# 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, (latitude 22° 28′ N, longitude 76° 26′ E, altitude 1075 m) consists of 25 telescopes deployed over an area of 80 m × 100m. Each telescope 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 $\sim$ 850 GeV and $10^5$ m$^2$ respectively. The accuracy in determination of arrival angle 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 $5\sigma$ 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, its sensitivity and results on some recently observed sources will be presented.

## Introduction

Atmospheric Čerenkov technique is the only method which has been successfully used to probe the sky in the TeV energy band. Using this technique, TeV $\gamma-$rays have been detected successfully at a high confidence level 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 two complimentary 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.* While 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 wavefront sampling technique (Ong *et. al.*,1998). The latter 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 and preliminary results from PACT.

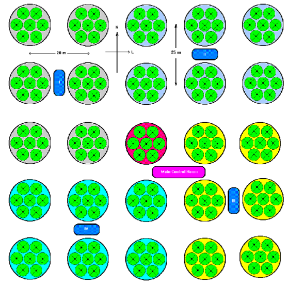

Figure 1. Layout of Pachmarhi Array of Čerenkov Telescopes. The array is divided into four sectors of six telescopes each. Sectors are numbered as I, II, III and IV. Main control room is at the center of the array.

## PACT Array

- Pachmarhi Array of Čerenkov Telescopes (PACT) consists of 5 × 5 array of 25 telescopes spread over a rectangular area of 80 m × 100 m (Bhat *et. al.* 1998)
- The array is divided into 4 sectors with 6 telescopes in each
- At the center of each sector there is a field signal processing center(FSPC), whereas at the center of the array information relevant to the entire array is recorded in the master signal processing center(MSPC)
- Each telescope consists of seven parabolic mirrors of diameter 0.9 m each with f/d $\sim$ 1
- Total reflector area per telescope $\sim 4.45m^2$
- Each mirror is looked at by a fast PMT behind a 3° circular mask
- The pulses from 7 PMTs are added linearly to form a telescope pulse called *'royal sum'* pulse.
- A coincidence of any 4 out of 6 telescopes in a sector generates the event trigger
- Event trigger rate for a sector is $\sim$ 2-5 Hz
- For each event TDC (timing) and ADC (density) information of 6 peripheral mirrors in each telescope are recorded. Relative arrival times of telescope trigger pulses and information on triggered telescopes are recorded in central control room along with other housekeeping information.
- All the telescopes are equatorially mounted and each telescope is independently steerable in both E-W and N-S direction within ±45° The movement of the telescopes is controlled by a low cost control system called Automatic Computerized Telescope Orientation System (ACTOS) (Gothe *et.al.*, 2000) The hardware consists of a semi-intelligent closed loop stepper motor system which senses the angular position using a *gravity based transducer* called clinometer.
- The two clinometers one in N-S and other in E-W direction are accurately *'calibrated'* using stars. The system can point to a source with an accuracy of $\sim (0.003 \pm 0.2)$ degrees. The source *pointing* is monitored with an accuracy of $\sim$ 0.05 degrees in real time.
- High Voltage to PMTs fed through CAEN HV Controller in central control room and regulated through *computer automated system*, (CARAMS)
- Alignment of mirrors is checked using Bright Star Scan and it is ensured that all the mirrors in a telescope are looking at the same region of the sky with an accuracy of 0.2 degrees
- The absolute arrival time of an event is recorded accurate to $\mu$s derived from a real time clock (RTC). RTC s in FSPC and MSPC are synchronized with each other and with a GPS clock
- Data Recording in FSPC as well as in MSPC is carried out using networked Linux based system

## Performance Studies for PACT

The night sky background (NSB) is the limiting factor in detecting Čerenkov photons from the primaries and this decides 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. 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 -1.65. 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 2 (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. (Chitnis *et. al.*,2001)

Lower panel of Figure 2 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.

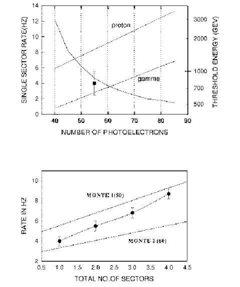

Figure 2. Top: Upper panel shows single sector trigger rate *vs* no. of photo-electrons per telescope. Curve corresponds to simulated data. Observed trigger rate is indicated by a point with error bar. Also shown in figure is the threshold energy (scale on right) as a function of number of photo-electrons 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

Figure 3 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 850 GeV for $\gamma-$rays and 2250 GeV for protons.

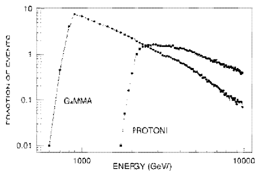

Figure 3. Differential energy spectrum of triggered simulated events for $\gamma-$ray and proton initiated showers. The peak of the energy spectrum or energy threshold is about 850 GeV for $\gamma-$rays

Sensitivity is defined as the minimum detectable flux of $\gamma-$ rays in presence of background (cosmic rays). For PACT, $5\sigma$ 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

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. To estimate the arrival direction accurately, the angular resolution has to be small. It is possible to reject a large fraction of cosmic rays from direction information alone if the angular resolution is small.

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 a plane, normal to which gives the direction of shower axis. Using the plane front approximation the angular resolution of the array has been estimated using both *royal sum* and individual mirror information.

Angular Resolution has been estimated to be 0°.24 using *Royal Sum* pulses and $\sim 2.4'$ using *individual mirror* information. (Majumdar *et. al.*,2002)

From simulation studies, it has been found out that it is possible to reject a significant fraction of cosmic ray 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. Assuming an extremely conservative figure of hadron rejection efficiency, 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 excercising 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 $5\sigma$ is $\approx$ 8 hours (4 hours ON source and 4 hours OFF source)

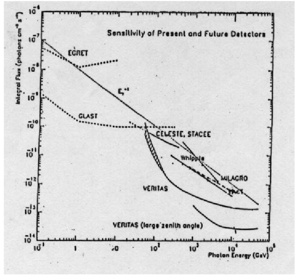

Figure 4. Sensitivity of PACT and various present and future experiments

## Observation 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 since November 1999. A total number of 75 hours of ON source and 41 hours of OFF source data have been used for analysis. The excess from the source direction amounts to 14933 ± 687 events yielding a excess event rate of 3.34 ± 0.15 per minute. This translates to a flux of about $3.7 \times 10^{-11}$ cm$^{-2}sec^{-1}$ above a threshold of 850 GeV.

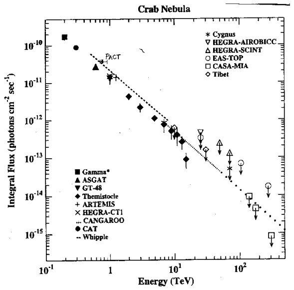

Figure 5. Integral Energy Spectrum of Crab Nebula

The nearest blazar Mkn 421 (z=0.03) has been observed by PACT (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 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)

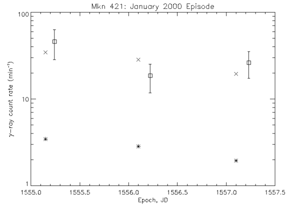

Figure 6. The $\gamma$-ray count rate from Mkn 421 as a function of epoch during January 2000. The count rate observed by CAT during January 2000 are shown as asterisks. These are re-plotted after multiplying by 10 (shown as crosses) for comparison of the variability in the two independent observations.

Figures 6 and 7 show the plot of $\gamma-$ ray counting rate as a function of epoch during both the episodes.

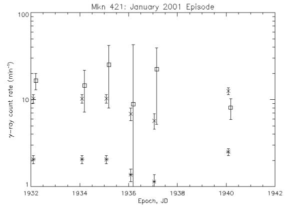

Figure 7. The $\gamma$-ray count rate from Mkn 421 as a function of epoch during January 2001. The count rate observed by observed HEGRA CT1 during January 2001 are shown as asterisks. These are re-plotted after multiplying by 5 (shown as crosses) for comparison of the variability in the two independent observations.

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 the source for any probable TeV afterglows from the source on 3 days, *viz* 8th, 9th and 10th of April. The source was observed in ON/OFF mode and data was collected for 207 mins. A preliminary analysis of data shows no significant excess from the source.

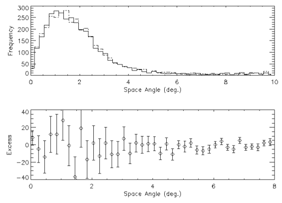

Figure 8. The upper panel shows space angle distributions of the source (solid line) and background (dotted line). The lower panel shows excess as a function of space angle. The total excess was 26 ± 82.7

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