Upgrade of the MAGIC telescopes

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Abstract: The MAGIC telescopes are two Imaging Atmospheric Cherenkov Telescopes (IACTs) located on the Canary island of La Palma. With 17m diameter mirror dishes and ultra-fast electronics, they provide an energy threshold as low as 50 GeV for observations at low zenith angles. The first MAGIC telescope was taken in operation in 2004 whereas the second one joined in 2009. In 2011 we started a major upgrade program to improve and to unify the stereoscopic system of the two similar but at that time different telescopes. Here we report on the upgrade of the readout electronics and digital trigger of the two telescopes, the upgrade of the camera of the MAGIC I telescope as well as the commissioning of the system after this major upgrade.

Keywords: MAGIC, Cherenkov telescopes, gamma-ray astronomy, acquisition systems, trigger

1 Introduction

The MAGIC telescopes (see Fig. 1) is a stereoscopic system of two Imaging Atmospheric Cherenkov Telescopes (IACTs) located at the observatory of Roque de los Muchachos in La Palma, Canary Islands. The telescopes are designed to observe very high energy gamma rays at energies between 50 GeV and tens of TeVs. The two MAGIC telescopes have been constructed 5 years apart (2004 and 2009, respectively), which, due to the technological progress along the time, led to rather significant differences in the two systems.

- The camera of the MAGIC I telescope consisted of 577 pixels (divided in small pixels, 1 inch diameter, in the inner part of the camera and large pixels, 2 inch diameter, in the outer part). The camera of MAGIC II consists of 1039 pixels, all small, 1 inch diameter.
- The trigger area of MAGIC II had an affective area of 1.66 times larger than the one of MAGIC I.
- MAGIC I readout was based on optical multiplexer and off-the-shelf FADCs (MUX-FADC), which was robust and had an excellent performance but was expensive and bulky). The readout of MAGIC II was based on the DRS2 chip (compact and inexpensive but performing worse in terms of intrinsic noise, dead time and linearity compared to the MUX-FADC system).
- Receiver boards of MAGIC I, which are responsible for converting the optical signals into electrical ones, to split the signal into the analogue branch of the readout and the digital branch for the trigger, as well as to apply a Level-0 trigger condition (L0-trigger) depending on the height of the signal in a trigger channel, were built using an old technology and were showing high failure rate (due to aging). This resulted in frequent problems in setting the discriminator thresholds (DTs) during the observations and only a rather slow reaction of the individual pixel rate control (IPRC), in order of several minutes, to adjust the DTs depending on the star field of the observations. This caused some loss of costly observation time. The receiver boards of MAGIC II allow instead a fast response (order of several seconds) of the IPRC thanks to a build-in FPGA and an easy and robust communication through the VME bus.

In years 2011-2012 MAGIC underwent a major upgrade program to improve and to unify the stereoscopic system of the two telescopes. This paper describes the main items of the upgrade and the commissioning of the upgraded MAGIC.

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1. see http://drs.web.psi.ch/
2. The Level-0 trigger is a discriminator applied on a signal amplitude.
2 Individual steps of the upgrade

The main goals of the upgrade were replacing the camera and the Level-1 trigger (hereafter L1, coincidence trigger for a group of neighboring pixels) of the MAGIC I telescope as well as changing the readout of the two telescopes. The readout was changed to a system based on the DRS4 chip, sampling the signals with 2 Gsamples/s. The new readout is cost effective, has a linear behavior over a large dynamic range, less than 1% dead time and low noise and negligible channel-to-channel cross-talk ([2, 3]). This allowed us to maintain the quality of the readout based on MUX-FADCs while reducing cost and saving space as we needed to accommodate the readout for more than 2000 channels (the two MAGIC telescopes) into the space available in the control house of the experiment where the readout and the trigger are located. The receiver boards and the trigger of MAGIC I have also been upgraded to be equal to the ones of MAGIC II. The individual items of the upgrade program are shown in Fig. 2. The blue boxes represent hardware items which have been replaced and commissioned during the upgrade.

The upgrade was staged. In the first stage, which required a shutdown of the telescopes between June and November 2011, the following tasks were performed:

- Restructuring of the electronics and the computing rooms. A dedicated computing room was created for the subsystems machines as well as for the analysis farm. The electronics room was instead completely renewed, including installing new electrical lines, a new cooling system, closed racks for electronics and second floor for better cable routing.

- The readout electronics of the MAGIC I telescope was changed from MUX-FADC to a system based on the DRS4 chip (see Fig. 3).

- The readout electronics of the MAGIC II telescope was changed from the one based on DRS2 chip to a system based on the DRS4 chip (see for the advantages above and in [4]). As a major goal it was important to unify the readouts of the two telescopes to ease maintenance and increase the robustness.

The MAGIC telescopes restarted physics programm by December 2011, which lasted until June 2012 when the second part of the upgrade took place.

In the second phase of the upgrade, which resulted in a scheduled shutdown between mid June 2012 and end of October 2012, the following tasks were achieved:

- Exchange of the camera of the MAGIC I telescope (see Fig. 4) by a clone camera of the MAGIC II telescope. This also meant an exchange of the optical fibers and power cables of the MAGIC I telescope as the number of channels increased from 577 to 1039. A rearrangement of the counter weights in the
structure took also place to compensate the weight increase of the camera.

- Upgrade of the readout of the MAGIC I telescope from 577 to 1039 channels

- Upgrade of the L1 trigger of the MAGIC I telescope. The new trigger is a clone of the MAGIC II L1 trigger and has a 66% larger area than the previous trigger. The increase of the trigger area provides a more homogeneous gamma-ray efficiency across the camera, which is especially important for observations of extended sources and off-center observations.

In addition, two resting pillars were installed for the MAGIC I and MAGIC II cameras in Summer 2012. The cameras of the telescopes rest on top of the corresponding pillar while in the parking position, which greatly improves the stability of the telescope structure during storms, snowfall and strong winds.

3 Commissioning of the system

The commissioning of the upgraded system required a dedicated, well experienced and highly motivated team of 5 to 10 physicists to stay on La Palma at the site of the experiment for a duration of several months after the installation of the hardware. The work has been mainly devoted to the following items:

- Mapping of the channels. The 1039 pixels of the PMT camera have to be connected individually to the corresponding optical fibers at the camera side. The other ends of the fibers are then connected individually to the receiver channels. It is unavoidable that some mis-mappings take place. In order to correct mistakes, identify broken channels and other problems in the signal transmission, a dedicated pulse injection system of the camera is used. Artificial test pulses are generated at the base of the PMTs so that the whole signal transmission chain, including the trigger and readout, can be tested during the day.

- L1 trigger check. The L1 trigger consists of 19 macrocells, each has 36 channels. Following logic algorithms are implemented: 2 next neighbor trigger (2NN), 3NN, 4NN, and 5NN. The L1 trigger is then programmed as an OR of the macrocells trigger. A dedicated hardware and software have been built to test all multiplicities. The L1 trigger systems of both telescopes have been extensively tested, hardware mistakes identified and repaired.

- HV flatfielding. Each PMT has a different gain at a fixed HV. The spread of the gains is unavoidable during the manufacturing process and is around 30-50%. The signal propagation chain introduces further differences in the gain: the optical links as well as the PIN diodes of the receivers mainly contribute to them. For the purpose of easier calibration of the signals, the HVs applied to PMTs are adjusted such that the resulting signal from calibration pulses (equal photon density at the entrance of the PMTs) is equal in all pixels when extracted after the digitization process. The resulting HV distribution for MAGIC I and MAGIC II cameras can be seen in Fig. 5. The distribution of the MAGIC I camera is narrower. This is due to the fact that during the construction of the MAGIC I camera the PMTs have been divided into two categories: those which have a higher gain than 30000 when applying 850 V and those with a lower gain. The ones with a higher gain are attenuated in the PMT base reducing the signal amplitude by a factor of two. This had the effect that the resulting gain and, therefore, also HV distributions are rather narrow. The quality of the HV flatfielding can be seen in Fig. 6 and stays constant with RMS/Mean at about 5-7% RMS for months.

- L0 delays and L0 width adjustment. Due to the different light propagation times of the signals from the focal plane of the camera to the trigger system, the arrival times from different channels are slightly different (of the order of 2-3ns). This is mainly due to the differences in photo-electron 3. In the current configuration the readout can host up to 1152 channels per telescope
propagation time in the PMTs when applying different HVs. An L0 delay is implemented on the receiver boards for each trigger channel in order to equalize arrival times of the signals at the L1 trigger for photons arriving at the same time at the camera plane. A dedicated hardware and software has been built to adjust the L0 delays automatically within several minutes. The delays are adjusted by injecting signals in each trigger pixel combination (e.g. every 3NN combination) and varying the delays of the pixels to identify the parameter space producing valid macrocell trigger signals. Finally the delays are set to the best values obtained from this scan. A minimum L0 signal width, which gave consistent results for all trigger channels, has been identified to be between 3ns to 5.5ns FWHM per pixel. In order to be on the safe side, all L0 trigger widths are then set to 5.5ns FWHM. The resulting gate of the L1 trigger is about $6 \pm 0.5$ ns.

**Discriminator threshold (DT) calibration** The DTs of the trigger channels (L0 trigger) are adjusted such that the sensitivity of the channels is flat in terms of photon density of Cherenkov photons. This is achieved by means of a rate scan over the range of DTs for each trigger channel when firing short (FWHM <2 ns) calibration pulses with a given photon density (e.g., equivalent to a mean of 100 photoelectrons (phe) per pixel of the PMT camera). Then, for each trigger channel the required DT is determined, at which half of the calibration pulses is accepted, and the other half is rejected. In such a way, the DTs are calibrated in terms of phe’s. We then scale the DTs linearly to obtain a DT for a desired phe level. As there are some small differences between the analogue and digital signal chains, and the DT is applied to the amplitude, whereas the HV flatfielding is done for the integrated signal, there is some $10\%$ spread of the resulting DTs (pixel-to-pixel).

**Adjusting the operating point of the trigger** Rates scans have been performed at clear nights at low zenith angles to determine what is the shape of the trigger rate as a function of the DTs in phe. Mono rate scans as well as stereoscopic rates scans have been performed and the performance has been shown to be stable for several nights. An example of the rate scans is shown in Fig. 7. One can see the steep slope of the rate at low DTs, where the rate is dominated by the chance coincidence. At higher DTs, the trigger rate is dominated by the rate of the cosmic ray showers. One can see that the coincidence trigger (stereo trigger) is strongly suppressing the chance coincidence triggers. The operating point for MAGIC has been chosen to be around 4.5 phe, resulting in a stereo rate of around 280 Hz, whereas around 40Hz out of it is a chance coincidence trigger.

**Individual pixel rate control (IPRC)** The fielded DTs may result in very different individual pixel rates (IPRs, measured on the receiver boards) during the operation since a) the spectral sensitivity of PMTs is different and b) the rates depend on the sky region the pixel is exposed to (e.g. it may contain stars, which would increase NSB fluctuations and, therefore, the IPR). As long as the IPRs are between 300kHz and 1.1MHz (mean being around 800kHz), no action is taken. For IPRs outside of these programmable limits, a IPR control software takes care of increasing or decreasing of the DTs for the affected pixels in order not to spoil the resulting L1 telescope rate.

The performance of the upgraded system can be found in [4][5]. In addition to the upgrade as described in these proceedings, we are planning to install a complementary trigger system, dubbed *sumtrigger*, which has a lower energy threshold and will operate parallel to the existing L1 digital trigger [5].

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