THE SYSTEM OF IMAGING ATMOSPHERIC CHERENKOV TELESCOPES: THE NEW PROSPECTS FOR VHE GAMMA RAY ASTRONOMY.

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Using Monte Carlo simulations the possibilities are investigated for registration of VHE gamma radiation by means of systems of imaging air Cherenkov telescopes (IACT). It is shown that even a system of IACT's with moderate properties (three telescopes with the geometrical area of the optical reflector $\approx 5\ m^2$ and the angular size of the pixel $\approx 0.41^o$) could provide the energy resolution 20–25% and achieve the sensitivity (minimum detectable flux) up to $10^{-12} photon/cm^2 s$ at the effective energy threshold $\approx$1 TeV.

1. Introduction.

So far all observations of primary gamma rays at E$\approx$ 1 TeV have been made with Air Cherenkov Telescopes (ACT). In the foreseeable future this technique will dominate at least at energies E$\leq$10 TeV.

One of the most remarkable features of the ACT's is their high rate capability. For collection area $S_{eff} \geq 3 \cdot 10^8 cm^2$, easily achieved by simple ACT, the counting rate of VHE gamma rays from the Crab Nebula should be higher than 0.1 events per minute. However, this important feature can acquire its practical significance only in the case of effective suppression of the background induced by the proton-nuclear component of the primary cosmic radiation. Different ways for cosmic ray background rejection were proposed (for review see, e.g., Weekes, 1988); however at present only the so called imaging technique is realized as a powerful method for significant improvement of the sensitivity of detectors in VHE gamma ray astronomy. The application of the multichannel Cherenkov light receiver in the focus of the high quality optical reflector gives a possibility to separate gamma ray- and proton-induced showers, analyzing the

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differences in the shape and orientation of the Cherenkov light spot in the focal plane. High efficiency of such a separation was established on the base of Monte Carlo simulations (Hillas,1985;Plyasheshnikov et.al.,1985) and observations of the Whipple collaboration: $\approx 45\sigma$ signal from the Crab Nebula has been observed recently by the 10m Cherenkov telescope of this collaboration (Lang et.al.,1991).

Further development of the IACT technique seems to be in two principal directions: (i) reduction of the angular size of the cells of multi-channel camera down to $\Delta\Psi \leq 0.1^o$. With the aperture $\approx 3^o - 4^o$, which is necessary to provide a collection area $S \geq 3 \cdot 10^8 cm^2$, it means the construction of the camera having about 1000 channels (PMT's). Besides, it means an essential improvement of the optical characteristics of the reflectors; (ii) by coupling several imaging ACT (≥ 3) in a system, separated with about 50-100 meters.

We hope that forthcoming systems of the imaging ACT equipped with high resolution cameras will raise VHE gamma ray astronomy to the status of HE (≥ 100 MeV) gamma ray astronomy based on the satelite experiments. With the imaging ACT (IACT) arrays it will be possible to achieve the angular resolution $0.1^o - 0.2^o$, the energy resolution 20-25 % and the sensitivity (minimum detectable flux) up to 10^{-12} photon/$cm^2 s$ at the effective energy threshold ≈ 1 TeV. It should be noted that owing to a high angular resolution and an effective background rejection it becomes real to study the cosmic gamma rays from the point sources under background-free conditions. Consequently, the sensitivity of the detector will be determined only by the statistics of gamma rays.

The aim of this paper is to show that an essensial improvement of the sensitivity is possible even with relatively moderate arrays. The Monte Carlo calculations presented here were realized for the prototype of the Cherenkov telescope which will be used in the HEGRA observatory (Aharonian et al., 1991).

2. A Brief Description of the HEGRA System and Its Hardware Logics.

Each multi-mirror optical reflector of 5 HEGRA telescopes has a geometrical area 5 m^2. The Cherenkov light receiver, placed in the focus of the reflector (F$\approx$ 5 m), consists of 37 PMT's close-packed in a hexagonal arrangement. The full aperture of the telescope (full angle of view) is about 3^o, the angular size of each pixel is $\approx 0.41^o$. The mean number of photoelectrons emitted from the cathode of PMT per one Cherenkov photon falling on the reflector surface, taking into account the mirror reflectivity, the light pipe transparency and the quantum efficiency of the PMT, is about 0.1 (Aharonian et al., 1991a).

The HEGRA IACT's will be situated at the altitude of 2200 m above the sea level (Canary Island La Palma).

In the present version of the HEGRA telescopes the following trigger condition will be used: the signal in at least two pixels from 19 inner PMT's should exceed some critical value q_O (in units of number of photoelectrons), hereafter the criterion «$2/19>q_0$». This criterion has been successfully used in observations with the 10m Whipple Cherenkov telescope. It provides rather good precision for determination of basic parameters of the detected Cherenkov images. Besides, this criterion provides quite high gamma ray detection efficiency even at threshold, while for the proton-nuclear component of cosmic rays the detection efficiency is much lower. In other words, this criterion gives a possibility to achieve an essential rejection of background events already at the hardware level.

The choice of the optimum value of q_0 depends on several factors (the background rejection efficiency, the gamma ray collection area, the angular resolution). The Monte Carlo calculations show that the optimum value of q_0 is within 10-15 photoelectrons. It should be noted here that the minimum acceptable value q_0 for the hardware criterion «$2/19>q_0$» following from the requirement of reliable rejection of the night-sky background has to be equal ≈ 9 photoelectrons (Aharonian et al., 1991a).

The Cherenkov telescopes of HEGRA installation are planned to be placed in the vertices and the center of the rectangle with the length of the side l=50-100 m. At present two possible regimes of IACT system operation are being discussed: mode 1 — the system switches when the hardware condition «$2/19>q_0$» satisfied for central and two neighbouring peripherial telescopes (three fold regime); mode 2 — the information from all the telescopes is registered when the requirement «$2/19>q_0$» takes place at least for one telescope (this regime can be realized by means of so called «two-level» trigger logic).

Mode 1, the simplest one from the point of view of technical realization, provides the best efficiency of CR background rejection due to the high quality of Cherenkov images. Mode 2 has an apparent advantage since this regime provides the largest collection area and high statistics.

3. Calculation Technique.

The numerical analysis presented in this paper is based on detailed Monte Carlo simulations of the cascade development of air showers induced by gamma rays and cosmic rays, as well as simulations of the processes connected with the registration of Cherenkov radiation of the showers by IACT system. The description of the simulation algorithms is given by Plyasheshnikov and Bignami (1985), Konopelko (1990) and Konopelko et.al.(1992). It was supposed that the charged component of primary cosmic rays consists only of protons (95 %) and α-particles (5 %).

A real layout of the IACT system of HEGRA installation as well as the configuration of the multi-channel Cherenkov light cameras were taken into consideration in accordance with the algorithms described by Aharonian et al. (1990). Here we present the calculations for a system consisting of the 3 IACT placed in the vertices of the isosceles triangle with the length of the side: 50, 100 m. This configuration of the telescopes is considered as the basic one for the system. More complicated

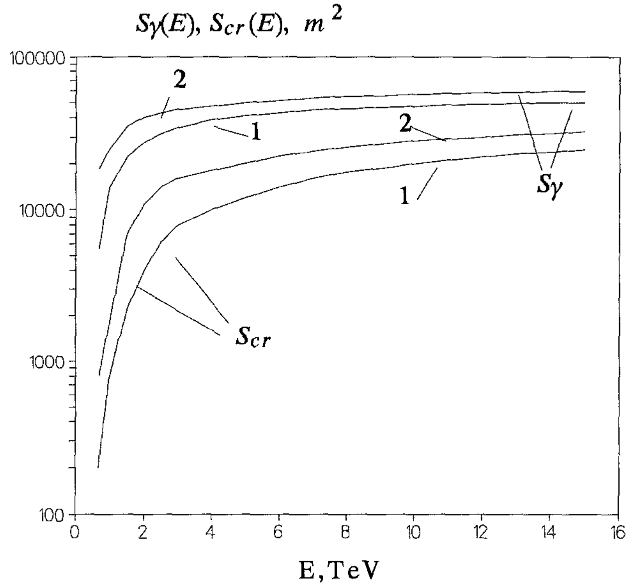


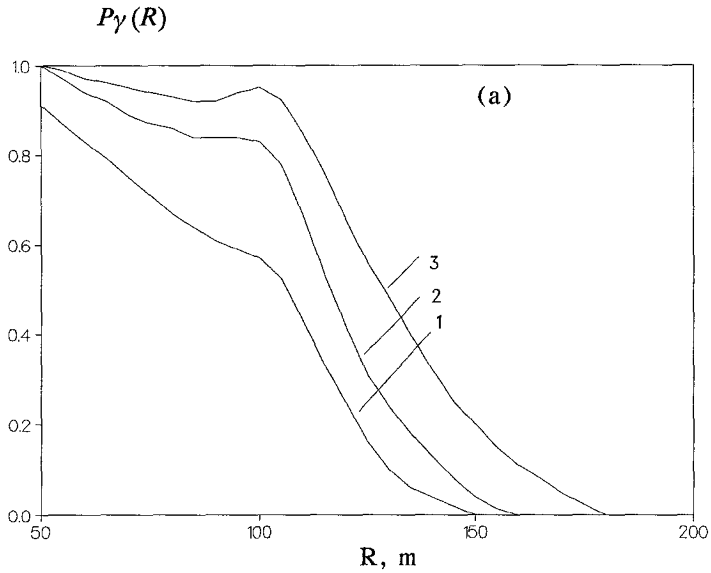
Fig.1. The effective collection area of a single IACT for primary gamma rays and protons. Curve 1— q_0=15 ph.e., curve 2— q_0= 9 ph.e.

configurations, coupling more than 3 IACT can be analyzed, in more cases, using the results obtained for this basic configuration.

4. Characteristics of the Single Imaging Atmospheric Cherenkov Telescope.

The effective collection areas of detection of the gamma rays and protons ($S\gamma$ and S_{cr}) are very important characteristics of the IACT. Particularly, the precise estimation of $S\gamma$ is necessary for the determination of the gamma ray flux from discrete sources. Moreover, the ratio $S\gamma/(S_{cr})^{1/2}$ determines the level of the statistical confidence of observations (before software separation of the registered events on gamma- and proton-induced showers).

So far the detailed quantitative calculations of the effective collection areas of the Cherenkov telescopes have not been carried out. In many works (see,for example,Cawley M.F.,1988) the values $S\gamma$ and S_{cr} are supposed to be the same and independent from the primary energy. In the general case such approximations are rather rough. In particular, in the case of IACT this assumption may lead to an essential error in the estimation of gamma ray fluxes. This is clear from fig. 1, where the energy dependence of $S\gamma$ and S_{cr} for vertical air showers is shown. We see that there is an evident difference between $S\gamma$ and S_{cr} especially near the



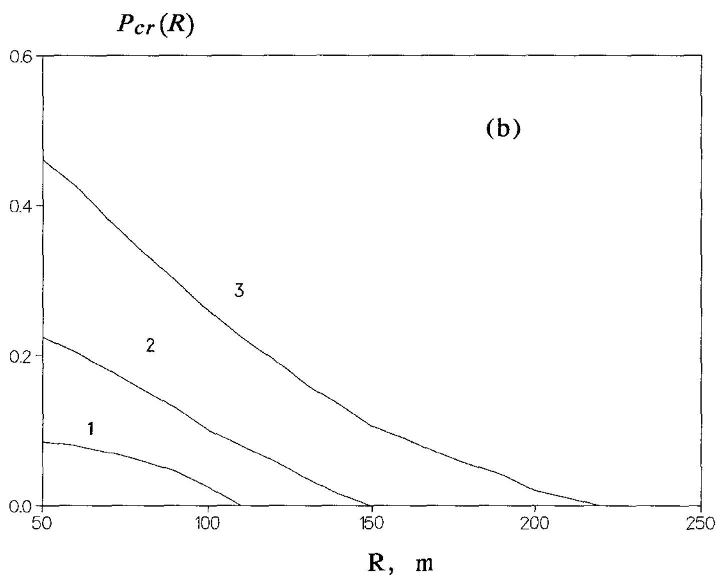


Fig.2. The probability of detection of gamma rays (a) and protons (b) via the impact parameter. The hardware criterion «2/19>q_O», q_O = 9 ph.e.. Curve 1 — E = 1 TeV, curve 2 — E=2.5 TeV, curve 3 — E =10 TeV.

threshold energy (E $\approx$1 TeV). This can be explained by the fact that the hardware condition «2/19>q_O» is more suitable for showers initiated by

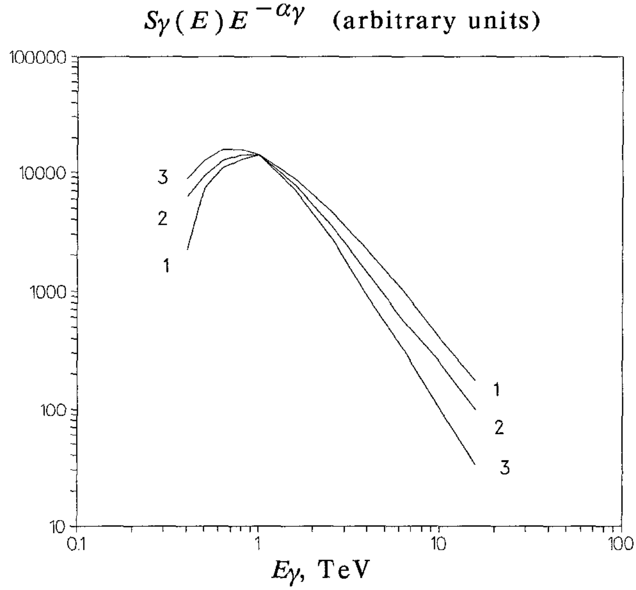


Fig.3. The detection rate of gamma rays $S\gamma E_{\gamma}^{-\alpha\gamma}$ for the single IACT. Curve 1— $\alpha\gamma = 2$, curve 2— $\alpha\gamma = 2.25$, curve 3— $\alpha\gamma$=2. 6.q_o = 15 ph.e.

the gamma rays than for proton-induced showers. The Cherenkov image of a proton-induced shower is distinguished by its «diffuse-like» spot, consequently, the hardware condition «2/19>q_o» (especially near threshold) leads to a low registration efficiency of these showers. On the contrary, the Cherenkov images induced by gamma rays on average have a quite compact spot, therefore the detection probability of the gamma-events remains rather high (at least 50%) for impact parameters up to R $\approx$ 100 m (see fig. 2).

As follows from fig. 1 the collection area for gamma rays becomes large enough ($S\gamma \approx 10^8 cm^2$) already at E $\approx$1 TeV and falls sharply at E< 1 TeV.

To make clear what is the «effective» energy threshold of IACT for gamma rays, we present in fig. 3 the energy dependence of the detection counting rate for gamma-showers defined as $S\gamma I\gamma(E\gamma)$, where $I\gamma(E\gamma)$ is the differential energy spectrum of the gamma rays with different power law indexes $\alpha\gamma$=2; 2.25; 2.6. We can conclude from fig. 3 that the detection rate of the gamma-showers has a maximum value near the energy 1 TeV and this value is practically independent on $\alpha\gamma$. Consequently, we can state that the «effective» energy threshold of the IACT is about 1 TeV. At the same time Cherenkov images of rather high quality are expected to be at energies ≈2-3 TeV when the total number of photoelectrons in image exceeds 100, and the separation of gamma- and photon-induced showers can be done with high efficiency.

The minimum detectable flux of the gamma rays at the level of confidence of m standard deviations («sigma») for a single IACT may be expressed as

$$F_{\gamma}^{\min}(\geq E) = m\,\frac{P_{cr\to\gamma}^{1/2}\,S_{cr}^{1/2}}{P_{\gamma\to\gamma}\;S_{\gamma}}\left(\frac{I_{cr}(\geq E)\,\Delta\Omega}{t}\right)^{1/2} \qquad (1)$$

where $P_{\gamma\to\gamma}$ is the probability of the right classification of the Cherenkov images produced by gamma ray showers, $P_{cr\to\gamma}$— the probability of missclassification of cosmic ray background events as gamma ray events; $I_{cr}(\geq E)\approx 10^{-5}\left(\frac{E}{1TeV}\right)^{-1.65}\ cm^{-2}s^{-1}ster^{-1}$ is the flux of the cosmic rays (Linsley,1980); $\Delta\Omega$ — the solid angle of the aperture of the IACT; t — the duration of observations in «ON source» mode.

Probabilities $P_{\gamma\to\gamma}$ and $P_{cr\to\gamma}$ for HEGRA IACT were studied by Aharonian et al., 1990. The efficiency of the cosmic ray background rejection for different Cherenkov image parameters is presented in table 1. For evaluation of the parameters of the two-dimensional air shower image we used technique from Weekes et.al.,1989. The night sky nois was taken into account. The calculations were carried out for the gamma ray spectrum with power law index α_{γ}=2.25. In contrast to Hillas A.M., 1985, in the software selection criteria we paid no attention to the number of the multichannel receiver ring zone containing the maximum of the Cherenkov light spot. This was done to have a possibility to compare the data corresponding to a single IACT and an IACT system.

As it follows from the table 1 the factor:

$$\eta=\frac{P_{\gamma\to\gamma}}{\sqrt{P_{cr\to\gamma}}}, \qquad (2)$$

which determines the improvements of the signal-to-noise ratio $S/\sqrt{B}$ after the software analysis, has the maximum value in the case of the AZWIDTH parameter. Particularly, for q_O =15 ph.e. the imaging analysis based on the AZWIDTH parameter makes it possible to achieve the background rejection factor $(P_{cr\to\gamma})^{-1}\approx 60$ retaining at the same time more then 40% of the useful (gamma ray) events ($P_{\gamma\to\gamma}\approx$ 0.41). As a result the improvement factor η is equal 3.4.

It should be mentioned that factor η increases with enhancing q_O, but after q_O =15 ph.e. this increasing becomes slow. On the other hand the effective collection area decreases with increasing q_O. That is why the range of $q_O\approx$ 10-15 ph.e. seems to be optimal.

For estimation of the optimum value of q_O we consider the following parameter:

$$X=\eta \frac{S\gamma}{\sqrt{S_{cr}}} \qquad (3)$$

which characterizes the improvement of the signal-to-noise ratio due to the joint application of both the hardware $S\gamma/(S_{cr})^{1/2}$ and the software $P_{\gamma\to\gamma}/(P_{cr\to\gamma})^{1/2}$ criteria. The results of the calculations realized for different values of the gamma ray spectrum index and for various hardware thresholds q_0 are presented in table 2. From this table we can state that for all α_γ the parameter X takes the maximum at q_0 =15 ph.e.

The minimum detectable flux of gamma rays for a single IACT may be estimated according to the next list of necessary variables: the time of observations in the «on source» mode t=100 h; the parameter $X\approx 6.3 \cdot 10^4 cm$ taken from table 2 for q_0 =15 ph.e.; the aperture of the telescope $\Delta\Omega\approx 2\ 10^{-3} (\Delta\Theta_{1/2} \approx 1.5^o)$. Substituting these values in the expression (1) and assuming m=5 we can get

$$F_\gamma^{\min}(\geq 1\ TeV) \approx 2\ 10^{-11} \text{ photon } /cm^2/\text{s}. \qquad (4)$$

By the joint application of several Cherenkov image parameters more effective rejection of the cosmic ray background can be achieved. Such an approach was used in Hillas,1985, but it paid no attention to the correlations between the shower image parameters. Essentially more promising approach to this problem is the method of the multidimensional correlation analysis basing on Bayes decision rules and on the nonparametric estimation of the multidimensional function of the probability density (Aharonian et al., 1991b). The effectiveness of this approach will be discussed below in application to the IACT system.

5. The System of Three Imaging Atmospheric Cherenkov Telescopes.

The multidimensional correlation analysis carried out by us (Aharonian et al., 1991b) for a single IACT allowed us to conclude that the simultaneous application of more than 3 Cherenkov image parameters does not give any essential improvement of the discrimination efficency. That is why we take three parameters for each telescope in the IACT system. Earlier (Aharonian et al., 1990) the following combinations were found as the best ones: (WIDTH, AZWIDTH, LENGTH) and (DIST, MISS, WIDTH).

The main results of the multidimensional correlation analysis applied to the classification of the gamma ray and proton-induced showers detected by the 3 IACT system are presented in table 3. The numerical results correspond to different modes of the system operation (called above as mode 1 and 2) and to various basic distances of the telescopes layout l = 50, 100 m. From table 3 some conclusions may be done:

(1) The application of the multidimensional correlation analysis to the three IACT system makes it possible to achieve the background rejection at the level of some decimal parts of a percent, losing only half of the gamma ray events.

Table 1. The efficiency of CR background rejection for different values of hardware threshold q_0 and different parameters of the Cherenkov light image. Only one Cherenkov image parameter is used for classification of events.

q_0		LENG	WIDTH	DIST	ALPHA	MISS	AZWID
	$P_{\gamma\to\gamma}$	0.442	0.871	0.890	0.842	0.867	0.249
9	$P_{cr\to\gamma}$	0.171	0.736	0.697	0.679	0.611	0.024
	η	1.068	1.015	1.066	1.022	1.108	1.619
	$P_{\gamma\to\gamma}$	0.611	0.861	0.924	0.736	0.602	0.353
12	$P_{cr\to\gamma}$	0.231	0.591	0.653	0.409	0.252	0.018
	η	1.273	1.120	1.144	1.150	1.200	2.639
	$P_{\gamma\to\gamma}$	0.733	0.925	0.928	0.729	0.659	0.416
15	$P_{cr\to\gamma}$	0.251	0.622	0.589	0.378	0.238	0.015
	η	1.461	1.173	1.209	1.186	1.349	3.390
	$P_{\gamma\to\gamma}$	0.783	0.827	0.967	0.719	0.735	0.496
20	$P_{cr\to\gamma}$	0.306	0.506	0.632	0.392	0.242	0.021
	η	1.416	1.163	1.216	1.149	1.493	3.449

Table 2. The dependence of the factor X on the hardware threshold q_0 and on the power index of the differential spectrum of gamma rays. The AZWIDTH discrimination is used.

α_γ / q_0	9	12	15	20	25
2.00	700	832	948	788	714
2.25	480	563	627	504	442
2.65	268	308	327	247	206

(2) With increasing the distance between telescopes from 50 m to 100 m the efficiency for separating gamma ray and proton-induced showers is improved. It can be explained in the following way: with increasing the distance between the telescopes the existing correlations in the Cherenkov images detected by different telescopes could be lost and a set of such images becomes more informative. At the same time if the distance between the telescopes is greater than 100 m the probability for simultaneous detection of shower by three IAC telescopes falls down sharply (see fig. 2).

(3) The IACT system operating in mode 1 provides higher efficiency of the cosmic ray background rejection. For mode 1 the Cherenkov images detected by IAC telescopes have on average a higher density of the Cherenkov photons and, consequently, a lower level of fluctuations.

The effective collection areas for the gamma ray showers calculated for two distances between telescopes (l= 50, 100 m) are presented in fig. 4. The maximum effective collection area is achieved in mode 2 with the basic distance l = 100 m. However in this case the effective collection area S_{cr} is also large, and the factor $S_\gamma / \sqrt{S_{cr}}$ characterizing the signal-to-noise ratio at the hardware level depends weakly on the distance between

Table 3. The maximum available value of the efficiency of the CR background rejection for system of 3 IACT. Different modes of operation of the system and different distances between telescopes are considered. q_0= 15 ph. e., α_γ=2.25$\cdot$# γ ; # cr - number of images of gamma- and proton-induced showers considered in the analysis.

l,m	Mode	#γ/#cr		$P_{\gamma\to\gamma}$	$P_{cr\to\gamma}$	η
50	1	$\frac{1008}{780}$	*width* *azwid* *length*	0.360	0.002	7.28
50	1	$\frac{1008}{780}$	*width* *dist* *miss*	0.457	0.003	8.03
50	2	$\frac{3161}{2553}$	*width* *dist* *miss*	0.218	0.002	5.10
100	2	$\frac{2964}{2345}$	*width* *dist* *miss*	0.269	0.001	8.07

telescopes and the mode of the system operation (see fig. 5). Nevertheless, due to the hard trigger condition in mode 2 the parameter $S_\gamma/\sqrt{S_{cr}}$ for this mode is greater than in mode 1.

Thus, if mode 1 provides higher efficiency of the background rejection, the mode 2 makes it possible to achieve a larger collection area for gamma rays. That is why the sensitivity of the IACT system operating in modes 1 and 2, are expected to be comparable.

Let us estimate now the sensitivity of the IACT system operating in mode 2 with l = 100 m. Substituting to the equation (1) the following parameters: $P_{\gamma\to\gamma}$= 0.27, $P_{cr\to\gamma}$ =0.001, $S_\gamma/\sqrt{S_{cr}}$= 8 10^4 cm (taken from fig.5 and table 3), the minimum detectable flux of the gamma rays above 1 TeV can be estimated for a 5σ DC signal from a point source as:

$$F_\gamma^{min}(\geq 1\,\mathrm{TeV}) \approx 1.7\ 10^{-12}\,\mathrm{photon}/cm^2/\mathrm{s}. \qquad (5)$$

Thus, even for the simplest IACT system the sensitivity is approximately as much as 10 times better than the sensitivity of a single IACT.

It should be noted that for the gamma ray flux I_γ ($\geq$1TeV) $\approx 10^{-11}$ photon/cm^2 s the detection rate of gamma-events is expected to be about

$$\nu_\gamma \approx P_{\gamma\to\gamma} S_\gamma I_\gamma\ (\geq 1\ \mathrm{TeV}) \approx 2.5\ 10^{-3}\ \mathrm{event/s}, \qquad (6)$$

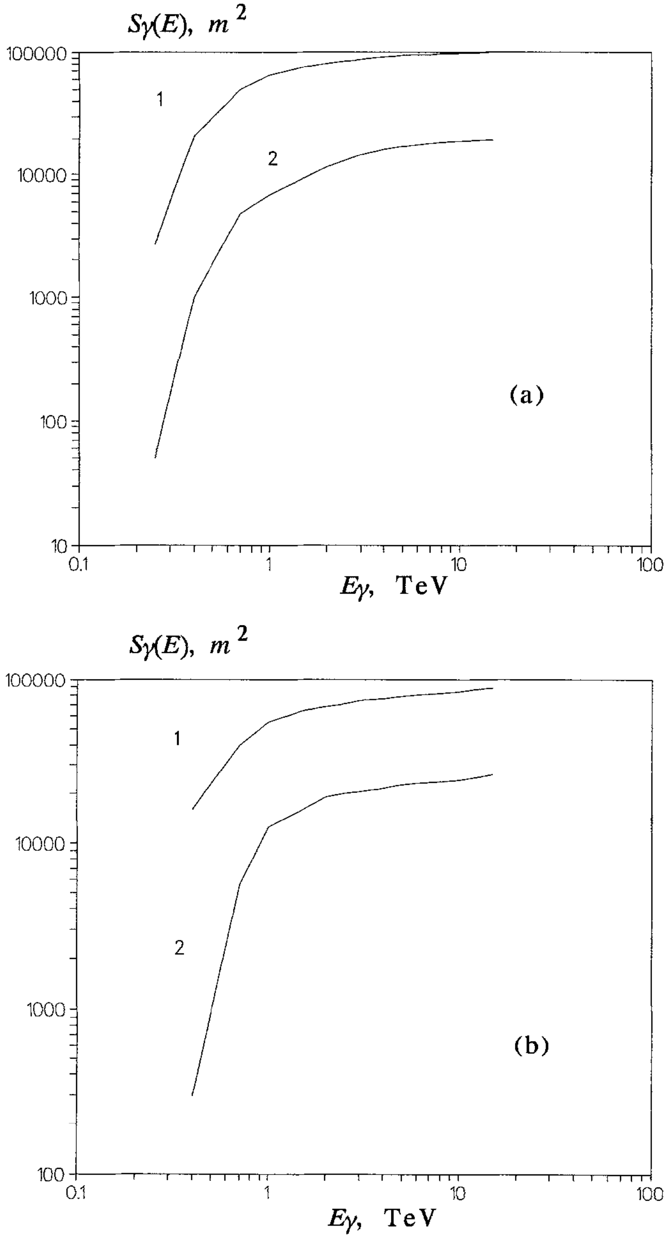


Fig.4. The effective collection area of gamma rays and protons for the system of 3 IACT. (a) l= 100 m, (b) l= 50 m. Curve 1— mode 2, curve 2 — mode 1.

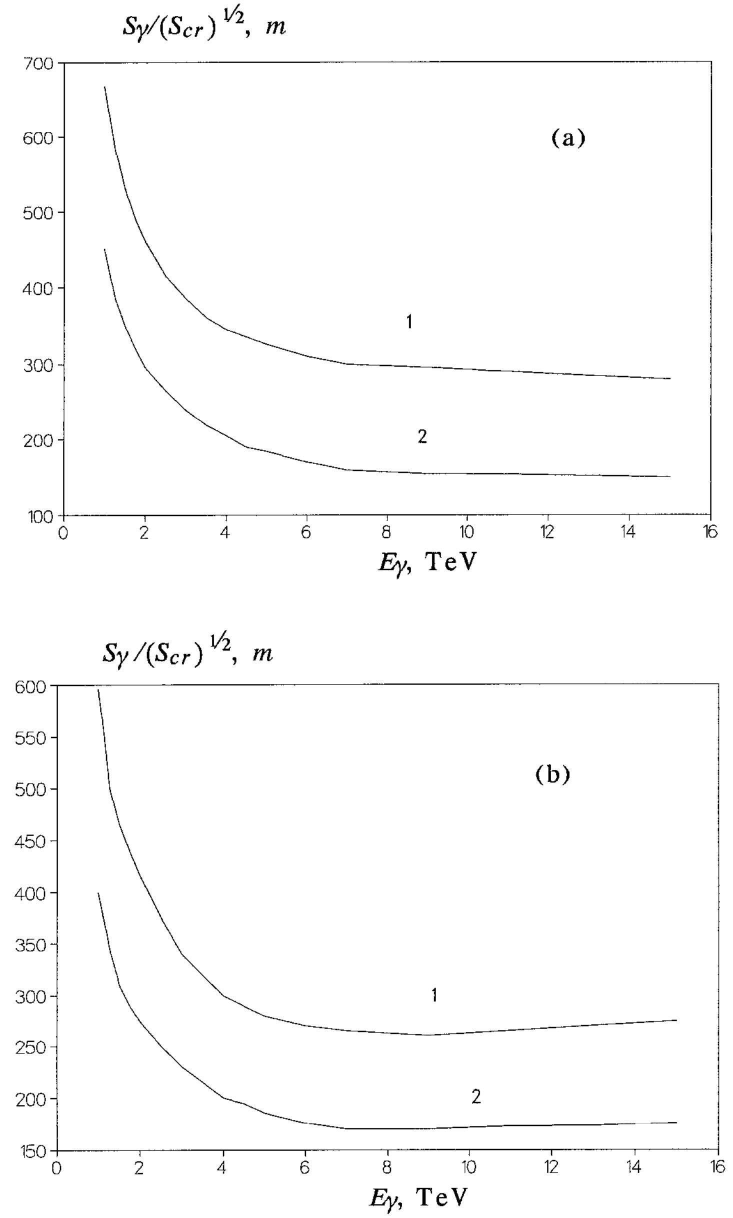


Fig.5. The ratio $S\gamma/\sqrt{S_{cr}}$ for the system of 3 IACT. (a) l = 100 m, (b) l = 50 m. Curve 1— mode 2, curve 2— mode 1.

Table 4. The energy resolution for the system of three IACT. Mode 1, l=50 m, q_0 = 9 ph.e. The power law index of gamma ray differential spectrum α_γ=2.25. E_t — the truth value of energy, E_m, δE_m— the mean value and fluctuations of the reconstructed energy, respectively.

E_t,TeV	1.0	1.5	2.5	4.0	7.0	10.0
E_m,TeV	1.0	1.5	2.61	4.03	7.01	10.0
δE_m,%	18	24	21	23	26	25

and for the cosmic rays

$$\nu_{cr} \approx P_{cr \to \gamma} S_{cr} I_{cr} \ (\geq 1 \text{ TeV}) \Delta\Omega \approx 2\ 10^{-3} \text{ event/s}. \quad (7)$$

Thus, if the flux of the gamma-rays above 1 TeV exceeds 10^{-11}photon/cm^2s then the absolute value of the detected gamma ray signal would exceed the cosmic rays background (S>B) and, consequently, it becomes possible to study with the imaging atmospheric technique strong VHE gamma ray sources under conditions practically free from the background.

For determination of the energy spectrum of gamma ray sources with a single IACT or an IACT system the measurement of the individual gamma-induced shower energy is needed (see Plyasheshnikov et.al.,1989; Lewis D.A. et.al.,1991). In the case of a single IACT the technique for such a measurement is developed in Plyasheshnikov et.al.,1989; Lamb,1989. Recently the technique Lamb,1989, has been successfully applied (Vacanti et.al.,1991) for the analysis of the gamma-radiation from the Cram Nebula.

In the case of a single IACT for the energy estimation the total number of registered Cherenkov photons and the shower impact parameter determined on the base of the image centroid position may be used. For several IACT's it is possible (see Konopelko,1990) to use for localization of the shower core a set of the main axis directions of the images registered by IACT's. This allows us to remote an uncertainity in the value of the impact parameter being significant in the case of a single IACT.

In table 4 we present the data on the estimation of the energy resolution of the system of 3 IACT's obtained by Monte Carlo simulations. These data correspond to the technique of the shower energy estimation (Plyasheshnikov et.al.,1989) with usage for the shower core location the method (Konopelko,1990).As can be seen from the table the energy resolution of the system should be about 20-25%.

6. Conclusion.

The theoretical predictions concerning the prospects of the imaging atmospheric Cherenkov technique, first of all from the point of view of effective CR background rejection, recently were confirmed in the observations realized by the 10 m Whipple telescope. Further step in the improvement of the imaging Cherenkov technique is associated with forthcoming systems of IACT's. At least two such installations are under construction now (Akerlof et al., 1990; Aharonian et al., 1991a).

The Monte Carlo simulations applied to the system of three IACT show that a significant progress in improvement of the VHE Cherenkov technique sensitivity could be achieved even with a moderate system of IACT's (several ACT's with limited number of channels of the Cherenkov light receivers and relatively moderate-size reflectors).

A successful application of the IACT systems gives an advance in the understanding of the complicated relativistic processes acting in astrophysical objects.

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