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Status of the new Sum-Trigger system for the MAGIC telescopes

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Abstract: MAGIC is a stereoscopic system of two 17 m diameter Imaging Air Cherenckov Telescopes (IACTs) for γ-ray astronomy. Lowering the energy threshold of IACTs is crucial for the observation of Pulsars, high redshift AGNs and GRBs. A lower threshold compared to conventional digital trigger can be achieved by means of a novel concept, the so called Sum Trigger, based on the analogue sum of a patch of pixels. The Sum-Trigger principle has been proven experimentally in 2007 by decreasing the energy threshold of the first Magic telescope from 55 GeV down to 25 GeV. The first VHE detection for the Crab Pulsar was achieved due to this low threshold. After the upgrade of the MAGIC I and MAGIC II, a new Sum-Trigger system will be installed in both telescopes in Summer 2013. The expected trigger threshold in stereo mode is about 25-30 GeV. It is a an improvement over the existing threshold about 50 GeV of the digital trigger. We will report about the current status of the project.

Keywords: Magic, Hardware, trigger, analogue, Sum-Trigger, Crab.

1 Introduction

One of the main attempt of γ-ray astrophysics detector development is to cover the energy range from a few GeV to 80 GeV, since this region is difficult to access, for both, space-based and ground-based instruments. There are strong scientific motivations to extend the IACT technique below 80 GeV. The main goal is to study transient objects such as high redshift AGNs and GRBs, which are not easly detectable by satellites due to the low flux. In addition, lowering the threshold also favorites both the study of EBL and the measurements of the spectra of VHE pulsars [2].

Therefore, the development of new strategies to decrease trigger thresholds and increase the sensitivity in this gap is crucial. In 2008, MAGIC already succeeded in this sense by developing a prototype analog Sum-Trigger (single telescope) that lowered the trigger threshold significantly down to 25 GeV. This trigger system achieved excellent results, since it allowed the first detection of very high energy pulsed gamma radiation from the Crab pulsar [2].

Using the experience acquired during the construction and operation of the first prototype, a new analog trigger, the Sum-Trigger-II, was designed and developed. This paper aims to explain the concept, development, and status of this system.

1.1 Description of the MAGIC experiment

The MAGIC telescopes are located at a height of 2200 m a.s.l. on the Observatorio del Roque de los Muchachos (28°N, 18°W) on Canary Island. It is a stereo system composed of two 17 m diameter (f/D $\sim$1) IACTs for VHE γ-rays observation. Both telescopes are built using the same light-weight carbon-fiber structure which allows for a rapid repositioning time, necessary for observations of short phenomena such as GRBs. The camera of each telescope is composed of 1039, 0.1° hexagonal pixels (PMTs), it has a 3.5° field of view and a trigger area of 1.25° radius. The signals from the PMTs in each pixel are optically transmitted to the counting house where the trigger and digitization of the signals take place.

Since 3 years, regular observations are performed in stereoscopic mode using the standard trigger system, composed of different stages. The level-zero trigger set the discriminator threshold in real time for each pixel in the trigger region, excluding the electronic noise and part of the night sky background (NSB). Each telescope separately has a level-one digital trigger with the 3 next neighbour (3NN) topology, it means that it only selects close compact events that should include at least 3 next neighbouring pixels. Only events that trigger both telescopes are recorded. The stereo trigger, level-three, makes a tight time coincidence between both telescopes.

Aiming for the lowest possible threshold, as an alternative to the current standard level-one trigger, the Sum-Trigger-II will be installed by end of this summer.

1.2 Low energy observations with IACTs

The physics principles of cascades in extended air shower are the same in all the energy range. But the observation of low energy cascades is more difficult due to the fact that less energy gets converted while the particles are crossing the atmosphere. The cascades reach their maximum development around a depth of 180-240 g/cm2 (11-12 km a.s.l.), very far away from the position of the IACTs thus a large part of the shower photon signal is absorbed in the atmosphere. Adding the fact that the energy threshold for the Cherenkov photon production is higher in the upper layers of atmosphere due to reduced air density (35-40 MeV for electrons), the number of emitted photons is further reduced. On top, the higher is the altitude, the lower is the refraction index and thus, the smaller is the Cherenkov angle, and the generated photons are strongly collimated along the charged particles trajectory. In the case of showers initiated by γ-rays, which have a modest transversal development, the main consequences are small shower projections (small size) and a limited number of triggered events at large impact parameters.

Monte Carlo simulations at the camera level of the morphology of low energy events ($\sim$10-60 GeV) has been done [3]. This studies revel us that most of these events are concentrated in a thin doughnut shaped region around the camera center. Although the primary shower energy is very low, the photons span on a wide region. Fig. 1 shows three typical gamma showers between about 13 GeV to about 60 GeV. However, the photon density in most single pixels is very low ($\leq$10 photons, violet and blue pixels) but there are pixels (green, yellow and red), typically arrange in a group of 3,4 or 5 pixels, with enough signal to be detected. Usually, up to 25 GeV, 2 or 3 groups or islands of signals are observed. At higher energies these islands start to overlap and the ovoid like image of the Cherenkov light is recover.

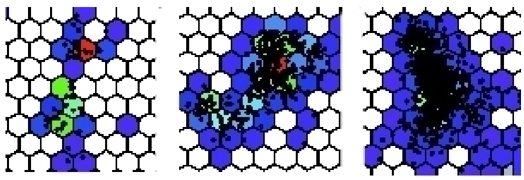

Fig. 1: Distribution of photons (black points) at camera level for three different γ-ray energies, from left to right: 12.9 GeV, 21.5 GeV & 58.6 GeV

All these studies led to the construction of a new trigger system, the Sum-Trigger, particularly sensitive to low energy cascades.

2 The Sum-Trigger-II

2.1 The Concept

The basic principle of the Sum-Trigger is to add up the signals from a group of neighboring pixels (Macrocell) and then apply a threshold to the summed signal. For this propose the trigger region has been covered with three overlapping layers of Macrocells, see Fig.2. Monte Carlo studies suggested that the optimum solution is to use roundish Macrocells composed by 19 pixels (of size 0.1 deg), then a Macrocell contains most part of a low energy shower image.

One of the advantages of this technique is that it improves the signal to noise ratio (shower signal to NSB), since all pixels within a Macrocell contribute to the trigger decision, i.e. it use small photon signals below the single channel threshold (below which the standard trigger is sensitive to).

Besides the simplicity of the idea, the Sum-Trigger-II construction required the development of fast, high precision, analog electronics. The PMTs in the cameras do not have exactly identical properties, there are differences in signal propagation times, gains and pulse widths.

In addition, these different signal delays will be worsened due to small length differences in the 162 m long optical fibers that transport the signal from the camera to the readout electronics. The skew must be minimized in the whole trigger area to assure a proper pile up among signals.

The pulse width itself is perfectly optimized for the temporal evolution of a shower core started from a low energy gamma even. If it is too small then the signal of

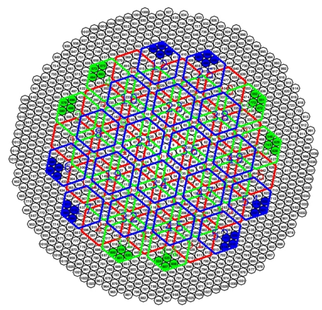

Fig. 2: Layout of the trigger region of Sum-Trigger-II, each color represent a different layer. 19 pixel hexagonal Macrocell shape was selected to guarantee both a symmetrical overlap and an angular symmetry.

the shower does not sum up at the same time, if it is too slow then one integrates too much night sky noise. The optimum was determined to be between 2.5ns and 3.0ns FWHM pulse.

The best threshold level for a patch of 19 pixels for an acceptable ratio between accidental NSB and lowest trigger energy threshold was about 24-27 PhE.

A drawback of classical PMTs is so-called afterpulse noise which are random signal noise pulses of high amplitude and high rate. Such afterpulses could trigger the Sum-Trigger-II and need to be vetoed. The simple way of reducing the effect of those afterpulses was to clip the signal at a certain (optimized) amplitude. For the PMTs that are used in MAGIC the optimum was around 6-8PhE clipping level for the single telescope (corresponding to avoiding triggers in a three-fold afterpulse coincidence). In stereo mode (coincidence between two telescopes) this clipping level can be relaxed (increased) which further improves the sensitivity at lowest energies.

The Monte Carlo studies (3) show us the improve on the sensitivity and the lower threshold (around 30 GeV) respect to the 3NN digital trigger already stated.[3]

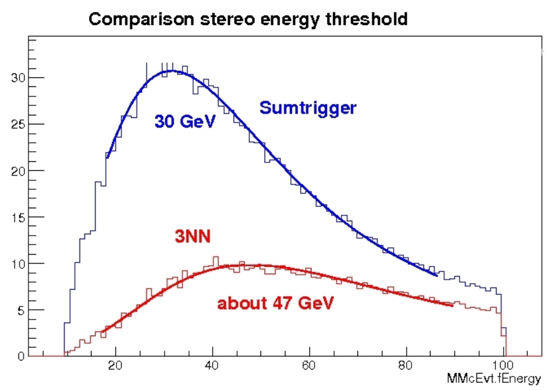

Fig. 3: Monte Carlo simulations shows the threshold comparison between the digital trigger and the Sum-Trigger-II.

2.2 Functional setup of the overall trigger system

The Sum-trigger-II system is structured in several subsystems (see Fig.4). The signals first arrive to so-called Clip-boards. After delaying, adjusting amplitude and clipping, the signals propagate over the backplane (so-called Sum-backplane) differentially to Sum-boards. There they are summed up also passed to a discriminator. Finally, the digital trigger signals propagates, again over the Sum-backplane, to a computer control board that also contains an FPGA which counts the macrocells triggers and perform a global OR that genertaes the final trigger signal. This over-all trigger is connected to the MAGIC telescope trigger coincidence logic (level 3) and from there to the readout.

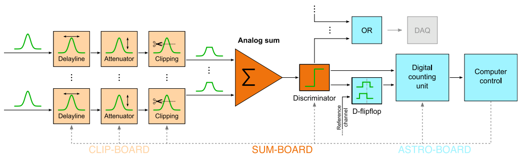

Fig. 4: Sum-Trigger II schematics. Each channel has an analogue delay adjustment, a amplitude adjustment and a clipping mechanism. The sum of 19 channels is fed into a discriminator.

2.3 The Clip-Boards and the Analogue Delay Modules

The Clip-board is a 9U analogue board where the necessary corrections to the signal are performed (see Fig.4, light orange shaded boxes).

- Delay: To correct individual PMTs timing differences and fibers delays. The delays range is about 6.5 ns.
- Attenuation: To obtain perfect flat-fielding of all channel gains. Besides the difference's on gains are normally small, we can apply attenuation from 0 to -32 dB.
- Clipping: To avoid that the PMT's afterpulses generate fake triggers. Monte Carlo shows that this is the main source of noise [3].

Because of ultra high channel density it was necessary to incorporate the three above functions in so-called delay modules, of which 32 units are plugged onto the clip board. This is the most crucial component of the system. It contains a newly developed, adjustable analog signal delay module.

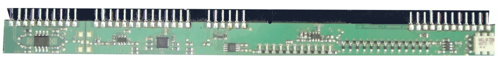

Fig. 5: Analogue Delay module.

The analogue delay lines have been completely tested, showing high precision during timing, amplitude and clipping adjustment. The temperature dependency is negligible and the signal's integrity is accetable. The output pulse with maximum delay shows just a slight widening of 0.2 ns compared to the input signal [4]. At this time, mass production and quality control of the delay lines is taking place.

There are 18 Clip-boards for each Sum-Trigger (for each telescope). The main component of each Clip-Board are these 32 programmable delay lines, and a CPLD (MAX-II, Altera) that allows the control of the board, and the delay modules.

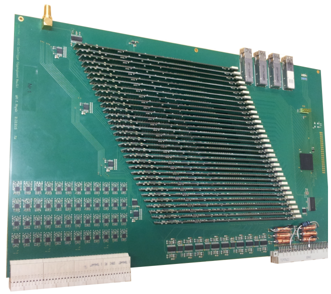

Fig. 6: Picture of a clip-board equipped with delay lines.

The Clip-Board has passed and, also, functionality test, where different delay, and amplitude settings were tested.

The gain could be set with a precision below 5% in a dynamic range from -15dB to +8dB. The delay (pulse position) can be adjusted with a resolution of 200ps. The measured RMS noise was ($\leq 0.05 phe$) and crosstalk was ($\leq 1\%$), thus fulfills by far the requirements.

2.4 The Sum-Backplane

The Sum-backplane is a passive 10U printed circuit motherboard which connects the Clip-boards to the Sum-board. From the electronic point of view, this is the most complex part of Sum-Trigger-II. The PCB layout has been developed considering that 997 fast differential analogue signals have to be routed to 55 macrocells, preserving the isochronism inside 50 ps, a bandwidth higher than 650MHz and a low cross-talk ($\leq 1\%$).[3] Both Sum-Backplanes have already passed the electronic test and it fulfills the requirements.

2.5 The Sum-Boards

The Sum-board (Fig.4, dark orange. Fig.7) is the main board for the final event selection. It can handle up to three macrocells, covering the whole mapping with only 19 units, still keeping the compactness of a small 3U card. It is a high-speed mixed analogue and digital system, which can be controlled automatically by the computer control board. [3]

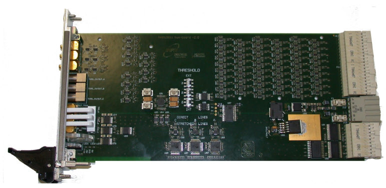

Fig. 7: Sum-Board.

The performances of the Sum-Board meets the requirements: The bandwidth is around 550MHz and its flatness is inside 0.5dB up to 100MHz. The peak to peak electronics noise is quite low, similar to 0.6 phe. The cross-talk is less than 1% up to 300MHz. The maximum skew in the analogue part (pile-up synchronization) is 80ps. And its linearity is perfect up to 3.7V. The comparator threshold has a resolution of 0.1phe, a perfect linearity and stability.

The digital trigger output signal goes to the Astro-board where the final decision will take place.

2.6 The computer control Board

The Astro-board (see Fig.4, blue boxes) is a fully digital 9U board. It is the final stage of the Sum-Trigger-II electronic chain. It contains a cyclon IV FPGA and a FOX-G20 linux computer. The combination of a FPGA with the linux computer is very powerful and also simple. The complete sum-trigger control program communicating with the MAGIC central control is running on this computer.

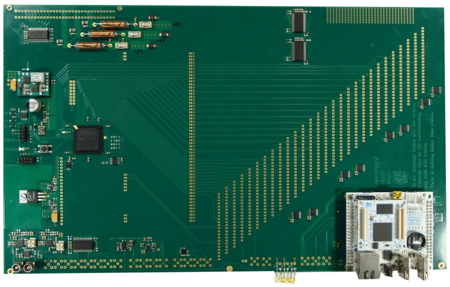

Fig. 8: Astro-Board.The board contains a FPGA (Altera Cyclone IV) and an embedded Linux PC (FOX G20), bottom corner of the board

It take cares of:

- The FPGA manages 55 macrocell triggers and adjusts the thresholds. At the same time, it merges these local triggers through a global OR, finally triggering the MAGIC-DAQ.
- The trigger rate is kept quite stable and below the limits, adjusting continuously the discriminator thresholds of the Sum-boards. The correct parameters are computed by the embedded PC.
- Interface with Central Control Software: The Sum-Trigger give reports and can be control by the Central Control of the telescopes thanks to this embedded computer.
- Automatic calibration of delay, amplitude, and clipping can be perform since the PC can control the applied voltages on the Clip-board pins, so it can fully control the delay lines. An automatic calibration procedure is under development.

2.7 Calibration process

Due to occasionally required tuning of the high-voltages applied to the PMTs, the amplitude and signal transit time can change for individual pixels and have to be re-adjusted on a regular basis for optimal trigger performance. Hence, Sum-Trigger-II includes a computer controlled automatic adjustment of amplitude and delay of the signals. In order to keep the complexity of the new circuits low, an innovative measuring technique based on the evaluation of a series of rate measurements is introduced, requiring only very few additional electronics. In particular, the discrete trigger output of the discriminator is used to measure amplitudes by counting the number of events that exceed the discriminator threshold within a certain time span. Similarly, the rates to determine the delay of each channel are derived from the output of a D-type flip-flop that is used to compare the arrival times of two pulses.
When performing the gain adjustment, the discriminator threshold is fixed to the target amplitude level, and the attenuation value is varied while counting the number of trigger signals from the discriminator. Likewise, the optimal delay is derived by tuning the delay line module. Here, the counter is incremented by the D-type flip-flop comparing the signal arrival time with the timing reference channel. The result is a series of rate measurements of the transition region from maximum to minimum number of trigger counts. Due to the time and amplitude jitter inherent in the signals, the rate scans show a cumulative distribution function, which is used to derive the optimal settings, being found at 50% of the maximum rate (Fig. 9).

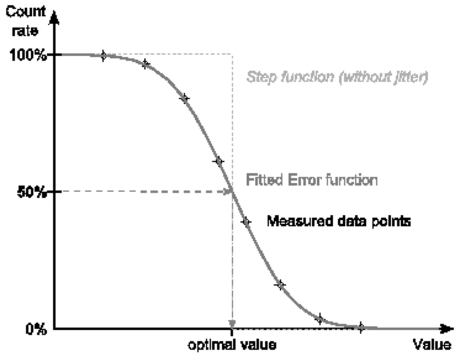

Fig. 9: Principle of the measurement process. Here, "value" means *gain* or *delay*, depending on the property calibrated.

3 Summary

The analogue Sum-Trigger is a new trigger concept that has been invented, developed and tested on the single MAGIC telescope. It was designed to lower the trigger threshold down to 25 GeV. The proof of principle was the detection of the Crab pulsar in 2008. The Sum-Trigger-II has been designed for stereo observations. Thanks to the computer control it is able to compensate the signal delays, to equalize the gain and to stabilize the trigger rates such that observations at lowest thresholds inside the night sky regime are possible.

The Sum-Trigger-II has been tested and mass production of the individual elements and boards has started. The installation, on the Magic Telescopes, is foreseen the end of this summer (2013). This system will allow us to lower the trigger threshold of MAGIC and observe many interesting objects such as Pulsars, high redshift AGN and GRBs.

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References

[1] T. M. Kneiske, K. Mannheim, and D. H. Hartmann. Astronomy Astrophysics, 386(1):111, April 2002. doi: 10.1051/0004-6361:20020211
[2] MAGIC collaboration. Science, 322(5905):12211224, November 2008. doi: 10.1126/science.1164718.
[3] Francesco Dazzi.PhD thesis, University of Udine, March 2012.
[4] Dennis Hfner.Diploma Thesis, Munchen,November 2010.