Optical Observations of the Crab Pulsar using the first H.E.S.S. Cherenkov Telescope

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Abstract

For the understanding of the mechanisms of particle acceleration in pulsars, it is necessary to determine the high energy cutoff of the pulsed emission. In order to derive upper limits (or detections) on the pulsed emission in the TeV energy range using Cherenkov telescopes, typically data taken over periods of months or even years are superimposed. It is therefore necessary to use a time capture system and analysis tools which provide a base for pulsar phase analysis which is stable over a time-scale of years. We have built a device consisting of a photomultiplier tube with a fast current digitization system and components of the timing system of the H.E.S.S. experiment, which allows to measure pulsed optical emission making use of the large mirror area of Cherenkov telescopes. The system was installed into the first H.E.S.S. Cherenkov telescope in January 2003, where data was taken over 8 nights on the Crab and Vela pulsars. Optical pulsation from the Crab pulsar could be measured with observation times as short as a second. This system can therefore be used to determine the pulsar phase and to monitor the short term and long term stability of the timing system of the H.E.S.S. experiment.

1. Introduction

The new generation of ground based gamma-ray experiments currently under construction will provide improved sensitivity and thresholds in the sub-100 GeV region. One of the science goals of these experiments (H.E.S.S., MAGIC, CANGAROO, VERITAS) is to investigate the upper energy range for pulsed emission from EGRET pulsars.

Detections or upper limits on pulsed emission will likely involve the combination of data taken over months and even years. It is therefore necessary to prove the long term stability of the timing systems used by these experiments and also the proper performance of the analysis software. It should also be noted that contemporary ephemerides are not always available and that many of the pulsars of interest suffer frequent glitches. There is, therefore, a clear motivation

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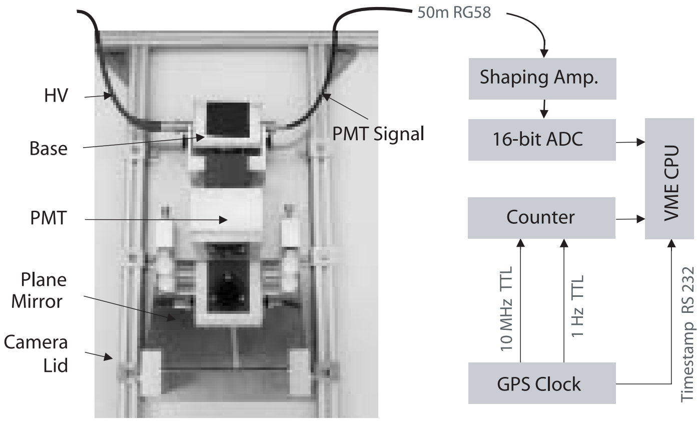

Fig. 1. Mechanical and electronic setup of the experiment.

for regular optical monitoring of pulsars by gamma-ray observatories.

The goal of the experiment described here was to develop and demonstrate an apparatus for fast timing measurement of optical signals to be used for monitoring the timing system of the H.E.S.S. experiment. Previous optical fast timing measurements are described in [1,2].

2. Experimental Method

The H.E.S.S. Experiment is an array of four Cherenkov telescopes with 15 m focal length and 107 m^2 mirror area, located in Namibia (23°16′ S, 16°30′ E, at 1800 m). The optical properties of the H.E.S.S. telescopes are described in [3].

The experiment described here utilized the first complete H.E.S.S. telescope and a custom-built detector installed on the closed lid of the Cherenkov camera. A silver coated plane mirror mounted at 45° to the telescope axis was used to place a lid-mounted photomultiplier tube (PMT) in the centre of the focal plane of the primary mirror. An aperture stop limited the field of view of the PMT to 23 mm (equivalent to 5′), matched conservatively to the point-spread-function (PSF) of the telescope. The average spectral sensitivity (quantum efficiency × reflectivity of primary and secondary mirrors) in the 300-600 nm range was 0.11.

The PMT (Photonis XP2960 with passive base) signal was read out via a shaping amplifier (FWHM of response $100\,\mu$s) and digitized using a 16-bit ADC, sampling at 20 kHz. Each sample is accompanied by a timestamp derived from a GPS clock (Meinberg 167, precision $< 1\,\mu$s) via a custom-built VME counter module. The anode signal was DC coupled in order to easily measure background light levels as well as pulsation. See Figure 1 for details.

3. Measurements

To achieve the required tracking precision of $\sim 1'$ it was necessary to make online corrections for atmospheric refraction and bending in the arms of

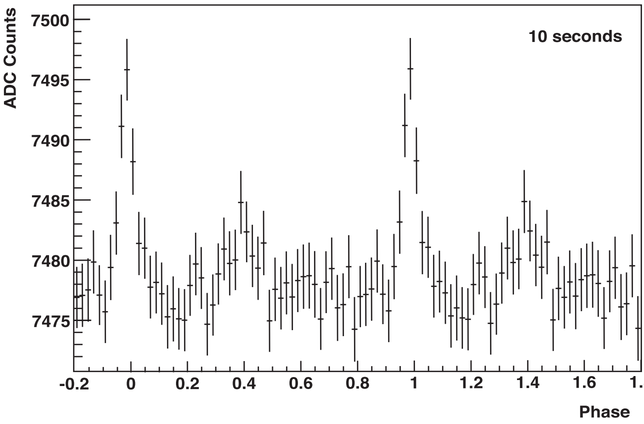

Fig. 2. Optical signal from the Crab pulsar from a 10 second observation

the telescope. To verify the absolute pointing of the instrument, several offset pointing runs and drift scans were made of bright stars (with an 0.01 neutral density filter in place). These runs verified that $> 80\%$ of the light in the PSF was collected onto the PMT. Observation runs were made in a cycle of HV off (to monitor the ADC pedestal position) and on-source runs. Several empty fields were also observed as background references. The typical PMT anode current was 2-6 μA depending on the region observed.

After removing data compromised by unstable weather conditions, 6 hours of data on the Crab (spread over 8 nights from the 21- 29 January) remain. 10 hours of data were obtained on the Vela pulsar.

4. Results and Discussion

The first step of the analysis is to barycentre the time associated with each sample using the standard H.E.S.S. software scheme. The barycentred time is then folded using radio ephemerides from the Jodrell Bank Observatory [4] (with frequency and first derivative from 15.1.03 and second derivative from the period 12.02-2.03). After a phase position is established, 4 consecutive samples are summed to provide independent current measurements for the light-curve. The data are then split into 10-second slices, each of which is tested for stability by examining the RMS of the DC signal. Figure 2 shows the phasogram extracted from a single 10 second slice. The expected double-peaked structure is clearly visible on top of a large DC background.

The sum of slices passing the RMS cut (with the DC component subtracted) is shown in Figure 3. The position, width, and relative heights of the two peaks are consistent with the measurement made by the Hubble Space Telescope [1]. The significance of the pulsation is $\approx 4\sigma/\sqrt{t/\text{seconds}}$. Each complete phase contains ≈ 800 photoelectrons, seen against a background of $\approx 2 \times 10^6$ pe. The phase position of the mean peak can be determined with a precision of $30\,\mu$s in $\sim$30 minutes and is stable over the period of observations (see Figure 4 right).

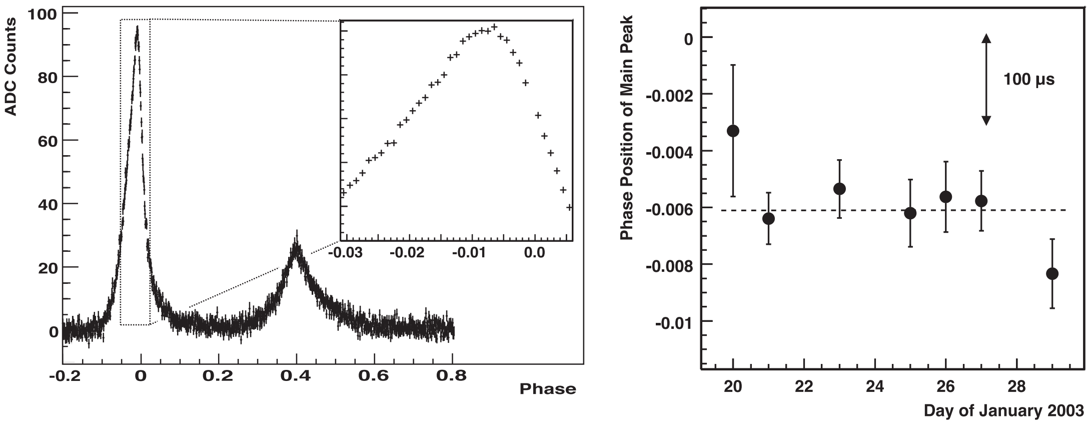

Fig. 3. Left: the Crab pulsar phasogram extracted from the full data-set of 3 hours of best quality observations. Right: The position of the main peak as a function of time during the measurement. The mean position of -0.0061 ± 0.0004 is consistent with the result of -0.0058 given by [2].

Observations of the Vela pulsar were also made during this period, however, with the 10 hours obtained, no significant pulsation was observed (using ephemerides from [5]). We estimate ~ 30 hours would be required for a 5σ detection with this instrument.

5. Outlook

This prototype device has demonstrated the utility of an optical monitoring device for high energy gamma-ray experiments. We are currently developing an improved device with multiple light sensors (for the exclusion of optical transients, for example meteorites) and possibly higher quantum efficiency light sensors. A search for optical Giant Pulses in our data-set is under way.

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6. References

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