

## Analysis of the efficiency of the spectral DCT trigger in arrays of surface detectors

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**Abstract:** The trigger based on the Discrete Cosine Transform (DCT) allows recognition of ADC traces with a very short rise time and fast exponential attenuation related to a narrow, flat muon component of very inclined extensive air showers generated by hadrons and starting their development early in the atmosphere. Extensive air-showers (EAS) generate in the water surface detectors the Cherenkov light. For very inclined showers, the light falls directly mostly on two PMTs. A probability of 3-fold coincidences of direct light corresponding to a simultaneous hitting of three PMTs is relatively low. Much more probable are 2-fold coincidences of a direct light. The 3rd PMT is next hit by reflected light, but with some delay. By fast sampling (120 MHz) this delay gives signal in the next time bin. Two-fold coincidences of DCT coefficients allow triggering signals currently being ignored due to either too high amplitude threshold or due to their de-synchronization in time causing a tank geometry. The paper presents the analysis of the efficiency of the DCT trigger for simulated inclined showers. ADC traces from the digitized PMT signals are next analyzed by the DCT FPGA engines. Traces were simulated for the sampling of 120MSps - the speed of the next generation of the Front-End for detectors in cosmic rays experiments anticipated in the near future. The main goal of the analysis is to prepare the limits of the DCT coefficients to select showers from arbitrarily selected angle range and to correlate the shapes of signals with the zenith angle and the shower energy. These preliminary known estimators stored in the internal memory of the FPGA could dynamically select of the ranges of the spectral triggers.

**Keywords:** Pierre Auger Observatory, Discrete Cosine Transform, trigger, surface detector, FPGA.

### 1 Introduction

Very inclined showers are different from the ordinary vertical showers, because they have to penetrate deep into the atmosphere. At large zenith angles the slant atmospheric depth to the ground level is sufficient to absorb the early part of the shower that follows from the standard cascading interactions, both of electromagnetic and hadronic type. Only penetrating particles such as muons and neutrinos can traverse the atmosphere at large zenith angles to reach the ground or to induce secondary showers deep in the atmosphere and close to an air shower detector.

The fronts of deeply penetrating muon showers (“old” showers) have only a small longitudinal extension, which leads to short detector signals, also in time. To identify these showers a very good spectral sensitivity to the fast muon component in the trigger is needed.

Cherenkov light generated by very inclined showers crossing a water Cherenkov tank, such as in [1], can reach the PMT directly without reflections on Tyvek liners [2]. The muonic front is very flat especially for “old” showers. This together corresponds to a very short direct light pulse falling on the PMT and, in consequence, a very short rise time of the PMT response. For vertical or weakly inclined showers, where the geometry does not allow Cherenkov light to reach the PMT directly, the light pulse is collected from many reflections on the tank walls. Additionally, showers developing for not so a large slant depth are relatively thick. These give a signal from the PMT as spread over time and with a relatively long rise-time.

A very short rise-time together with a relatively quickly attenuated tail could be a sign of very inclined “old” show-

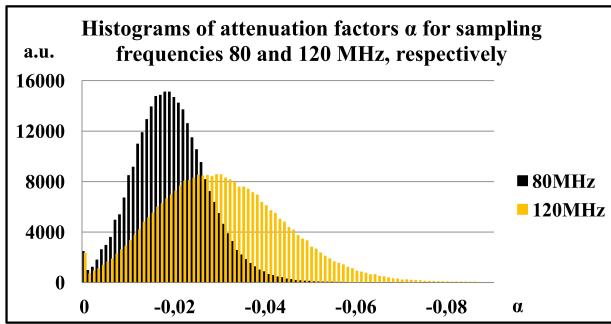
ers. Numerous very inclined showers crossing the full array were observed; however, those “fired” only few surface detectors [3]. In the case of those showers many more tanks should have been hit. The muonic front produces PMT signals either too low for three-fold coincidences or desynchronized in time.

Auger data (40 MHz sampling) show that hadron induced showers with the dominant muon component (investigated at a zenith angle of  $70 - 90^\circ$ ) give an early peak with a typical rise time mostly from 1 to 2 time bins and an exponentially attenuated tail with an attenuation factor  $\beta = 0.2 - 0.45$  [3] (compare with  $\alpha$  defined below). Very inclined showers with a well defined shape can be detected by a pattern recognition technique, in particular by a spectral trigger based on the Discrete Cosine Transform (DCT) [4].

### 2 Triggers

Two different triggers are currently implemented at the 1st level [5]. The first is a single-bin trigger generated as three-fold coincidence of the three PMTs at a threshold equivalent to 1.75 vertical emitted muons (VEM) [6]. The estimated current for the VEM is the reference unit for the calibration of ADC traces signals and corresponds to  $\sim 50$  ADC-counts. This trigger is used mainly to detect fast signals, which correspond also to the muonic component generated by horizontal showers. 1.75VEM corresponds to  $\sim 85$  ADC-counts above a pedestal.

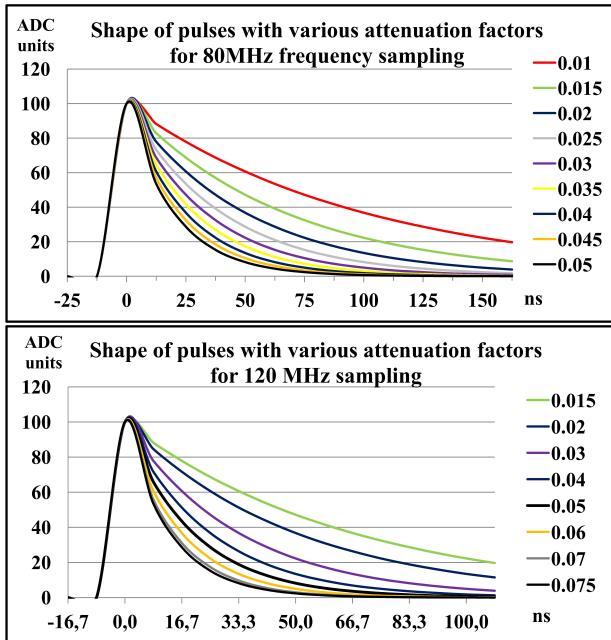
The sampling frequency  $f_{smp} = 40$  MHz in the surface detectors of the Pierre Auger Observatory was selected in 90's of the previous century. Challenges of a modern



**Fig. 1:** Histogram of attenuation factors for simulated  $10^5$  events with  $f_{smp} = 80$  and 120MHz, respectively

physics demand much higher  $f_{smp}$  which can be easily implemented due to a huge progress in electronics. An analysis of a response speed from PMTs recommends a higher  $f_{smp} = 120$ MHz.

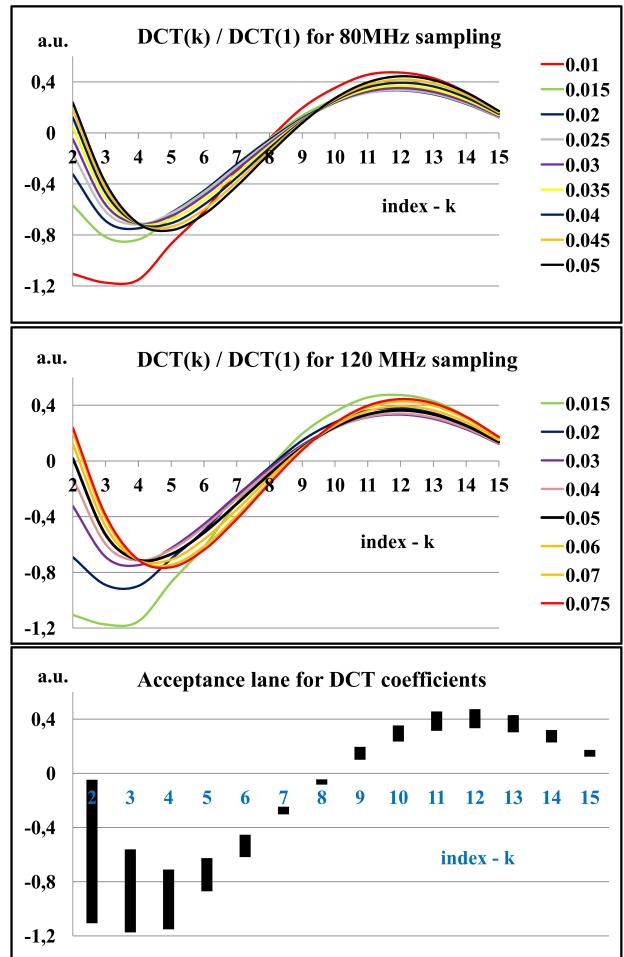
The analysis of an efficiency of the DCT approach has been performed for two  $f_{smp}$ : final 120MHz and a reference 80MHz, a intermediate between the standard Auger and the new one. For both  $f_{smp} 10^5$  traces (treated as a background) have been generated from standard Auger simulation package (see Acknowledgment). Fig. 1 shows a distribution of attenuation factors  $\alpha$  for both  $f_{smp}$ , where  $ADC_k = Ae^{-\alpha t_k}$ . The factor  $\alpha$  were fitted after a pedestal removal. Time  $t_k = k \cdot 12.5(8.333)$ ns for 80 (120)MHz, respectively.



**Fig. 2:** Shapes of traces with various attenuation factors  $\alpha$  for 80 (upper graph) and 120MHz (lower graph)  $f_{smp}$ , respectively

The factor  $\beta$  in [3] was calculated as follows:  $ADC_k = Ae^{-\beta \cdot k}$ . So, the range of  $\beta = 0.2 - 0.45$  corresponds to the scaled range of  $\alpha = \beta/25(ns) = 0.008 - 0.018$ .

Fig. 2a,b show expected ADC traces for fitted attenuation factors. According to expectations shapes are the same for  $\alpha_{80MHz} = \frac{80}{120} \cdot \alpha_{120MHz}$



**Fig. 3:** Scaled DCT coefficients for 80 (upper graph) and 120MHz (middle graph)  $f_{smp}$ , respectively, as well as the acceptance lane for DCT coefficients, the same for both  $f_{smp}$  (lower graph)

The DCT scaled coefficients (Fig. 3a,b) were calculated for two first ADC bins roughly on a pedestal level (Fig. 2a,b) with a sharp rising edge in a single time bin. This shape corresponds to a PMT response by a direct falling of the Cherenkov light.

The acceptance lane shown on Fig. 3c is practically the same for ranges of attenuation factors:  $\alpha = (0.1 - 0.3)$  and  $\alpha = (0.15 - 0.45)$  for  $f_{smp} = 80$  and 120MHz, respectively.

The 1st level trigger based on the 3-fold coincidences with 1.75VEM thresholds for three channels selects less than 0.1% of events for  $f_{smp} = 80$ MHz (Fig. 5a). For  $f_{smp} = 120$ MHz and for a such high thresholds, 3-fold coincidences are not detected at all.

A pure geometrical analysis showed [2] that very often signals in two channels give 2-fold coincidences only while the signal in the 3rd channel is delayed. Most likely, it comes not from a direct but from multiple reflected light. This induces a de-synchronization and splitting of signals above a threshold on several neighboring time bins. But these even strong but de-synchronized signals do not produce a standard trigger. The effect of de-synchronization becomes stronger for higher  $f_{smp}$ , when time bins become shorter.

The direct light can be recognized by the spectral DCT trigger. An expected shape of the ADC trace is a sharp rising edge and an exponential tail due to multiple reflection

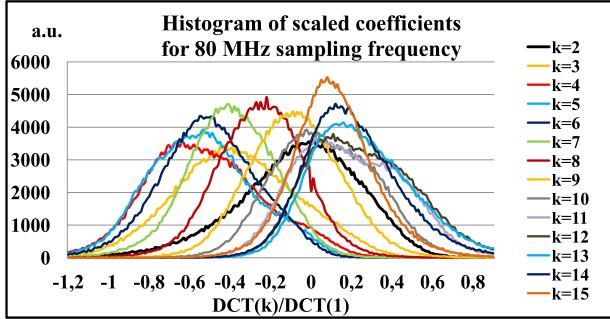


Fig. 4: Distributions of DCT coefficients for  $f_{smp} = 80\text{MHz}$

of light from tank walls. A high transparency of water allows an signal fade out for several tens of nanoseconds. A probability of falling of direct light simultaneously on two PMTs is high [2]. Such events can be detected by the 2-fold coincidences of spectral sub-triggers generated independently by each channel. The spectral sub-trigger is generated if a sub-set (called an occupancy - Occ) scaled DCT coefficients are inside of the acceptance lane. We have 14 available scaled DCT coefficients, however, a requirement all coefficients to be inside the lane is definitely to restrictive. Even non-distorted signals does not provide all DCT coefficients inside the lane due to a quantized ADC levels. Electronic noise reduces additionally this amount.

DCT coefficients scaled to the 1st harmonics are independent of the amplitude. They are determined by the shape only. This causes that the DCT trigger could also be accidentally generated by very low noise pulses with the required characteristics. In order to cut this type of the spurious triggers, the spectral trigger was also supported by the veto amplitude threshold. Pulses above this threshold are analyzed next with the DCT FPGA "engines".

### 3 Simulation of a "background"

Fig. 4 shows distributions of calculated  $DCT_k/DCT_1$  coefficients for 80MHz simulation. Distributions of particular DCT coefficients for simulations of  $10^5$  events of both  $f_{smp}$  are similar, although distributions for  $f_{smp}$  of 120MHz are slightly wider. This is a result of narrower time bins and a higher susceptibility to fluctuations.

Fig. 5b shows an amount of events registered by a spectral trigger for various occupancies and veto thresholds. Veto threshold =  $\sim 30\text{ADC}$ -counts is estimated as a reasonable value reducing evidently spurious triggers, but still allowing an analysis of low-level signals. For occupancy  $\geq 7$ , signal shapes differ from the perfect ones slightly. These signals can be treated with a high probability as generated by direct lights from muons coming to the tank at a very high azimuth angle.

Two-fold coincidences of sub-triggers (generated for an arbitrary occupancy) from any pair of two PMTs give the final spectral trigger, which can register events recognized by the shape of ADC traces. For Occ=7 and Thr=30 the spectral trigger allows a registration of several hundreds events with an almost perfect spectral characteristics, which cannot be detected by the standard 1st level (amplitude) trigger either due to too high thresholds or due to the desynchronization effects. Btw. none "background" event registered by the 3-fold coincidences have a spectral characteristic good enough to be detected by the spectral trigger.

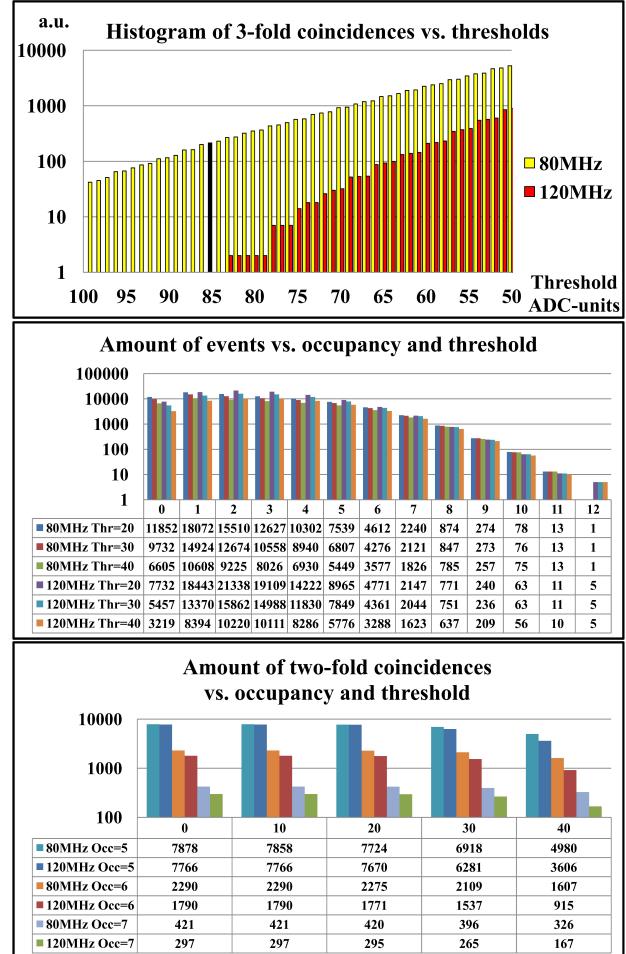


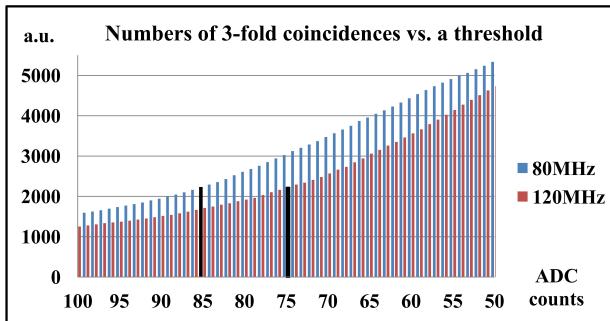
Fig. 5: A dependence of an amount of registered events as a function of veto threshold (upper graph), a dependence of an amount of events registered for various Occ and Thr (middle graph) as well as an amount of finally registered events by the spectral trigger for various Occ and Thr (lower graph)

### 4 Simulation of "events"

We analyzed 10268 and 7125 events of very incline showers (the zenith angle  $\theta = 84^\circ$  and the primary energy of initial particle =  $10^{18.5}\text{eV}$ ) simulated for  $f_{smp} = 80$  and 120MHz, respectively. The standard Auger trigger based on the 3-fold coincidence allows a registration of 2283 (22.2%) and 1225 (17.2%) events for  $f_{smp} = 80$  and 120MHz, respectively, and 1.75VEM threshold (corresponding to  $\sim 85\text{ADC}$ -counts above a pedestal. Fig. 6 shows a dependence of registered events (normalized to  $10^4$  ones) as a function of thresholds used for 3-fold coincidences for signals from three PMTs.

The width of a time bin decreases with increasing of  $f_{smp}$ . Signals above thresholds in a single time bin for  $f_{80\text{MHz}}$  may appear above the thresholds in neighboring time bins for  $f_{120\text{MHz}}$ . This causes the probability of 3-fold coincidences for  $f_{120\text{MHz}}$  is lower than for  $f_{80\text{MHz}}$ . This is easily visible on Fig. 6. Only  $\sim 20\%$  of simulated horizontal showers can be detected by the standard trigger based on a single time bin 3-fold coincidences.

Due to a geometry, the probability of direct falling of direct light on three PMTs simultaneously is low [2]. However, a probability of simultaneous light falling on any



**Fig. 6:** A dependence of registered events as a function of thresholds (values normalized to  $10^4$  events)

two PMTs may reach even 50%. Nevertheless, reflected light likely is registered in the next time bin and such an event is not detected. Such de-synchronized events can be easily detected for 2-fold coincidences in any pair of two PMTs (sub-trigger) followed by 3-fold coincidences with delayed (a single time bin) signal from the channel not "fired" for the sub-trigger. Fig. 7a shows that a such simple amplitude analysis can recognize additional 10-15% of events ignored by a standard approach.

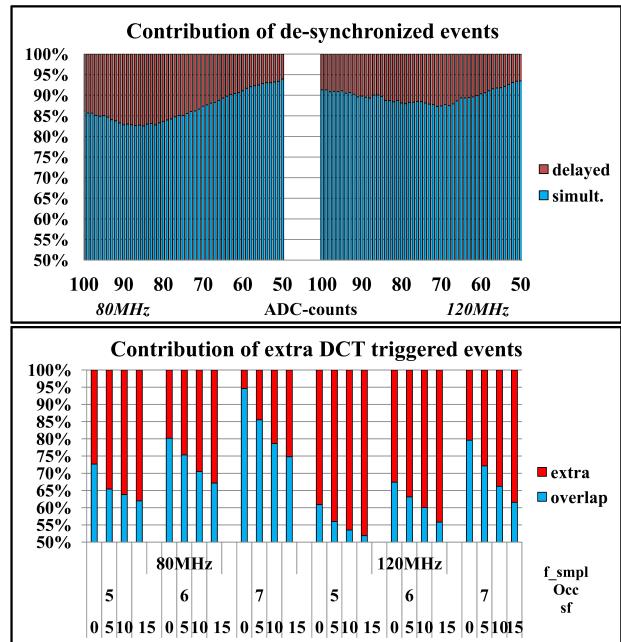
The spectral DCT trigger could be implemented as parallel one supporting the standard trigger for specific shapes of the ADC traces. Parameters of the DCT trigger are flexible and they can be optimized to improve the detection of very inclined showers, simultaneously keeping the DCT trigger rate on a level non-concurrent to the standard trigger.

The acceptance lane shown on Fig. 3c is calculated for an ideal exponentially attenuated traces without any noise or signal distortions. The lane is very narrow. In fact, noise and other signal distortions deviate the signal shape from the ideal one and may kick out the DCT coefficients outside the acceptance lane. A wider acceptance lane can compensate an influence of contamination factors. Fig. 7b shows a contribution of the DCT triggered events in a total registered ones. A significant amount of DCT triggered event are also triggered by the standard trigger. They are denoted as "overlap". However, for some configurations (i.e.  $Occ = 5$ ,  $f_{smp} = 120\text{MHz}$ ) a contribution of events triggered by the DCT may reach 40-50%. Typically, an extension of the acceptance lane of 15% increases of the DCT events contribution on a level of 10%.

## 5 Conclusions

The analysis of the simulated events shows that the pure amplitude trigger taking into account delayed signal from a single channel may improve an detection efficiency on a level of  $\sim 10\text{-}15\%$ . However, the DCT trigger may detect additionally events neglected by the standard trigger due to either too low amplitudes or a de-synchronization and an improvement of the efficiency may reach even 20-50%. A relatively high amount of the "overlap" factor confirms that the signals with high amplitudes and registered by the standard trigger have also the spectral characteristics which can be recognized by the DCT trigger.

By this analysis we assumed almost instantaneous PMT response, which manifested by a signal jump from the pedestal to the maximal value. Although, these are rather idealistic conditions, the DCT trigger recognized 20-50% more events than the standard trigger. This should improve



**Fig. 7:** Contribution of desynchronized and DCT events

a detection of very inclined showers. The spectral DCT engines can be easily implemented in the modern FPGAs with large amount of logic elements and DSP blocks.

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