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Pachmarhi Array of Čerenkov Telescopes and its sensitivity

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Abstract. Pachmarhi Array of Čerenkov Telescopes (PACT) has been designed to search for celestial TeV $\gamma-$rays using the wavefront sampling technique. PACT, located at Pachmarhi, (latitude 22° 28′ N, longitude 76° 26′ E, altitude 1075 m) consists of 25 telescopes deployed over an area of 80 m × 100m. Each telescopes consists of 7 parabolic reflectors, each viewed by a fast phototube behind a 3° mask at the focus. The density and the arrival time of the photons at the PMT are recorded for each shower. The energy threshold and collection area of the array are estimated, from Monte Carlo simulations, to be $\sim$ 900 GeV and 10^5 m^2 respectively. The accuracy in determination of arrival angle of a shower is estimated to be about 0.1° in the near vertical direction. About 99% of the off-axis hadronic events could be rejected from directional information alone. Further, at least 75% of the on-axis hadronic events could be rejected using species sensitive parameters derived from timing and density measurements. These cuts on data to reject background would retain $\sim$ 44% of the $\gamma-$ray signal. The sensitivity of the array for a 5σ detection of $\gamma-$ray signal at a threshold energy of 1 TeV has been estimated to be $\sim 4.1 \times 10^{-12}$ photons cm^{-2} s^{-1} for an on source exposure of 50 hours. The PACT set-up has been fully commissioned and is collecting data. The details of the system parameters and sensitivity will be presented.

1 Introduction

Ground based atmospheric Čerenkov technique is, at present, the only way by which VHE $\gamma-$rays from astronomical objects are detected. Using this technique TeV $\gamma-$rays have been detected successfully from a number of galactic sources including pulsars, supernova remnants etc as well as from extra-galactic objects which are AGNs of blazar class. There are a number experiments based on this technique operating across the globe using either angular imaging technique or wavefront sampling technique. These are two complementary ways of studying the Čerenkov emission from air showers generated by $\gamma-$rays from astronomical sources. Imaging technique has been successfully exploited by several experiments including Whipple, CAT, CANGAROO, HEGRA, TACTIC etc. On the other hand, the experiments like CELESTE, STACEE, SOLAR-2, GRAAL and PACT are based on wavefront sampling technique. These experiments consist of an array of Čerenkov telescopes which sample the Čerenkov pool at the observation level. These experiments measure the arrival time of Čerenkov shower front and Čerenkov photon density at various locations in the Čerenkov pool. In this paper we discuss some of the design aspects and performance parameters of Pachmarhi Array of Čerenkov Telescopes or PACT, which is based on wavefront sampling technique.

2 PACT : Instrument Details

Pachmarhi Array of Čerenkov Telescopes is located at Pachmarhi (latitude 22° 28′ N, longitude 76° 26′ E, altitude 1075 m) in Central India. This array consists of 5 × 5 array of 25 Čerenkov telescopes spread over a rectangular area of 80 $m \times 100$ m (see Figure 1). Spacing between the telescopes is 20 m in E-W direction and 25 m in N-S direction. Each telescope consists of seven para-axially mounted parabolic reflectors of diameter 0.9 m each with f/d ratio being ~ 1 (see Figure 2). These reflectors are fabricated indigenously and their optical quality is such that the size of the image of a point source is $\leq 1°$. They are back-coated and their reflectivity in visible range is $\sim$ 70%. These reflectors are mounted in hexagonal pattern and total reflector area per telescope is $\sim$ 4.45 m^2. A fast phototube of the type EMI9807B is mounted at the focus of each reflector. Field of view defined by the photo-cathode diameter is $\sim 3°$ FWHM.

Telescopes are equatorially mounted and each telescope is independently steerable in both E-W and N-S direction within ±45°. The movement of telescopes is remotely controlled by Automatic Computerized Telescope Orientation

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Fig. 1. Panoramic view of Pachmarhi Array of Čerenkov Telescopes. Several telescopes and stations housing electronics for various sectors can be seen. Control room is at the centre of the array.

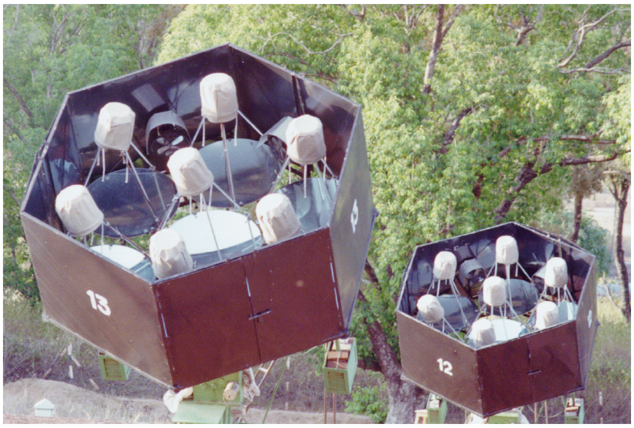

Fig. 2. Two telescopes from PACT. Each telescopes consists of seven para-axially mounted mirrors arranged in hexagonal pattern. There is a phototube at the focus of each mirror.

System (ACTOS). The hardware consists of a semi-intelligent closed loop stepper motor system which senses the angular position using a gravity based transducer called clinometer with an accuracy of $1'$. The two clinometers, one each in N-S and E-W direction, are accurately calibrated using stars. The system can orient to the putative source with an accuracy of $\sim$ (0.003 $\pm$ 0.2). The source pointing is monitored at an accuracy of $\sim$0.05° and corrected in real time whenever the error exceeds 0.05°.

High voltages to individual phototubes are applied through a computerized control system (called CARAMS, Computerized Automated Rate Adjustment and Monitoring System) and voltages as well as count rates from individual phototubes are continuously monitored. Array is divided into four sub-groups or sectors of six telescopes each for data acquisition. At the centre of each sector there is a field signal processing centre (FSPC). Pulses from phototubes are brought to the respective stations using low attenuation coaxial cables of the type RG213, of length $\sim$ 40 m. These pulses are processed by front end electronics in the FSPC and informations such as Čerenkov photon density (ADC) and arrival time of Čerenkov shower front at the mirror given by TDC (resolution 0.25 ns) and event arrival time (UTC) correct to 1 μs are recorded. The ADC and TDC data are recorded for six peripheral mirrors of each telescope. In addition to this, some information relevant to the entire array is recorded by master signal processing centre (MSPC) in the control room at the centre of the array. This information includes relative arrival time of Čerenkov shower front at individual telescopes, absolute arrival time of the shower front accurate to μs derived from a real time clock. The real time clocks (RTC) in FSPC's and MSPC's are synchronized with each other and with a GPS clock. Using RTC information events recorded in individual FSPC's are collated with those recorded in MSPC offline. Data recording in MSPC as well as in FSPC is carried out using networked Linux based system. Details of the data acquisition system are given elsewhere (Bhat *et al.*, 2001a). This array is fully operational since December, 2000. Preliminary results obtained from observations carried out by this array on sources including crab nebula and mkn 421 are discussed elsewhere (Vishwanath *et al.*, 2001 and Bhat *et al.*, 2001b).

3 Energy threshold of PACT

The night sky background (NSB) is the limiting factor in detecting Čerenkov photons from low energy primaries and this decides the low energy threshold of the experiment. The NSB measured at Pachmarhi, over the range of the spectral response of the phototube, is $\sim 3.3 \times 10^8\ ph\ cm^{-2}\ s^{-1}$.

In order to estimate the expected performance of the array, large number of $\gamma-$ray and proton showers are simulated taking into account various design features of the array. For $\gamma-$ray primaries, energies are chosen from a power law spectrum with a slope of -1.4 over the range of 500 GeV to 20 TeV. Whereas for protons, slope of the spectrum is -1.66. Factors like atmospheric attenuation, reflectivity of mirrors, quantum efficiency of phototubes, attenuation in cables etc.

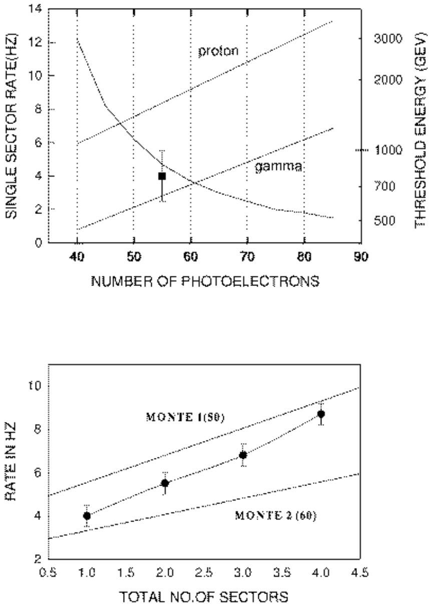

Fig. 3. Upper panel shows single sector trigger rate vs no. of photo-electrons per telescope. Curve corresponds to simulated data. Observed trigger rate is indicated by a point with error bar. Also shown in figure is the threshold energy (scale on right) as a function of number of photo-electrons per telescope for $\gamma-$rays and protons. Lower panel shows the observed trigger rate vs number of sectors. Also shown are the expected trigger rates with photo-electron threshold of 50 and 60 per telescope, based on simulations.

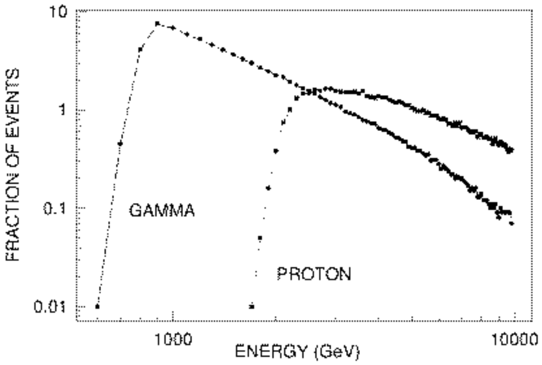

Fig. 4. Differential energy spectrum of triggered simulated events for $\gamma-$ray and proton initiated showers. The peak of the energy spectrum or energy threshold is about 900 GeV for $\gamma-$rays.

are taken into account in simulations. Same trigger criteria as used in the experiment are applied to the simulated events. In the experiment, the seven individual mirror outputs are added to get the analog sum called the 'royal sum' for each telescope. Each sector has six royal sum pulses corresponding to six telescopes. The royal sums are discriminated to yield a counting rate of $\sim 40\ kHz$. A trigger is generated when at least four out of six royal sums are present. From the simulated data, the trigger rates were obtained for each sector for various photo-electron thresholds ranging from 35 to 100. The variation of trigger rate as a function of photo-electron threshold is shown in Figure 3 (upper panel). The observed trigger rate is also shown. It can be seen that the trigger rate corresponds to the threshold of about 55 photo-electrons per telescope.

Lower panel of Figure 3 shows the experimental trigger rates when the number of sectors increased from 1 to 4. The overall trigger rate essentially varies as the square root of total mirror area. It increases from about 4 Hz for a one sector to 9 Hz when all the four sectors are used. Also shown in the figure are the expected trigger rates from simulated data, for photo-electron thresholds of 50 and 60 per telescope. It can be seen that for all the cases, from single sector trigger rate to the entire array, experimental data is consistent with the trigger rate of about 55 photo-electrons per telescope.

All the simulated events are again examined taking into account photo-electron threshold of 55 photo-electrons per telescope. Figure 4 shows the differential energy spectra for both $\gamma-$ray and proton events. The peaks of these distributions give the energy thresholds of the array. These are 900 GeV for $\gamma-$rays and 2250 GeV for protons.

For each simulated event, the collection area is calculated. Figure 5 shows the collection radius for single and all the sectors of the array for showers initiated by $\gamma-$rays and protons. It should be noted that the relatively large collection radius (defined as the radius containing 67% of the events) of the PACT is essentially due to the large extent of the array. The saturation at large values of collection radius occurs because the events were generated only upto 300 m radius.

4 Sensitivity of PACT

Sensitivity of the experiment is minimum detectable flux of $\gamma-$rays in presence of background of cosmic rays. It is related to the signal to noise ratio given by

$$\frac{S}{N} \propto \sqrt{\frac{A_p T}{\Omega} E^{0.85-G}} \qquad (1)$$

where G is the $\gamma-$ray spectral index, A_p the effective collection area, T observation duration and Ω the solid angle of the telescope.

For PACT, 5σ sensitivity for an observation duration of 50 hours, above energy threshold of 1 TeV, is estimated to be $\sim 4.1 \times 10^{-11}\ ph\ cm^{-2}\ s{-}1$ for no background rejection. The angular resolution of PACT is estimated to be $\sim 0.1^\circ$ (Majumdar *et al.*, 2001). This allows the rejection of about 99% of off-axis background events using the arrival angle information alone. According to simulation studies, it is possible

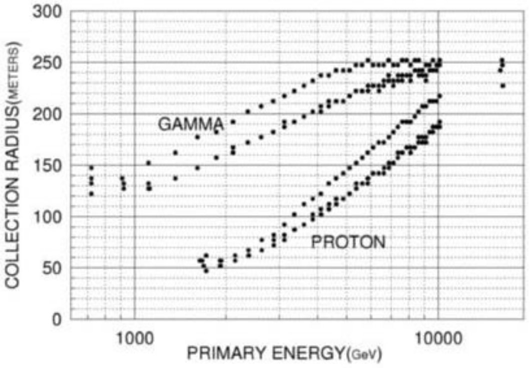

Fig. 5. Collection radius *vs* primary energy for showers initiated by $\gamma-$rays and protons. For both the species lower curve is for single sector and upper one for entire array.

to reject a significant fraction of cosmic ray proton showers based on the information about arrival time of shower front at various telescopes (Chitnis and Bhat, 2001) and fluctuations in density of Čerenkov photons at different telescopes (Bhat and Chitnis, 2001). We assume that at least 75% of the background showers can be rejected using simulation based cuts. It may be mentioned here that the rejection efficiency of cosmic rays is much better than what is assumed here, as per simulation studies. However, we have not yet applied these cuts to the actual data. Hence we assumed an extremely conservative figure of hadron rejection efficiency. As a result, at least 99.75% of the cosmic ray showers enetering the field of view could be rejected. Accordingly, the sensitivity improves to $\sim 4.1 \times 10^{-12}\ ph\ cm^{-2}\ s^{-1}$. The efficiency of retaining $\gamma-$ray showers while exercising cuts for rejecting hadronic showers is estimated to be $\sim$ 44%. Based on these conservative estimates, the minimum duration of observation required to detect Crab nebula at a significance level of 5σ is $\approx$ 8 hours (4 hours ON source and 4 hours OFF source). The sensitivity of PACT is compared with the present and future atmospheric Čerenkov experiments in Figure 6.

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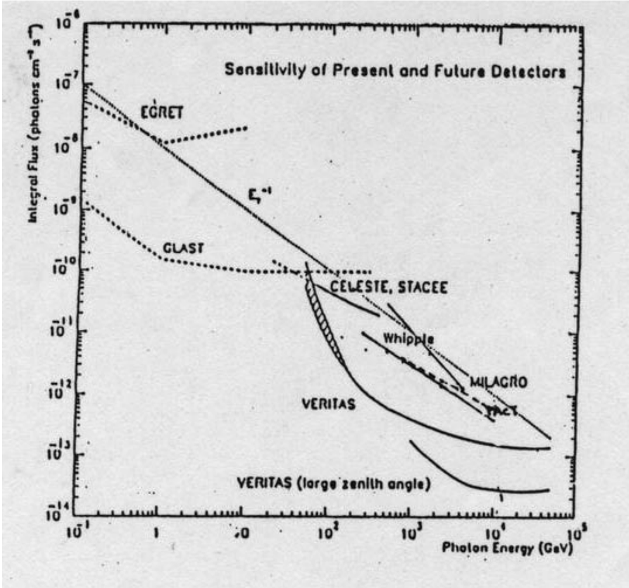

Fig. 6. Sensitivity of PACT and various present and future experiments.

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