ABSTRACT

The VHE gamma-ray imaging telescope CAT started taking data in October 1996. Located at the Themis solar site in southern France (2°E, 42°N, 1650 m a.s.l.), it features a 17.7 m² Davies-Cotton mirror equipped with a 600 PMT camera at the focal plane. The mechanics and optics, the PMTs and the electronics are presented. The performance, based on the first 7 months of operation, is described.

INTRODUCTION

A new atmospheric Cherenkov imaging telescope (Figure 1), designed for VHE gamma-ray astronomy, has been operating since October 1996. It was built by a Franco-Czech collaboration and installed at the same site, at Themis, as the two existing timing arrays ASGAT (Goret et al., 1993) and THEMISTOCLE (Djannati-Ataï et al., 1995). The ensemble of these three instruments, using complementary detection techniques, has been named CAT for Cherenkov Array at Themis. The heart of the imaging telescope consists of a fine grained camera with a pixel size of the order of the width of gamma-ray images. The different parts of the telescope are described below.

THE REFLECTOR

The Davies-Cotton reflector of the CAT imager consists of 90 spherical mirrors 50 cm in diameter with a radius of curvature of $R = 12.0 +0.24 _{-0.0}$ m. The total collecting area is 17.7 m² and the focal length is 6 m. The weight and rigidity of the supporting structure were optimized by using state of the art design and manufacturing. The 1 cm thick individual glass mirrors are first surface aluminized and protected by SiO₂. They are positioned on the frame according to their measured radii of curvature and aligned to better than 0.1 mrad using an autocollimation technique. Regular checks of mirror alignment are performed. The focal spot obtained, when imaging stars onto a white sheet, is of the order of 1.8 mrad FWHM. The relative time delay across the mirror resulting from the Davies-Cotton design is 1.6 ns from center to edge. The encoding system of the alt-azimuth mount of the telescope...
allows a pointing resolution of \( \sim 0.14 \) mrad in both azimuth and elevation. The pointing corrections, needed for an accurate determination of the source position in the focal plane, are described later in this paper.

THE FOCAL PLANE DETECTOR
The layout of the focal plane detector is shown in Figure 2. An inner zone consists of a densely packed array of PMTs with a center to center spacing of 13 mm equivalent to 2.2 mrad. This zone, used for the fine imaging of Cherenkov showers, is filled with 546 fast 11 mm diameter PMTs (Hamamatsu R1635-02). The full field of view (f.o.v) of the inner zone is 3.1\(^\circ\) in diameter. An outer double ring of 54 larger PMTs, 28mm diameter (Hamamatsu R6076) extends the f.o.v. to 4.8\(^\circ\) with a coarse granularity. All 600 PMTs are equipped with aluminized Winston cones (Punch, 1994) in order to both reduce the dead space between photocathodes and cut off unwanted stray light. Measurements of the transmission of light to the photocathode confirm the sharp cutoff for incident angles on the Winston cones greater than \( \sim 32\)^\circ. With the use of such cones, the light collection efficiency is nearly doubled relative to the no-cone situation.

PMTS AND ELECTRONICS
The trigger electronics of the CAT telescope has been designed to be placed immediately behind the PMTs, allowing it to take advantage of the brevity of the Cherenkov pulse, the isochronism of the mirror, and the speed of the PMT response. A detailed description of the electronics can be found in Barrau (1997).

Photomultiplier Tubes
The Hamamatsu R1635 PMTs typically show a risetime of \( \sim 0.9 \) ns and a width of \( \sim 1.5 \) ns. A laboratory calibration was performed which yielded, first the gain as a function of high voltage, then the standard deviation \( \sigma \) and the mean value \( Q \) of the single photoelectron (p.e.) peak for each PMT. The value of \( \sigma/Q \) is 0.45\( \pm \)0.05 for a peak/valley ratio of \( \sim 2 \), allowing for a straightforward measurement of the gains. In the experiment, the PMTs are operated at a gain of \( 10^6 \) at a high voltage between 1050V and 1200V. The high voltage is supplied by a computer controlled CAEN SY527 generator. The gains are measured every month, using a pulsed LED at very low light level, and observing the single p.e. peak. After shaping by an OPA623 amplifier, PMT signals are split into two channels, one for the trigger generation and scaler updating and the other for charge measurement. The trigger and scaler channels are further amplified (\( \times 15 \)) with NEC1678 wide-band amplifiers.

Trigger Generation and Scalers
The PMT signals are discriminated using comparators. The thresholds are adjusted by software with a minimum value of \( \sim 1 \) photoelectron (at a gain of \( 10^6 \)). The inner 288 PMTs participate in the trigger generation (see Figure 2). The large combinatorial factor is avoided by dividing the trigger zone into 9 angular sectors of 48 PMTs, with an overlap of 16 PMTs between adjacent sectors, to prevent a loss of trigger efficiency at the boundaries. A majority logic trigger is formed, within each sector, requiring \( p \) pixels out of 48 above \( n \) photoelectrons. A final ‘OR’ of the outputs of all sectors provides the camera trigger. Comparator outputs are also sent to 100 MHz scalers to monitor the PMT count rates.

Charge Measurement
After a 140 ns delay cable, the charge signals are gated by 12 ns -wide fast analog switches opened by the camera trigger. Thus the contribution of the night sky background light to the charge measurement is minimized. The signals are then amplified (\( \times 4 \)) and analyzed by 15 bit Fastbus ADC’s (Lecroy 1885). These ADC’s feature a resolution of 50 fC/channel for signals up to 200 pC and of 400 fC/channel above. The effective dynamic range runs from \( \sim 2 \) p.e./pixel up to \( \sim 1000 \) p.e./pixel and the conversion factor is typically 12 counts/p.e..
In order to fully exploit the high definition of the CAT imaging camera, the position of the observed source in the camera has to be known to better than 0.5 mrad (~1/4 of the pixel size). However, misalignment of the rotation axes, mechanical deformations and other effects lead to pointing errors amounting to a few mrads. The true pointing position is measured by means of two CCD cameras. A first one, located at the center of the mirror, views the focal plane. Three green LED’s, one at the center and the others at the outer edge of the camera, provide an absolute reference relative to the camera coordinates. A second CCD camera, located near the first one and coaligned with the mirror axis, views the same sky region as the PMT camera. The information from both CCDs enables to localize the position of the observed source in the PMT camera with an accuracy of ~0.3 mrad. An independent cross-check was performed by analyzing the track of bright stars through the PMTs with the telescope pointing at fixed positions in azimuth and elevation. The pointing accuracy achieved with this method is ±0.2 mrad. A third analysis involved the identification of the star field in the PMT camera during observations. All three methods give consistent results leading to off-line pointing corrections accurate to better than 0.3 mrad.

PERFORMANCE
As of the writing of this paper, only the inner 546 small PMTs have been mounted in the camera. After 7 months of operation, 10 of them are not working properly. A small drift in PMT gains was detected and corrected for. All scientific data have been recorded with a trigger level of ≥ 4 pixels passing a threshold of 3 photoelectrons. The corresponding trigger rate at zenith is of the order of 15-20 Hz with a negligible random coincidence rate. The muon trigger rate is ~6 Hz as was measured under cloudy conditions. The night sky background light is routinely monitored using the shape of the ADC pedestals for random gates. It is fairly constant from night to night at a level of ~0.015-0.020 p.e./ns/pixel. The singles rates are of the order of a few kHz except for those PMTs which see a star. Whenever the singles rate for a given pixel reaches ~7 Mhz, as is the case when a bright star enters a PMT, the HV for this pixel is automatically lowered to avoid excessive anode current. The effective energy threshold for gamma rays is estimated at ~220 GeV at 20° from zenith. Joint observations of Mrk501 with the THEMISTOCLE experiment are under analysis to verify the absolute energy calibration. The good sensitivity of the CAT imager is demonstrated by the detection of the Crab nebula and of the blazars Mrk421 and Mrk501.

CONCLUSIONS
The VHE gamma-ray imaging telescope CAT has been taking data since October 1996. Its 546 pixel camera makes it the finest grained imager operating to-date. The mechanical structure and optics have met specifications to give a focal spot matching the 2.2 mrad pixel size. The dedicated electronics, tailored to the use of both fast and numerous PMTs, have met the requirements of good trigger efficiency, accurate charge measurement and reliability. Winston cones have proven to be efficient for eliminating stray light so that single rates are quite stable. Finally the overall sensitivity of the equipment has been checked by the positive detection of the Crab nebula, Mrk421 and Mrk501. Future improvements concern the implementation of a guard ring of 54 PMTs for more accurate energy determination and of a muon barrel for studying the response of the telescope to muons.

REFERENCES
Barrau, A., Nucl. Inst. and Meth. in Phys. Res. A, 387, 69 (1997).
Djannati-Ataï, A. Proc. 24th ICRC, 2, 315 (1995).
Goret, P., Palfrey, T., Tabary, A. et al., A&A, 270, 401 (1993).
Punch, M., in Towards a Major Atmospheric Cerenkov Detector III, ed. T. Kifune, pp. 215-220, Universal Academy Press Inc., Tokyo (1994)
Fig. 1: The CAT imaging telescope

Fig. 2: The very-high-definition camera. The spacing in the fine-pixel region is 0.12°. The 288 inner PMs, shown filled, are used in the trigger logic.