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Analysis techniques and performance of the Domino Ring Sampler version 4 based readout for the MAGIC telescopes

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ABSTRACT

Recently the readout of the MAGIC telescopes has been upgraded to a new system based on the Domino Ring Sampler version 4 chip. We present the analysis techniques and the signal extraction performance studies of this system. We study the behavior of the baseline, the noise, the cross-talk, the linearity and the time resolution. We investigate also the optimal signal extraction. In addition we show some of the analysis techniques specific to the readout based on the Domino Ring Sampler version 2 chip, previously used in the MAGIC II telescope.

1. Introduction

MAGIC (Major Atmospheric Gamma Imaging Cherenkov, [12,25]) is a system of two imaging atmospheric Cherenkov telescopes (IACTs, [27]), each equipped with a mirror dish of 17 m diameter. MAGIC is located on the Canary Island of La Palma at the height of 2200 m a.s.l. The telescopes are built to measure gamma rays in the energy range from about 50 GeV to 50 TeV by detection of short and weak Cherenkov light flashes from the extensive air showers. This requires fast time response and high sampling rate of the system in order to decrease the exposure to noise.

Presently both telescopes are using a readout based on the Domino Ring Sampler version 4 chip[1] (DRS4) [9,24] operated at a sampling speed of 2 GSamples/s. Such sampling speeds, larger than in other IACTs [10,13], are used in MAGIC since 2007, and allow us to exploit the timing information in recorded showers. Another presently operating IACT using the DRS4 chip in its readout, is FACT [5]. In addition, the DRS4 is the heart of the Dragon system [17], one of the possible readout systems considered for the next generation major IACT project called Cherenkov Telescope Array (CTA, [1]). Among the other analogue memories which are considered for the readout of CTA are TARGET [7] and NECTAr [21].

In this paper, we describe the pre-processing analysis procedures used to extract and calibrate the signal in each channel of the MAGIC telescopes. We also evaluate the performance of the basic parameters of the signal extraction. In addition, we describe methods used in the analysis of the data taken with the previous readout (based on the DRS2 chip, [8,22,23]) of the MAGIC II telescope. The older readout systems of the MAGIC I telescope are described in detail in Albert et al. [2] and Bartko et al. [6].

2. The MAGIC telescopes

Very High Energy (VHE, $\geq$100 GeV) gamma rays entering the atmosphere produce cascades of secondary particles. The charged particles moving faster than the propagation speed of light in the atmosphere will produce very short (of the order of 1 ns) flashes of optical and UV light (the so-called Cherenkov radiation, [16]). This light is emitted in a narrow cone with small half-opening angles of $\lesssim 1^\circ$ and illuminates an area on the ground with a radius of about 120 m.

IACTs, such as the MAGIC telescopes, can focus the Cherenkov light onto the camera composed of the order of 1000 individual photodetectors (pixels). Until summer 2012 the cameras of the MAGIC I and MAGIC II telescopes were equipped with 577 and 1039 photomultipliers (PMTs), respectively. At

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[1] http://drs.web.psi.ch/.

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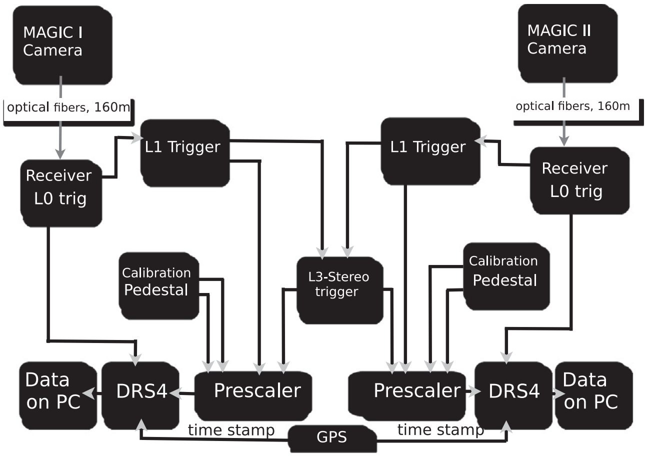

Fig. 1. Electronic chain of the MAGIC telescopes.

that time the MAGIC I camera was equipped with two kinds of pixels: 397 smaller, inner pixels with a FoV of 0.1°, and 180 larger, outer pixels with a FoV of 0.2° [11]. The MAGIC II camera is composed only of smaller pixels. The full electronic chain of the MAGIC telescopes is schematically shown in Fig. 1. The electrical signal from each pixel is converted into an optical one using a vertical-cavity surface emitting laser (VCSEL) diode in the camera [28]. Afterwards it is transmitted, still as an analog signal, via an optical fiber to the control house hosting the readout electronics. The signal then arrives to the so-called receivers where it is converted back into an electrical pulse and split into a trigger and readout branches. Between February 2007 and June 2011, the MAGIC I readout was based on optical multiplexer and off-the-shelf FADCs [6]. The second MAGIC telescope, in operation since 2009, was first equipped with the Domino Ring Sampler version 2 chip (DRS2, [26]). During the first stage of the MAGIC upgrade in 2011, both telescopes were equipped with a readout based on the DRS4 chip [9]. In a second stage of the upgrade, the camera of MAGIC I has been replaced by a close copy of the one presently installed in MAGIC II. As bigger outer pixels covered only the outer part of one of the MAGIC cameras and in the present system there are only small pixels, in this paper we concentrate on those.

The DRS4 readout system is based on an array of 1024 capacitors for each channel. When running the system with a sampling speed of 2 GSamples/s, the input signal is stored in the analog form in the capacitors with a switching period of 500 ps, which results in a 512 ns deep buffer. After a trigger occurs, the sampling is stopped and the charges of the capacitors are read out by an ADC of 14 bit precision at a speed of 32 MHz [9]. The studies presented in this paper are based on data in which the waveforms for a time span of 40 ns (80 samples) around the pulse position (the so-called region of interest, RoI) were stored for each event and each pixel. Very recently the number of saved samples have been reduced to 60. With this sampling range, even large showers with long time development are contained in the readout time window. Such a readout window also ensures that the pulses will not be truncated due to the jitter or drifts of the trigger signal.

The calibration of the readout signals is done using calibration laser pulses of a wavelength of 355 nm and with a Full Width Half Maximum (FWHM) of ~1.1 ns that illuminate homogeneously the entire camera. The intensity of the light in the calibration pulses can be set to various values, spanning the whole dynamic range of the readout. Each stored event is tagged with a time stamp from a rubidium clock synchronized with a GPS system.

3. Signal processing

The purpose of the pre-processing analysis is to obtain two pieces of information for each pixel in a given event: the total signal (charge) and the arrival time. The signal is converted from the integrated readout counts (i.e. summed up ADC counts from 6 consecutive time samples) to photoelectrons (phe) according to the F-Factor (excess noise factor) method (see e.g. [14,19]). For the presently used integration window of 6 time samples (i.e. 3 ns), the conversion factor is typically ~90 readout counts per phe.

A single photoelectron generates a signal with an amplitude of the order of 30 readout counts. However, it should be noted that the individual photoelectrons come at slightly different times, both due to the time spread in the PMT and due to the intrinsic time spread of the calibration/cherenkov light flashes. By scaling down a ~100 phe pulse which includes all those time spreads we obtain an effective photoelectron which is broader and has the amplitude of ~18 readout counts.

The full span of 14 bit ADC used in the readout is 2 V, thus one readout count corresponds to 122 μV output voltage. However as the DRS4 has a differential gain of 2, one readout count corresponds to ~60 μV at the board input.

The position of the integration window is adjusted for each pulse such that it maximizes the obtained signal over the whole readout window (the so-called "sliding window" method). For each event, we select the pixels, which are likely to contain information about the shower based on their signals and arrival times in the so-called time image cleaning procedure [4]. The individual pixel charges are later used in the parametrization of the shower images [15]. In addition, timing parameters, if determined precisely enough, can be used to further enhance the performance of the telescopes e.g. in gamma/hadron discrimination [4,18].

All the procedures described in this paper are included in the standard analysis software for the MAGIC telescopes (MARS, [20]) and used in the automatic data processing chain. Moreover, some of them (e.g. the baseline correction) are done online during data taking by the MAGIC data acquisition program.

3.1. *Baseline with triggers arriving at fixed time intervals*

In Fig. 2 we show the mean cell offset (baseline) and its RMS, as a function of the absolute position of the capacitor in the domino ring for a typical DRS4 channel. Each capacitor of each DRS4 channel has its own cell offset. The differences in the mean offset caused by the physical differences in the storage cells are much larger than the RMS of the baseline of the individual cells. Also due

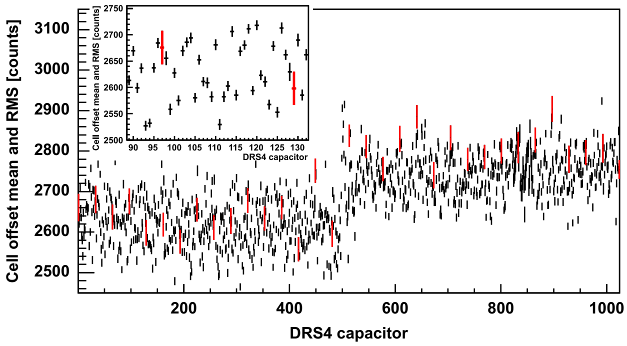

Fig. 2. Cell offsets of 1024 individual capacitors of one channel of the DRS4 chip, operating in the RoI mode. Vertical error bars show the standard deviation of the offset value for a given capacitor. Every 32nd capacitor is marked with thick line in red color. The inside panel zooms into some of the capacitors. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)