Pachmarhi Array of Čerenkov Telescopes

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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, India, consists of 25 telescopes deployed over an area of 80 m $\times$ 100m. Each telescope consists of 7 parabolic reflectors which are mounted paraxially and each one is viewed by a fast phototube behind a 3° (FWHM) mask at the focus. The density and the arrival time of the photons at the PMT are recorded for each shower. The threshold energy for vertically incident $\gamma-$rays and maximum collection area of the array are estimated, from Monte Carlo simulations, to be $\sim$ 800 GeV and $\sim 10^5$ m^2 respectively. Accuracy in the determination of arrival direction of a shower is estimated to be 0.04° 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 an energy of 1 TeV has been estimated to be $\sim 4.4 \times 10^{-12}$ 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, its sensitivity and results on some recently observed sources are presented.

1. Introduction

Atmospheric Čerenkov technique is the only method which has been successfully used to probe the sky in the TeV energy band of the electromagnetic spectrum. Using this technique, TeV $\gamma-$rays have been detected at a high confidence level from a number of galactic sources including plerions and supernova remnants as well as from extra-galactic objects which are AGNs of blazar class.

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There are two complementary ways to look at the atmospheric Čerenkov light resulting from extensive air-showers generated by a primary incident at the top of the atmosphere, *viz.* (a) *Angular imaging* and (b) *Spatial sampling.* The former method is by now an established one and is exploited successfully by several experiments including Whipple, CAT, Cangaroo, HEGRA, TACTIC etc. The experiments like CELESTE, STACEE, SOLAR-2, GRAAL and PACT exploit the second method known as the wavefront sampling technique (Ong *et. al.*,1998). These experiments measure the arrival time of Čerenkov shower front and photon densities at various locations in the Čerenkov light pool. We will discuss some of the design aspects, performance parameters of PACT and preliminary results from it.

2. Pachmarhi Array of Čerenkov Telescopes (PACT)

PACT is located at Pachmarhi (latitude 22° 28′ N, longitude 76° 26′ E, altitude 1075 m) in Central India. This array is in the form of 5 × 5 matrix and consists of 25 Čerenkov telescopes spread over a rectangular area of 80 m × 100 m (Bhat *et. al.*, 2000). Spacing between the telescopes is 20 m in E-W direction and 25 m in N-S direction. Every telescope consists of seven para-axially mounted parabolic reflectors of diameter 0.9 m each with $f/d \sim 1$. These reflectors are fabricated indigenously and the size of the image of a point source is $\leq 1°$. They are back-coated and their effective reflectivity in the visible range of the electromagnetic spectrum is $\sim$ 70%. The total reflector area per telescope is $\sim$ 4.45 m^2. A fast phototube (EMI9807B) is mounted at the focus of each reflector. The field of view, defined by the photo-cathode diameter, is $\sim$ 2.9° 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 System (ACTOS) (Gothe *et.al.*, 2000). The hardware consists of a semi-intelligent closed loop stepper motor drive 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 ± 0.2)°. The source pointing is monitored at an accuracy of $\sim$0.05° and corrected in real time whenever the error exceeds this value.

High voltages to phototubes are applied through a computerized control system called CARAMS (Computer Automated Rate Adjustment and Monitoring System) individually. Voltage as well as count rate from individual phototubes are continuously monitored during a run. The 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 and 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 relative arrival time of Čerenkov shower front at the mirror (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, there is a master signal processing centre (MSPC) in the control room at the centre of the array. It records information like 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 and some housekeeping information. All 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 off-line. Data recording in MSPC as well as in FSPC is carried out using networked Linux based data acquisition system using PCs.

The pulses from 7 PMTs in a telescope are added linearly to form a telescope sum pulse called *royal sum*. Each *royal sum* from the 6 telescopes in a sector are suitably discriminated (typical *royal sum* rates $\sim$ 30-50 kHz.) and a trigger is generated by a coincidence of any 4 of these 6 *royal sums*. The typical event rate is $\sim$ 2-5 Hz per sector and $\sim$ 9 Hz for the whole array (4 sectors).

3. Performance Studies for PACT

The night sky background (NSB) is the limiting factor in detecting Čerenkov photons from the primaries and this dictates the 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, a large number of $\gamma-$ray and proton showers are simulated taking into account various design features of the array. Factors like atmospheric attenuation, reflectivity of mirrors, quantum efficiency of phototubes, attenuation in cables etc. are taken into account in simulations. Same trigger criteria as used in the experiment are applied to the simulated events. From the simulated data, the trigger rates were obtained for each sector for various photoelectron thresholds ranging from 35 to 100. The variation of trigger rate as a function of photoelectron threshold is shown in Figure 1(a). The observed trigger rate is also shown and it corresponds to the threshold of about 55 photo-electrons per telescope (Chitnis *et. al.*,2001). 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. Figure 1(b) shows experimental trigger rates as a function of number of sectors of PACT. The overall trigger rate essentially varies as the square root of total mirror area. It increases from about 4 Hz for 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.

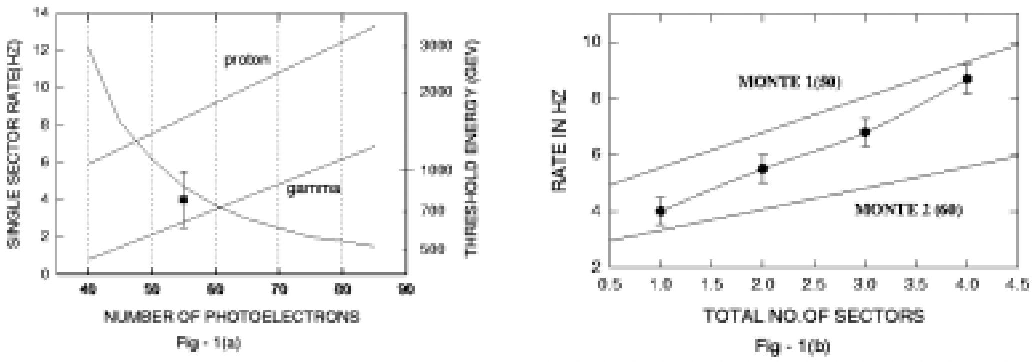

Fig. 1. *(a)*: Single sector trigger rate *vs* no. of photo-electrons per telescope. Curve corresponds to simulated data. Observed trigger rate is indicated by a point with error bar. Also shown in figure is the threshold energy (scale on right) as a function of number of photo-electrons per telescope for $\gamma-$rays and protons. *(b)*: Observed trigger rate *vs* number of sectors. Also shown are the expected trigger rates for photo-electron threshold of 50 and 60 per telescope, based on simulations

Sensitivity is defined as the minimum detectable flux of $\gamma-$ rays in the presence of background (cosmic rays). For PACT, 5σ sensitivity for an observation duration of 50 hours above 1 TeV energy threshold, is estimated to be $\sim 3.7 \times 10^{-11}\ ph\ cm^{-2}\ s^{-1}$ for no background rejection. This is for observations using a single sector.

However, it is possible to improve the signal to noise ratio of the experiment if the direction of arrival of primary particle is estimated accurately. For this, the angular resolution has to be small. It is then possible to reject a large fraction of cosmic rays from direction information alone. The accuracy in timing measurement has been estimated from data to be 1 ns. The arrival direction of a shower is determined by measuring the relative arrival time of Čerenkov photon front at each telescopes accurately and reconstructing the shower front. We assume the front to be a plane and fit the measured relative arrival time of Čerenkov photons to get the direction of shower axis. The angular resolution of the array

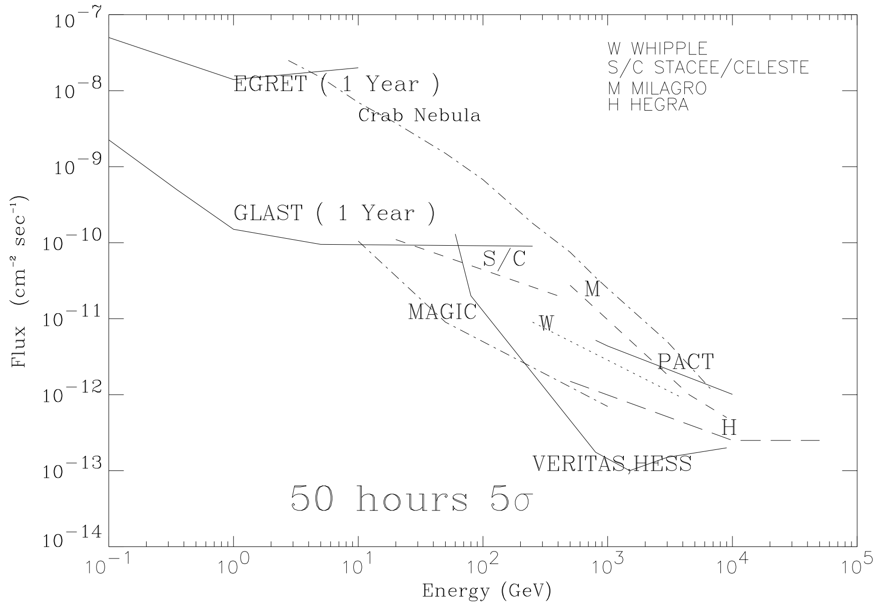

Fig. 2. Sensitivity of PACT and various present and future experiments

has been estimated using both *royal sum* pulses and individual mirror information as $0^{\circ}.24$ and $\sim 2.4'$ respectively (Majumdar *et. al.*,2002).

From simulation studies, it has been shown to be possible to reject a significant fraction of cosmic ray showers based on the information about arrival time of shower front (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 on-axis background showers can be rejected using simulation based cuts. Assuming an extremely conservative figure of hadron rejection efficiency, at least 99.75% of the cosmic ray showers entering the field of view could be rejected. Accordingly, the sensitivity improves to $\sim 4.4 \times 10^{-12}$ $ph\ cm^{-2}\ s^{-1}$. 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 ≈ 6 hours (3 hours ON source and 3 hours OFF source).

4. Observational Summary

Observations have been carried out on a number of sources *viz.* Crab pulsar, Mkn 421, Mkn 501, PSR0355, Geminga, 1ES1426+42.8 and other potential TeV sources. Crab nebula has been observed for a total number of 95 hours of

ON source and 50 hours of OFF source data since November 1999. The details about the analysis and the corresponding flux from the Crab nebula is given in the adjoining paper.

The nearest blazar Mkn 421 (z=0.03) has been observed by PACT (using 12 telescopes in the southern half of the array during January 2000 and all 4 sectors during January 2001). We have a total of 73.3 hrs of ON source data and 50.6 hrs of OFF source data during the season January 2000 to March 2000 while we have logged 45.6 hrs of ON source data and 39.7 hrs of OFF source data from January 2001 until end of February 2001. A preliminary analysis of the data shows flaring activity in both the seasons as reported by other groups (Gouiffes and Degrange, 2000, Boerst and Remillard, 2001). Evidence of nightly variability has been observed and the variability measurements by PACT are correlated with those of CAT and CELESTE during Jan 2000 flare and with those of HEGRA CT1 during Jan 2001 flare (Bhat *et. al.* 2001).

On 6th April, 2002, ASM detected a hard, brief, bright (peak 5-12 flux $\sim$ 2 Crab) X-ray flare which was tentatively identified as a GRB. We also observed this source for any probable TeV afterglows on 3 occasions, *viz* 8th, 9th and 10th of April. 12 telescopes were tracking the source while the remaining 12 were tracking a background region and the data were collected for 207 mins. A preliminary analysis of data shows no significant excess from the source.

5. References

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