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The central pixel of the MAGIC telescope for optical observations

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Abstract: The MAGIC telescope has been designed for the observation of the Čerenkov light generated in Extensive Air Showers. However, its 17 m diameter and optical design makes the telescope suitable for optical observations as well. In this work, we report on the development of a system based on the use of a dedicated photo-multiplier for optical observations installed at the center of the MAGIC camera (the *central pixel*). An electro-optical system has been developed in order to transmit through an optical fiber the PMT output signal to the counting room, where it is digitized and stored for off-line analysis. The performance of the system using the optical pulsation of the Crab nebula as calibration source is presented.

Introduction

The MAGIC telescope [1] is an innovative detector aimed to detect Very High Energy γ-rays from astrophysical sources using the Imaging Atmospheric Čerenkov technique [2]. The main characteristic of the telescope is its 17 m. tesselated mirror focusing the Čerenkov light onto a so-called camera placed at the main focus of the telescope. The camera consists of a matrix of 576 fast-response photo-multipliers (PMTs) which register the very fast Čerenkov light pulses emitted along the air shower direction. It has a diameter of 1.5 m and is composed by an inner ring of 397 1" diameter PMTs and an outer ring of 180 1.5" diameter PMTs. The PMT output is sent through optical fiber to the counting house where it is digitized using 300 MHz Flash-ADCs.

Besides the main γ-ray observations, the large mirror of the MAGIC telescope can also be used to perform optical observations of slow-varying astronomical objects showing periodic or quasi-periodic photon emission. Typical emission frequencies span between 1 Hz (Blazars) and 1 kHz (pulsars and GRBs). This can be done by integrating the slow DC current output of a PMT placed at the center of the MAGIC camera when the telescope is pointing to a variable source. A similar technique was already applied by other Čerenkov telescopes, like HESS [3], which detected the optical pulsed emission from the Crab pulsar. The OPTIMA collaboration has also performed similar measurements on several sources [4].

The central pixel

Fig. 1 shows the basic block diagram of the central pixel configuration and the readout chain. As photo-sensor for the central pixel, a standard 1" MAGIC PMT (ET9116) has been used and installed at the center of the MAGIC camera. The PMT peak quantum efficiency, which was improved by means of a wavelength shifter [5], is about 27%.

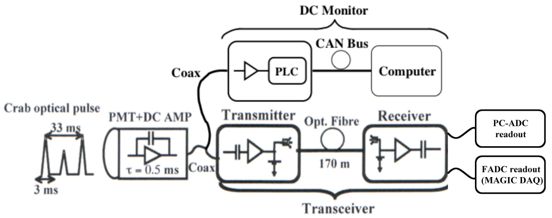

Figure 1: Basic block diagram of the central pixel and its readout.

The base of each standard MAGIC PMTs incorporates a fast pre-amplifier [6] composed by two branches: an AC branch for the amplification of the Čerenkov light-pulses and a DC branch (with an integration time constant of 3 ms) for the record of the slow-varying current induced by the Night Sky Background (NSB). In the case of the central pixel, which is meant to perform optical observations of Crab-like pulsating objects, thus with rotational periods below 1 kHz and a few ms-wide optical pulsations, the integration time constant of the pre-amplifier DC branch had to be lowered to $\tau = 0.15$ ms.

The PMT cathode is powered at negative HV set to 1.08 kVolt, resulting in a gain of about 20×10^3. The typical PMT DC current, at normal NSB conditions, is around 0.1μA.

The DC level at the PMT preamplifier output, a measure of the sky brightness in the observation area, is monitored using an analog input channel of the same Programmable Logic Controller (Modicon TSX Micro [9]) which is used by the MAGIC telescope to control the camera. The aim of this monitoring is two-fold: on one hand, to check proper working of the central PMT. On the other hand, to control the PMT anode current in order to prevent any damage to the PMT while observing under large NSB conditions.

The electro-optical transmission system

The transmission of the DC output signal from the PMT base to the counting house, where the signal is digitized and recorded for later analysis, is made through an optical fiber. This optical fiber connection avoids problems related with the different grounding potentials of the camera and the counting house, which rise due to the very large return current from the telescope motor drives and various power supplies. It also avoids pick-up noise during the signal transmission from the telescope camera to the counting house.

A large dynamic range LED (Honeywell HFE 4050-014 [7]) and a commercial PIN photodiode receiver (Honeywell HFD3038-002 [8]) are used, respectively, as electro-optical converter and optical-electric back-converter. The optical fiber (a step index multimode fiber with 50/125 micron core/cladding) was one of the 170 m optical fibers connecting the camera with the 100 m away counting house.

The optical receiver is AC-coupled to a chain of two amplifiers: the first one provides one output to be digitized by a commercial ADC (dubbed PC-ADC) placed in a dedicated PC. The second one provides a different output to be recorded by the MAGIC FADC system, dubbed FADC out (see next section for details).

The transceiver shows good linearity for a wide range of input signals from hundreds of microVolts to several milli-Volts. The overall bandwidth of the transceiver spans from 1Hz to 10 kHz. RC filters were installed at the transceiver in order to cut low and high frequency noise, while preserving Crab-like pulsed signals.

The data acquisition system and operation modes

The PC-ADC readout

The analog signal from the PC-ADC output of the receiver module is transmitted through a wide SCSI cable to an FADC module embedded on a PCI card (type National Instruments PCI-6034E [10]) mounted on a PC running under Linux. The ADC card can continuously sample the signal with 16-bit resolution at a rate in the range 1-20 kHz. The timestamp corresponding to each measurement is obtained from the rubidium clock-geared MAGIC timing system [11].

The FADC readout

In parallel with the above described readout mode, the signal from the driver amplifier at the receiver circuit is digitized by one of the FADC channels of the standard MAGIC readout system. This FADC channel digitizes the central pixel signal with 8-bit resolution every time a trigger associated to a gamma candidate event is produced ($\sim$ 200 Hz on average). The absolute timestamp for each sample is the same as for this trigger and is provided by the MAGIC timing system.

The two readout methods are complementary. Taking as an example the measurement of a pulsed source, the PC-ADC readout method, continuously sampling the signal up to 20 kHz, is obviously more sensitive than the FADC one, which only randomly samples signal lightcurves with a 3% duty cycle[1] However, the time stamp provided by the FADC readout to the optical Central Pixel samples is the same as that one of the VHE gamma events detected by MAGIC. That could help to tag possible coincident optical-gamma emission. It can also provide a crosscheck of the MAGIC timing system accuracy, by measuring the Crab optical pulsar frequency.

Crab observations

Expected sensitivity

The sensitivity for detecting Crab-like pulses will depend mainly on the fluctuations in the NSB which are expected to be at least two or three orders of magnitude greater than the RMS electronic noise. For the PMTs of the MAGIC telescope, the photo-electron rate due to the NSB measured at La Palma and the Crab Nebula are expected to be 3.6×10^9 phe/s, while the total pulsed photo-electron rate is expected to be of 3.7×10^6 phe/s [13].

Taking into account the central pixel PMT and preamplifier characteristics, the signal-to-noise ratio becomes of the order of 0.3. Thus, in order to have a 5σ detection of the Crab pulsation against the background, the digitized amplitude has to be folded using the Crab period (0.033 s, see next section for details) for at least 10 s.

Taking into account the MAGIC Point Spread Function (PSF)[2] and the fact that the PMT camera is displaced from the position at infinity focus by 3 cm, we estimate that only 50% of the light is contained within the central pixel. Thus, the expected detection time has to be further increased at least by a factor 2.

Data analysis procedure

As mentioned above, the optical Crab pulses are completely embedded in noise. Therefore, the absolute times associated with each sample must be folded with the expected period, as derived from the Jodrell Bank observatory [14] radio ephemeris. Moreover, these times have to be transformed to an inertial reference frame, for which the Solar Barycenter System (SBS) is used. A phaseogram is then produced for each of the frequencies in a set around the expected Crab rotational frequency, with the phase associated to the time of each sample corrected by the drift of the pulsar period. The set of independent test frequencies is defined by the Independent Fourier Spacing $IFS = 1/T_{obs}$. The folded intensities are tested against a uniform distribution by performing several statistical tests, such as χ^2, Z^2_m and H (see [15] and [16] for details).

Results

Since December 2005, the central pixel system was upgraded with the FADC readout and tested by observing the Crab pulsar. The data, recorded during a total period of two months between December 2005 and February 2006, were analyzed using the procedure described above. Fig. 2 shows the well-known double-peaked lightcurve calculated at the maximum χ^2 value, for a total time of 20 hours. The zero phase in this lightcurve is chosen in order to correspond to the peak of maximum intensity of the lightcurve measured in the radio band. The lightcurve obtained with the absolute time stamp peaks at phase zero too, confirming the MAGIC timing system accuracy which is of the order of 0.2 μsec.

In September 2006, the final set-up (including absolute time on PC-ADC readout and DC-level

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[1] Taking into account the average $\sim$ 200 Hz MAGIC trigger rate and the 0.15 ms integration time at the Central Pixel PMT base.

[2] MAGIC PSF is such that 80% of the light from a point-like source at infinity is contained within one pixel.

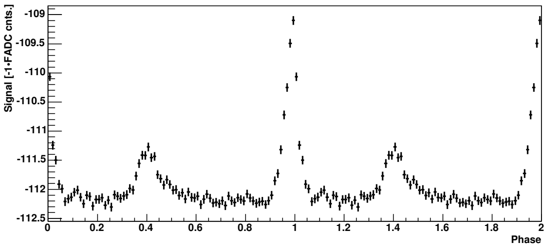

Figure 2: Crab lightcurve after 20 hours of observation with the central pixel of the MAGIC telescope, as recorded by the FADC readout system.

monitoring) has been finally commissioned. Figure 3 shows the Crab pulsar optical light curve as recorded by the PC-ADC readout for 24 seconds of observation ($\sim 5\sigma$ detection), proving the expected superior sensitivity of the PC-ADC readout method, as compared to the FADC readout method.

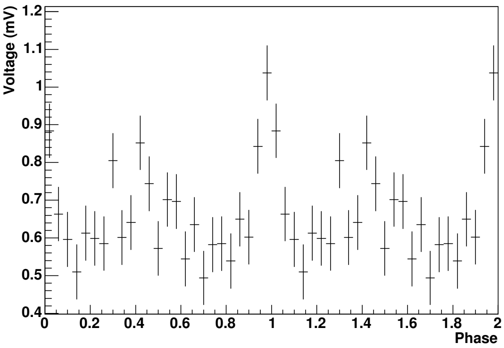

Figure 3: Crab light-curve for the frequency correspondent to the χ^2 maximum and after 24 seconds of observation.

Conclusions

In this work, we have reported about the final installation of the central pixel system of the MAGIC telescope, dedicated to optical observations. The central pixel has been successfully tested by the detection of the Crab optical pulsations. The minimum time requested for a 5σ detection is around 30 s. That is in agreement with the expected detection time calculated in [13] and with the estimates made in the previous chapter.

The applications of the central pixel will be focused mainly in the simultaneous observations of the Crab pulsar in the optical and γ regimes, in order to have real-time ephemerides for periodicity search in γ-rays.

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