High-Resolution Cherenkov Telescopes for the Observation of High-Energy Gamma Rays

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Abstract

Imaging resolution of telescope optics and camera used for recent Cherenkov telescopes is usually limited to be only about 0.1 degree. Therefore, small size images generated by low energy gamma rays are difficult to detect by such telescopes. We simulated using an ideal telescope which has no optical aberration and very high resolution camera with very fine pixels to detect the images of the Cherenkov photons generated by high energy gamma rays.

As a result we found that the threshold energy decreased significantly and the angular resolution was improved. Such high resolution telescopes with 10 m diameter placed at high altitude of about 4000m will be useful to observe the energy region a around a few 10 GeV. New realistic solutions of telescope optics using Fresnel lenses to observe the Cherenkov images are shown.

1. Introduction

To clarify origins of high energy gamma rays and acceleration and production mechanism of elementary particles around their regions are very important issues to resolve the actively evolving universe.

Nevertheless the gamma-ray energy region of 1-100 GeV is important for such object, we have difficulty to observe them. The energy region 1-10 GeV will be explored by satellite experiments such as GLAST in near future, and solar tower experiments utilizing large mirror area such as CELESTE and STACEE have been observing the region of several 10 GeV. Imaging air Cherenkov telescope(IACT) experiments such as CANGAROO, Whipple, HEGRA have performed very important role at TeV region, and a new project HESS is coming up to observe the energy around ∼100 GeV. Fundamental idea of the IACT is fascinating to explore the gamma-ray sky.

Overall imaging resolution of Cherenkov images for recent IACT experiments are limited to be around 0.1 degree. The limitation is mainly caused by telescope optics which uses only a principal reflector consisting of many number

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of segmented mirrors, and by limited number of pixels made of photomultiplier tubes (PMTs).

We, therefore, tried to examine validity of high-resolution Cherenkov telescopes by the Monte Carlo simulation, and some results are shown in this paper.

2. What is the High-Resolution Cherenkov Telescope?

The high-resolution Cherenkov telescope in this paper means a Cherenkov telescope using an ideal optics and a high-resolution camera where the ideal optics means optics without any aberrations and the high-resolution camera means pixel size of the imaging camera is much smaller than the camera used for recent IACT experiments. The Monte Carlo simulations of air showers are basically performed using the CORSIKA code. The Cherenkov photons generated from the air showers are detected by the ideal Cherenkov telescope for which we assumed to use only positions and angles of the incident Cherenkov photons and we did not use any telescope optics to realize the ideal optics.

2.1. Camera Images for Different Telescope and Camera Resolution

Comparison of the images using the ideal optics and high-resolution camera is shown in Fig. 1 for which a 1 TeV gamma ray is injected vertically at the top of the atmosphere. The telescope is assumed to be placed at an altitude of 4300 m. As a segmented mirror optics, the CANGAROO-III Cherenkov telescope optics which uses 114 segmented mirrors with curvature radius of 16 m is assumed. From these figures it is expected that even small shower images occupied by only 1 or 2 pixels of coarse pixel camera can be exploited by the high-resolution telescopes.

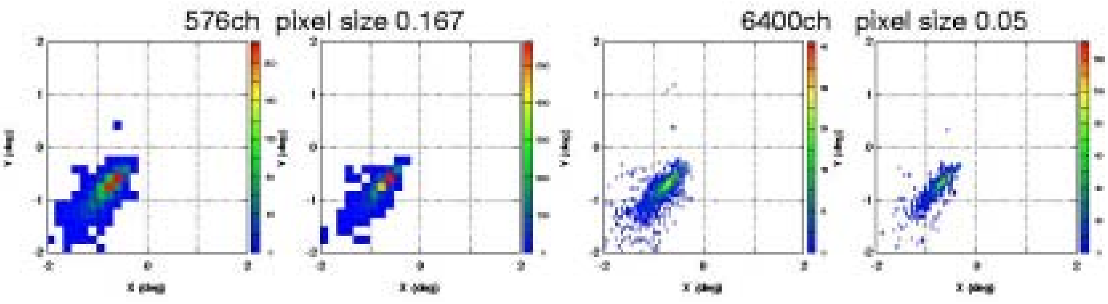

Fig. 1. Cherenkov images of the camera at the focal plane of the telescopes for different telescope resolution and camera resolution. F.O.V. of the camera is 4 degree $\times$ 4 degree. From left to right : a) Segmented mirror optics + pixel size of 0.167 degree. b) Ideal optics + pixel size of 0.167 degree. c) Segmented mirror optics + pixel size of 0.05 degree. d) Ideal optics + pixel size of 0.05 degree.

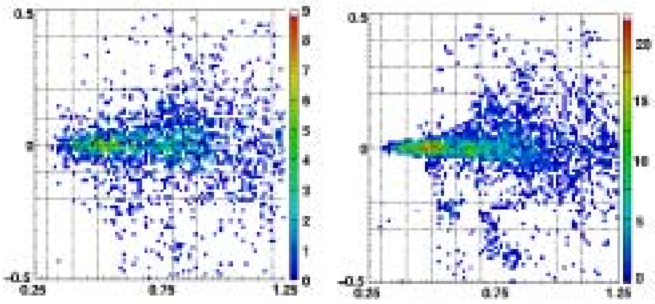

Fig. 2. Enlarged Cherenkov images for different optics for a 1 TeV gamma ray with the pixel size of 0.0125 degree. Left panel : Segmented mirror optics , Right panel : Ideal optics

2.2. Cherenkov images for Different Optics

Difference of the Cherenkov images between segmented optics and ideal optics is shown in Fig. 2. The Cherenkov photons at the central part of the image for the ideal optics can be well seen to be concentrating more than those for the segmented mirror optics. Therefore, the energy threshold can be expected to lower by using the high-resolution telescopes.

3. Simulation to estimate observation efficiency

3.1. Trigger Efficiency

We have simulated the trigger efficiency of gamma-ray events by the Monte Carlo method. Table 1 shows conditions of the simulation.

Obtained trigger efficiency as a function of gamma ray energy is shown in Fig. 3.

The results show that the threshold energy to have the trigger efficiency larger than 10 % is 170 GeV for the segmented mirror telescope of 10 m diameter with 576 ch coarse PMT camera at 0 m altitude, 75 GeV for the segmented mirror with the high- resolution camera, 35 GeV for ideal optics with high-reasolution camera.

The high-resolution telescopes make the energy threshold about a factor of 4 lower than the recently used IACT technique.

The threshold can be reduced by a factor of 2 by placing the telescopes to an altitude of 4300 m. Combining these techniques, the threshold can be reduced to around 20 GeV.

Energy range of incident gamma rays	between 10GeV and 1TeV
Incident zenith angle	0 degree
Observation altitude	0m , 4300m
Telescope diameter	10m
Trigger conditions	
F.O.V. of imaging camera	4 degree × 4 degree
Total number of pixels	576ch
Least number of photoelectrons / pixel for triggering	17 p.e.
Least number of pixels for triggering for pixel camera	3
Least number of pixels for triggering for HR camera	1

Table 1. Simulation conditions to estimate the observation efficiency.

3.2. Median of Alpha Distribution

Median of alpha distribution as a function of energy is shown in Fig. 3 (right panel). The parameter alpha is the angle between the long axis direction of the image and the direction of expected source. The high-resolution telescopes are more effective to reduce the alpha value at lower energy region, i.e. for smaller images.

3.3. Result

It is shown by the simulation that by utilizing the high-resolution Cherenkov telescope consisting of the ideal optics and high-resolution camera with a diameter of 10 m mirror at an altitude of 4300 m, gamma rays of energy region 20-100 GeV where it is important but difficult to observe can be observable.

4. Design Work to Approach the Ideal Optics

4.1. Optical Design Method

Recent IACT telescopes use optics consisting of only segment mirrors. To approach to the ideal optics of the Cherenkov telescopes, it is required to add more reflector or lenses. Wavelength of 300-600 nm , especially at 300-400 nm, of Cherenkov photons should be collected by the camera effectively.

To achieve it the optics should be simple, which is also important to reduce the construction cost.

To design the new optics we used optical design software, ZEMAX version XE (FOCUS Software Co.). Basic idea of the new optics we simulated is shown

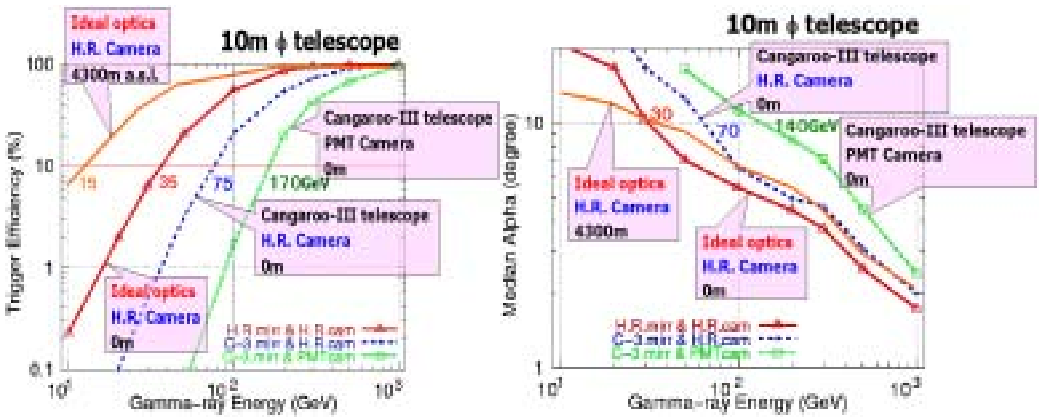

Fig. 3. Left panel : Trigger Efficiency, Right panel : Median of Alpha Distribution

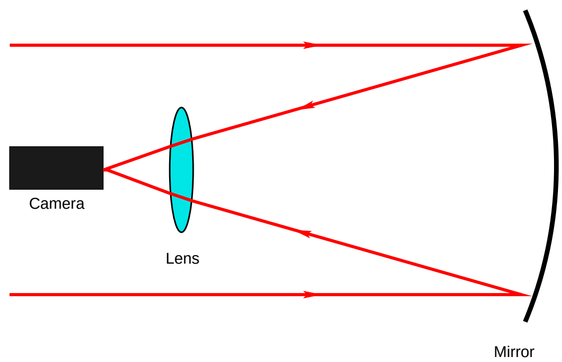

Fig. 4. Conceptual design to approach the ideal optics using simple optics.

in Fig. 4, where there are one large principal reflection mirror and 1 or 2 lenses in front of the camera. Two cases of spherical and paraboloidal mirrors for the principal mirror were simulated.

4.2. Results of Optical Design

Root mean square (rms) of the image spread for the spherical and paraboloidal mirrors as a function of incident angle of photons for various lenses are shown in Fig. 5.

Fresnel and aspherical lenses are tried to simulate for the lenses. F/1.0 is assumed for every optics.

Best optics were obtained for the case of using 2 Fresnel lenses for spherical principal mirror, for which the image spread was 0.024 degree at the incident angle of 1 degree. Similar results were obtained for the paraboloidal mirror.

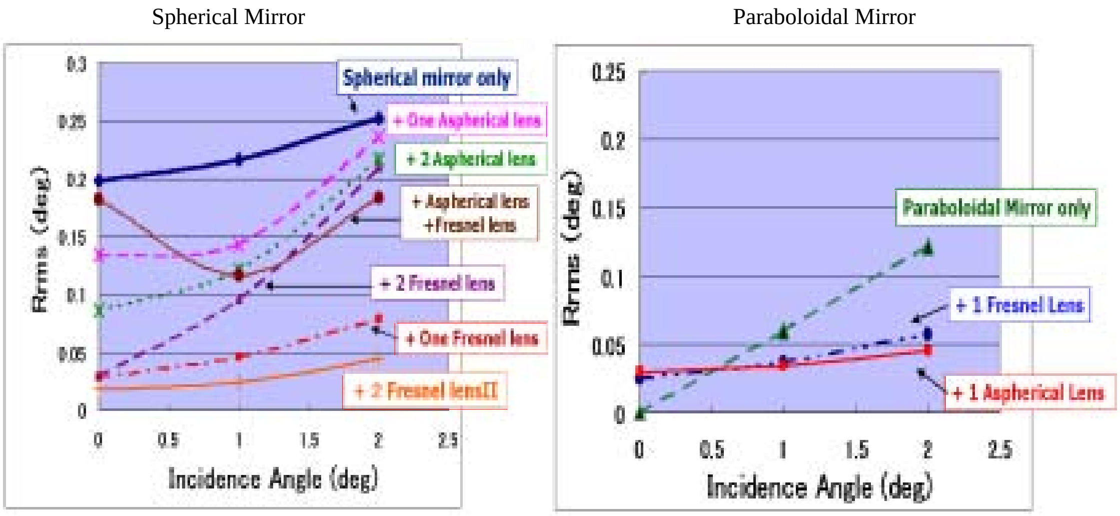

Fig. 5. Left panel : Image spread for spherical mirror for various cases of lens optics, Right panel : paraboloidal mirror.

5. Summary

We examined the validity of the high-resolution telescopes which consists of the ideal optics and high resolution camera, where the ideal optics was a new concept to examine the intrinsic resolution of the Cherenkov images. The obtained results show that the energy threshold decreases significantly by utilizing such telescopes.

We also tried to make new optics for the Cherenkov telescopes to approach the ideal optics. Some better solutions were obtained for the principal mirrors of spherical and paraboloidal shapes by using Fresnel and aspherical lenses. Better optics may be obtained in near future.