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Gamma-hadron separation using Čerenkov photon density fluctuations

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Abstract. In atmospheric Čerenkov technique $\gamma-$rays are detected against abundant background produced by hadronic showers. In order to improve signal to noise ratio of the experiment, it is necessary to reject a significant fraction of hadronic showers. The temporal and spectral differences, the lateral distributions and density fluctuations of Čerenkov photons generated by $\gamma-$ray and hadron primaries are often used for this purpose. Here we study the differences in Čerenkov photon density fluctuations at the observation level based on Monte Carlo simulations. Various types of density fluctuations like the short range (or local), medium range fluctuations and flatness parameter are studied. The estimated quality factors reflect the efficiencies with which the hadrons can be rejected from the data. It has been found that we can reject around 80% of proton showers while retaining about 70% of $\gamma-$ray showers in the data, based only on the differences in the flatness parameter. Density fluctuations particularly suited for wavefront sampling observations seem to be a good technique to improve the signal to noise ratio.

1 Introduction

In a typical wavefront sampling experiment, arrival time of Čerenkov photons and Čerenkov photon density are sampled at several locations in the Čerenkov pool generated by air showers initiated by $\gamma-$rays from astronomical sources, using distributed array of telescopes. Cosmic ray showers which also give rise to Čerenkov light similar to that produced by $\gamma-$rays constitute abundant background against which the $\gamma-$ray signal is to be detected. Hence it is necessary to devise methods to reject a large fraction of cosmic ray background and thereby improve the signal-to-noise ratio or sensitivity of the experiment. Previously we have studied the usefulness of parameters based on timing information recorded in wavefront sampling experiment for gamma-hadron separation (Chitnis and Bhat, 2001). Use of arrival time jitter and parameters based on shape of the Čerenkov pulse has been demonstrated. Here we investigate the efficacy of certain parameters based on Čerenkov photon density distribution for gamma-hadron separation.

2 Local density fluctuations

Pachmarhi Array of Čerenkov Telescopes (PACT) consists of 25 telescopes with each telescope consisting of para-axially mounted parabolic mirrors of diameter 0.9 m each (see Chitnis *et al.*, 2001 for details). Here we study the usefulness of local density fluctuations or LDF for gamma-hadron separation. LDF or density jitter is defined as the ratio of RMS to mean of photon densities from 7 mirrors of each telescope. We have simulated a large number of showers initiated by $\gamma-$rays of energy 500 GeV and protons of energy 1 TeV, incident vertically at the top of the atmosphere, for this purpose. Showers are simulated using CORSIKA (Heck et al., 1998). An array of telescopes spread over an area of 400 m $\times$ 400 m, much larger than PACT, is used for simulations. We have simulated 100 showers for each primary for each of the three observation altitudes, $viz.$, sea level, 1 km above sea level which corresponds to altitude of PACT and for 2.2 km above sea level.

Figure 1 shows the variation of LDF as a function of distance from core of the shower for showers initiated by 500 GeV $\gamma-$rays and 1 TeV protons at various observation altitudes. It can be seen that the LDF for protons is consistently higher than that for $\gamma-$ray primaries for all altitudes and at all core distances. This is expected due to differences in kinematics of these two types of showers (Chitnis and Bhat, 1998). Also fluctuations are not very sensitive to core distances. Hence LDF is a likely parameter to be used for gamma-hadron separation.

We use quality factor as a figure of merit of a parameter to distinguish between $\gamma-$ray and proton initiated showers. It is defined as

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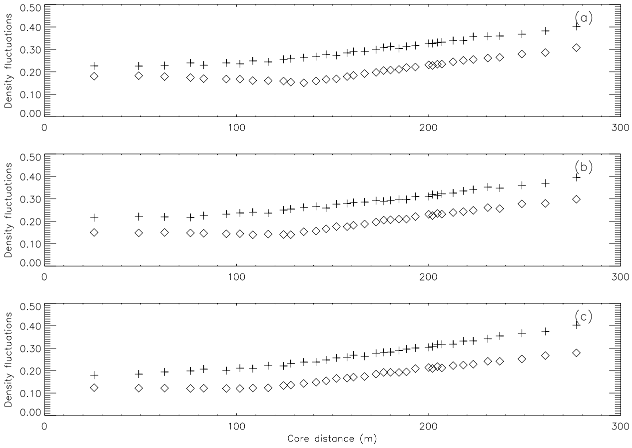

Fig. 1. Variation of local density fluctuations (LDF) as a function of core distance averaged over 100 showers initiated by 500 GeV $\gamma-$rays (indicated by diamond) and 1 TeV protons (indicated by +), for three different altitudes: (a) sea level, (b) 1 km from sea level and (c) 2.2 km.

$$Q_f = \frac{N_a^\gamma}{N_T^\gamma}\left(\frac{N_a^{pr}}{N_T^{pr}}\right)^{-\frac{1}{2}}$$

where N_a^γ is the number of $\gamma-$rays accepted (i.e. below threshold), N_T^γ is the total number of $\gamma-$rays, N_a^{pr} is the number of protons accepted and N_T^{pr} is the total number of protons. Larger the quality factor, better is the background rejection efficiency.

Figure 2 shows the distribution of LDF from 500 GeV $\gamma-$rays and 1 TeV protons, for three different altitudes. Optimum quality factors for each of the cases are listed in Table 1. It can be seen that it is possible to reject about 50% proton showers retaining about 85% of $\gamma-$ray showers, using LDF.

3 Medium range density fluctuations

PACT consists of four sectors of six telescopes each. We define medium range or sector-wise density fluctuations (MDF) as the ratio of RMS to mean density, where RMS and mean are calculated using total photon densities at each of the six telescopes of a sector. Figure 3 shows the variation of medium range density fluctuations as a function of core distance for showers initiated by 500 GeV $\gamma-$rays and 1 TeV protons for three different altitudes of observation level. As in the case of LDF using the distributions of MDF for showers initiated by 500 GeV $\gamma-$rays and 1 TeV protons, quality factors are calculated at three altitudes of observation levels. Optimum quality factors for different altitudes are listed in Table 2 and distributions of MDF are shown in Figure 4. It can be seen that it is possible to reject about 60-70% of proton showers retaining about 80% of $\gamma-$ray showers, based on MDF.

Table 1. Quality factors for local density fluctuations

Obs altitude (km)	Threshold value of LDF	Quality factor	Fraction of accepted $\gamma-$rays	Fraction of accepted protons
0	0.248	1.284 ± 0.012	0.842	0.429
1	0.257	1.215 ± 0.011	0.888	0.534
2.2	0.234	1.261 ± 0.012	0.870	0.476

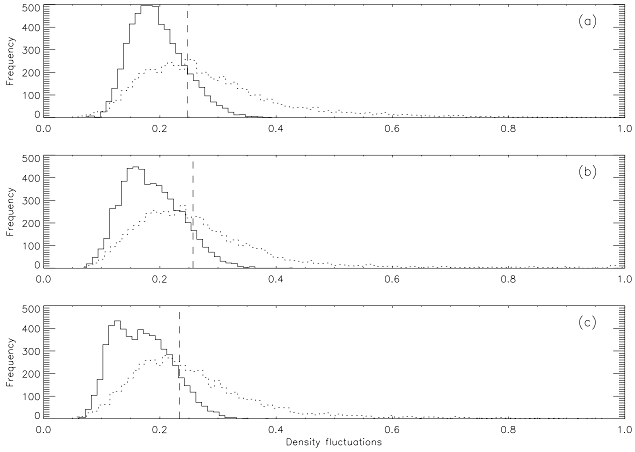

Fig. 2. Gamma-hadron separation based on LDF for 500 GeV $\gamma-$rays (continuous line) and 1 TeV protons (dotted line) for observation altitudes of (a) 0 km, (b) 1 km and (c) 2.2 km. Dashed line indicates the parameter value which yields optimum quality factor (see table 1).

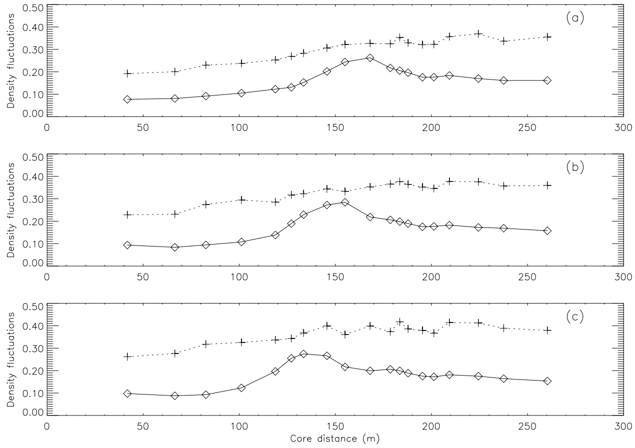

Fig. 3. Variation of medium range or sector-wise density fluctuations as a function of core distance averaged over 100 showers initiated by 500 GeV $\gamma-$ rays (indicated by diamond and continuous line) and 1 TeV protons (indicated by plus sign and dotted line), for three different altitudes: (a) 0 km, (b) 1 km and (c) 2.2 km

4 Medium range flatness parameter

Lateral distributions of Čerenkov photons (variation of Čerenkov photon density as a function of core distance) from showers initiated by $\gamma-$rays show a characteristic hump at

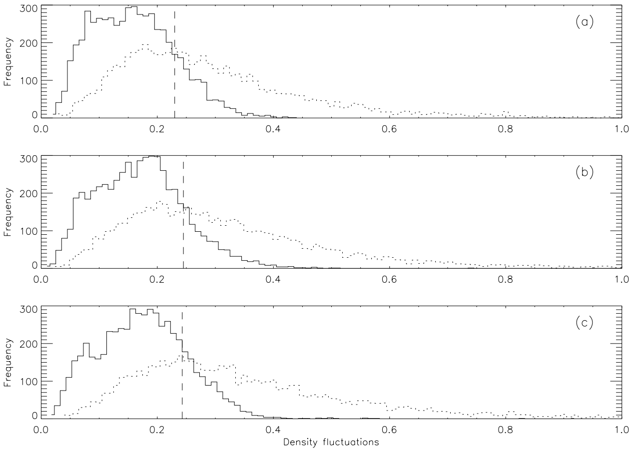

Fig. 4. Gamma-hadron separation based on medium range density fluctuations for 500 GeV $\gamma-$rays (continuous line) and 1 TeV protons (dotted line) for observation altitudes of (a) 0 km, (b) 1 km and (c) 2.2 km. Dashed line indicates the value of the parameter for optimum quality factor (see table 2).

the core distance of about 120-140 m, depending on the observation altitude. This is due to the effective focusing of Čerenkov photons from a large range altitudes. Distributions are flat within the hump region and density falls rapidly beyond the hump. Lateral distributions from proton showers, on the other hand, show continuously falling density distribution as core distance increases (Rao and Sinha, 1988 and Chitnis and Bhat, 1998). Also due to the kinematical differences, the lateral distributions from $\gamma-$ray showers are smooth compared to proton showers. These differences in lateral distributions can be parameterized using flatness parameter defined as :

$$\alpha = \frac{1}{N}\left[\sum_{i=1}^{N}\frac{(\rho_i-\rho_0)^2}{\rho_0}\right]$$

where N : no. of telescopes triggered, ρ_i : photon density measured by individual telescopes and ρ_0 : average density.

Lateral distributions from $\gamma-$ray showers are expected to have a smaller value of α parameter compared to proton generated showers, on the average. Figure 5 shows variation of α parameter as a function of core distance for showers generated by 500 GeV $\gamma-$rays and 1 TeV protons, for three observation altitudes. It can be seen that, on an average, $\gamma-$ray showers have smaller value of α compared to proton showers. Also for both $\gamma-$rays and protons, value of α increases with increase in altitude of observation. At all the three altitudes $\gamma-$ray showers show larger value of α near hump region of lateral distribution. As a result, the difference in value of α for $\gamma-$rays and protons near hump is reduced. Hence α can be useful discriminant at core distances away from the hump, on both the sides.

Table 2. Quality factors for medium range density fluctuations

Obs altitude (km)	Threshold value of MDF	Quality factor	Fraction of accepted $\gamma-$rays	Fraction of accepted protons
0	0.230	1.297 ± 0.030	0.819	0.399
1	0.245	1.332 ± 0.031	0.830	0.388
2.2	0.243	1.418 ± 0.034	0.795	0.315

Table 3. Quality factors for medium range flatness parameter for core distance < 100 m

Obs altitude (km)	Threshold value of α	Quality factor	Fraction of accepted $\gamma-$rays	Fraction of accepted protons
0	0.33	1.800 ± 0.119	0.690	0.147
1	0.52	1.556 ± 0.095	0.738	0.225
2.2	0.66	1.662 ± 0.108	0.677	0.166

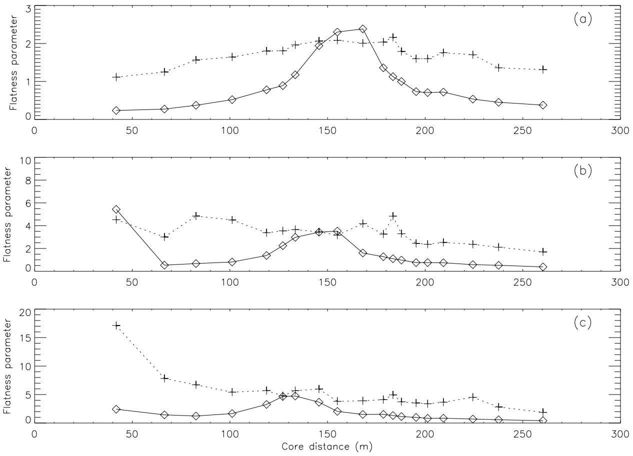

Fig. 5. Variation of α parameter as a function of core distance for showers generated by 500 GeV $\gamma-$rays (diamonds and continuous line) and 1 TeV protons (+ and dotted line), for altitude of (a) 0 km, (b) 1 km and (c) 2.2 km. α parameter is calculated for each sector.

Distributions of α parameter for telescopes within core distances of 100 m, for showers initiated by 500 GeV $\gamma-$rays and 1 TeV protons, for observation altitude of 1 km are shown in Figure 6. Optimum quality factors for all the three altitudes are listed in Table 3. It can be seen that the flatness parameter serves as a good discriminant for showers with smaller impact parameters. For telescopes within 100 m of shower axis it is possible to reject about 80% of the proton showers retaining about 70% of $\gamma-$ray showers based on flatness parameter alone.

5 Conclusions

In this work we have demonstrated the use of parameters based on Čerenkov photon density fluctuations for gamma-hadron separation. Using local density fluctuations it is possible to reject about 50% of proton showers retaining about 85% of $\gamma-$ray initiated showers. Whereas, based on medium

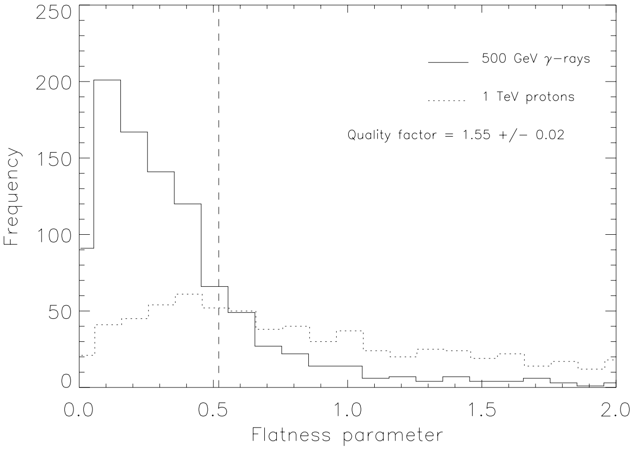

Fig. 6. Gamma-hadron separation based on α parameter for sectors within 100 m from shower axis for showers initiated by 500 GeV $\gamma-$rays and 1 TeV protons, at observation altitude of 1 km. Dashed line indicates the ordinate for optimum quality factor. Quality factors for this case as well as for other observation altitudes are listed in Table 3.

range density fluctuations, it is possible to reject about 60-70% of proton initiated showers retaining about 80% of showers produced by $\gamma-$rays. Flatness parameter, on the other hand, serves as a useful discriminant at core distances away from hump. Using this parameter it is possible to reject about 80% of proton showers, retaining about 70% of $\gamma-$ray induced showers, for core distances within 100 m. Using these three parameters in tandem it is possible to improve rejection efficiencies further. Table 4 lists the quality factors at various altitudes obtained by applying all the three parameters, LDF, MF and α together. Here we restrict to only the telescopes within the distance of 100 m from shower core. It can be seen that it is possible to reject about 95% of proton showers, retaining about 60% of $\gamma-$ray showers at different observation altitudes, using density based parameters in tandem. In addition, using these parameters in tandem with the parameters based on timing information such as timing jitter and Čerenkov pulse shape parameters will greatly improve the sensitivity of the experiments based on wavefront sampling technique.

Table 4. Quality factors with density parameters applied in tandem, for core distance < 100 m

Obs altitude (km)	Threshold value of LDF, MDF & α	Quality factor	Fraction of accepted $\gamma-$rays	Fraction of accepted protons
0	0.23, 0.10 & 0.33	2.221 ± 0.167	0.655	0.087
1	0.19, 0.09 & 0.52	2.177 ± 0.175	0.580	0.071
2.2	0.15, 0.09 0.66	3.365 ± 0.368	0.563	0.028

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