based method). When a single telescope event is reconstructed utilizing the $ELLIPT$ parameter, our approach provides an additional discrimination efficiency factor ≥ 1.4. This is particularly important for a detection of extended sources or sources whose position has not been accurately identified . The discrimination efficiency of the proposed method increases rapidly with the energy of the primary photon.

Acknowledgements. A.V. Plyasheshnikov thanks the Harvard-Smithsonian Center for Astrophysics for the opportunity to visit the Whipple Observatory. This work was partially supported by the US Department of Energy.

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Table 3. Discrimination efficiency of χ^2 photon selection technique as a function of lower bound on event estimated energy to be included into the analysis.

	System		$DIST$		$ELLIPT$	
$E_{\rm est}$, [TeV]	0.2	1	0.2	1	0.2	1
κ_γ	0.72	0.71	0.70	0.70	0.72	0.70
η_{χ^2}	1.91	3.33	1.62	3.92	1.52	2.47