
# DCT trigger in a high-resolution test platform for the detection of very inclined showers in the Pierre Auger surface detectors


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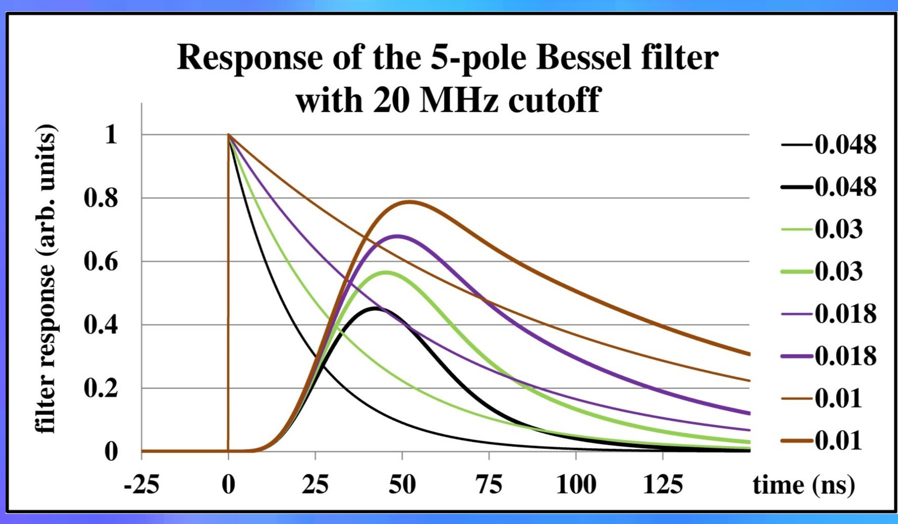
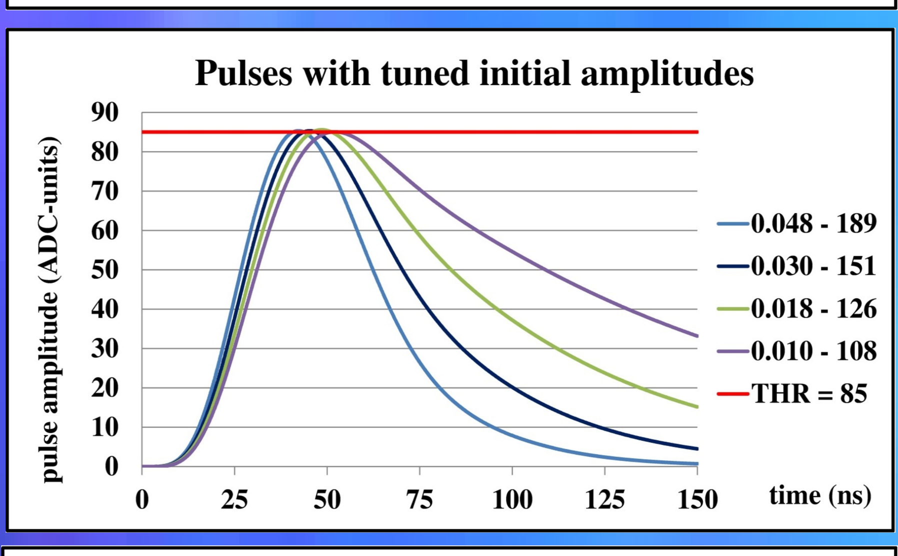
**ABSTRACT**

**We present first results from a trigger based on the Discrete Cosine Transform operating in new Front-End Boards with a Cyclone®V E FPGA deployed in 7 test surface detectors in the Pierre Auger TestArray. The patterns of the ADC traces generated by very inclined showers (arriving at 70° to 90° from the vertical) were obtained from the Auger database and from the CORSIKA simulation package supported by the Auger OffLine event reconstruction platform which gives predicted digitized signal profiles. Simulations for many values of the initial cosmic-rays angle of arrival, the shower initialization depth in the atmosphere, the type of particle and its initial energy gave a boundary on the DCT coefficients used for the online pattern recognition in the FPGA. Preliminary results validated the approach used. We recorded several showers triggered by the DCT for 120 and 160 MSps. Very inclined showers generated by hadrons and starting their development early in the atmosphere produce a relatively thin muon pancake ($\sim$1m thickness) at the ground detection level. Ultra-relativistic charged particles traversing the water in a surface detector \cite{PAO} generate Cherenkov light detected by three 9-inch hemispherical photomultiplier tubes (PMTs). Direct exposure to the Cherenkov light cone gives a signal pulse with a very short rise time and fast exponential attenuation. The trigger based on the Discrete Cosine Transform (DCT) allows recognition of ADC traces with such specific shapes Standard Auger trigger requires 3-fold coincidences of all 3 PMTs in the tank in a single time bin.**

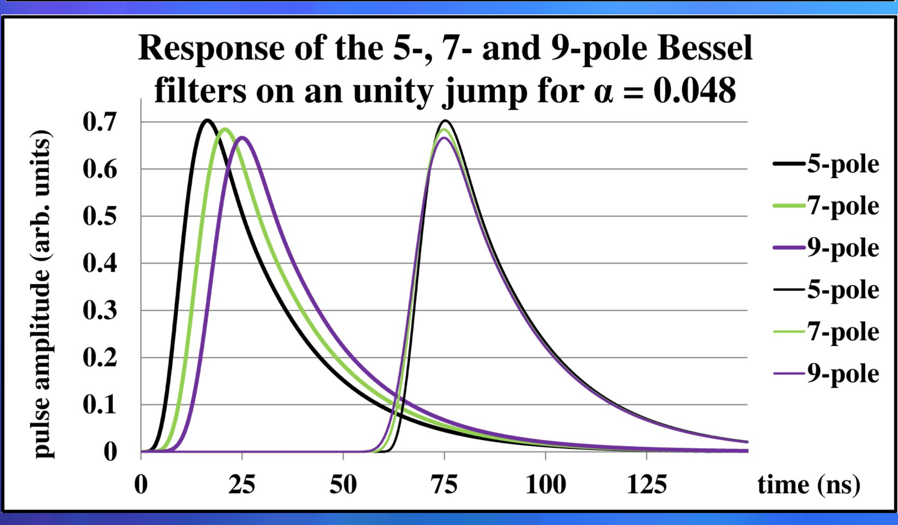
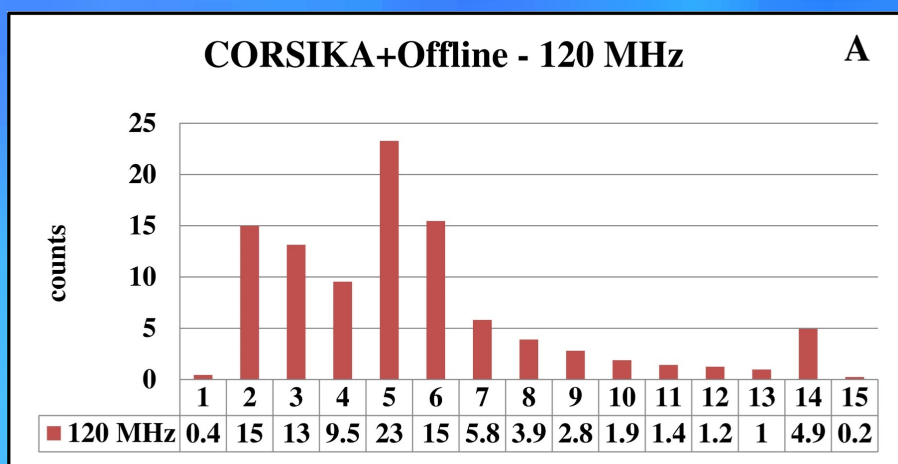




**Fig. 1** – Pulses filtered by the 5-pole Bessel filter with 20 MHz cutoff with amplitudes: 189, 151, 126 or 108 ADC-units, respectively for 0.048, 0.03, 0.18 or 0.01 exponential factors and with a unity jump (upper and middle graph). Response for a unity jump of Bessel filters with a 60 MHz cut-off and 5,7 and 9 poles, respectively (lower graph).




| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 120 MHz | 0.4 | 15 | 13 | 9.5 | 23 | 15 | 5.8 | 3.9 | 2.8 | 1.9 | 1.4 | 1.2 | 1 | 4.9 | 0.2 |

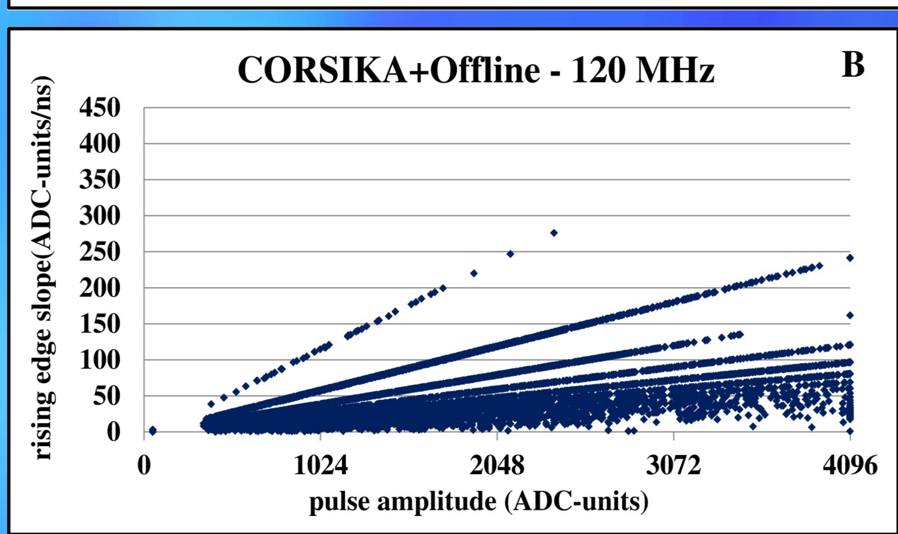
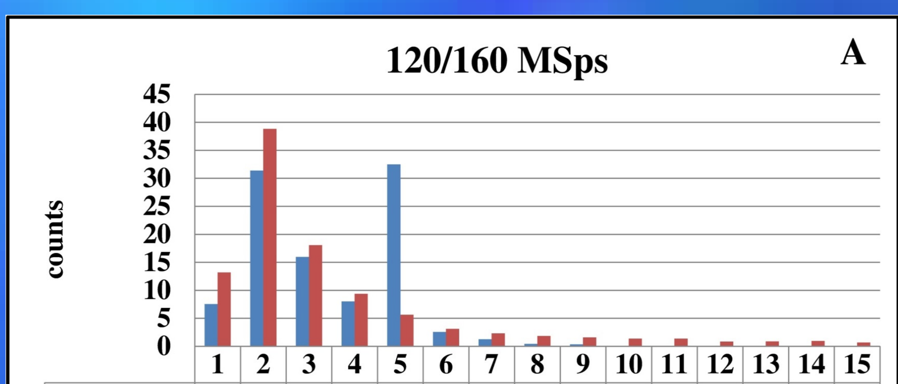
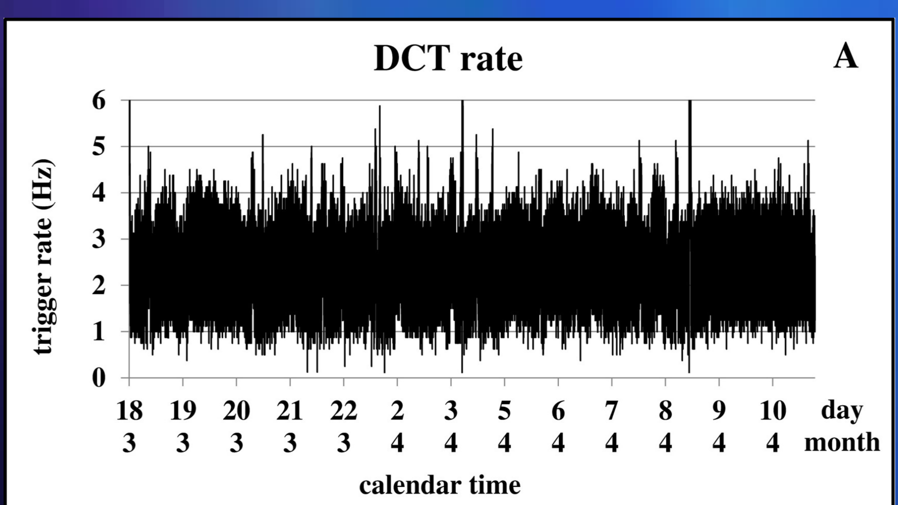



**Fig. 2** – Contribution of rise times for 1- ,2- and more time bins for CORSIKA + OffLine simulations with a 120 MHz sampling frequency (upper graph) as well as slope distribution of rising edges of signal waveforms as a function of an amplitude for 120 MSps sampling (lower graph). Branches correspond to 1-, 2- and more time-bin slopes from pedestal level to the maximum value.




| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 160 MSps | 7.5 | 31 | 16 | 8 | 32 | 2.6 | 1.3 | 0.4 | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 |
| 120 MSps | 13 | 39 | 18 | 9.4 | 5.6 | 3.1 | 2.3 | 1.8 | 1.6 | 1.4 | 1.4 | 0.9 | 0.9 | 1 | 0.7 |



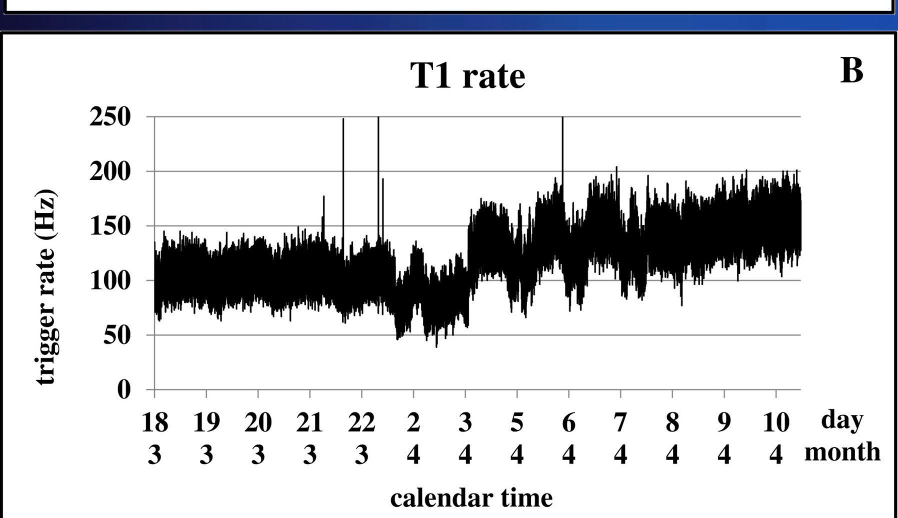
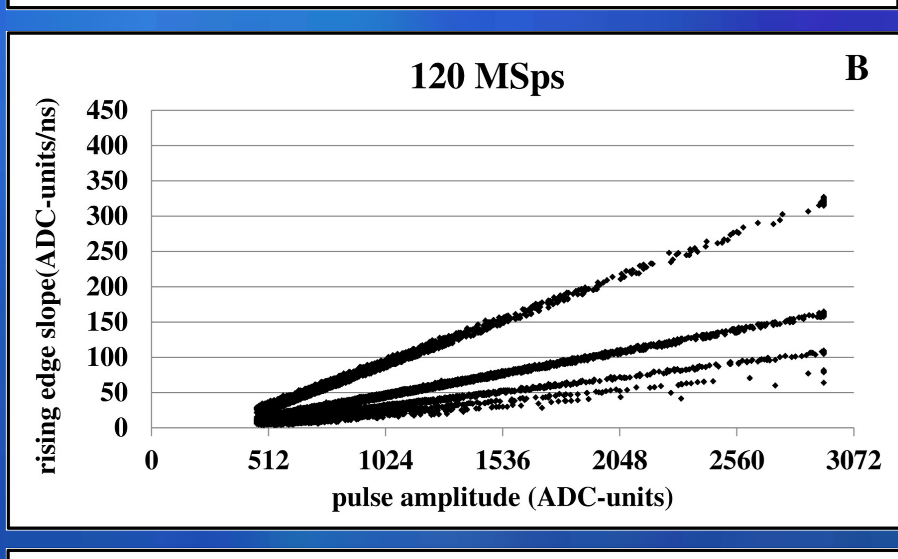




**Fig. 4** – DCT and T1 rates for DAQ test sessions in March 18 - April 10, 2016



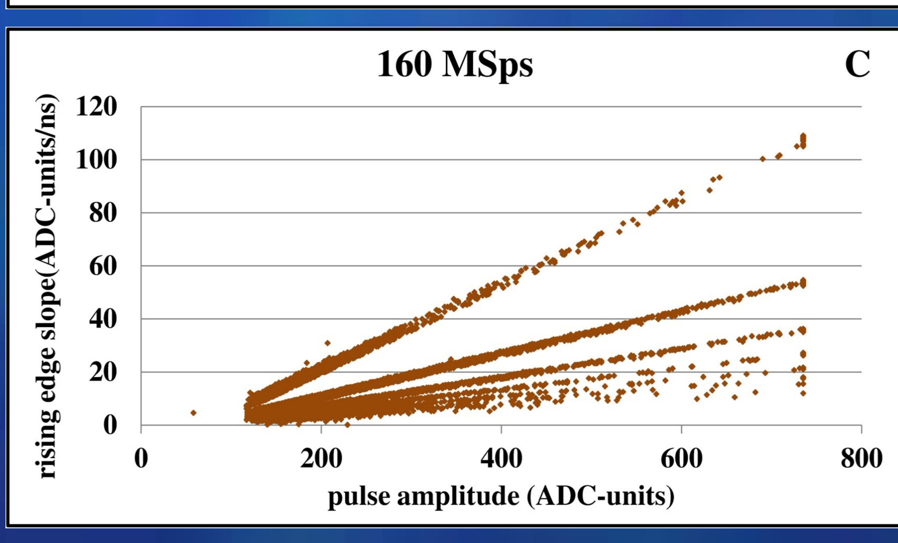
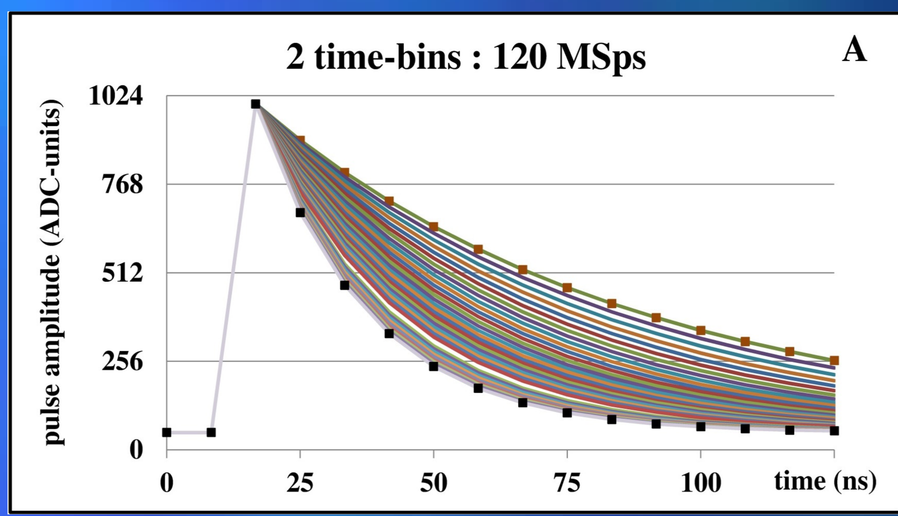




**Fig. 5** – Contributions of rise times for 1- ,2- and more time bins for real measurements and slope distribution of rising edges of signal.



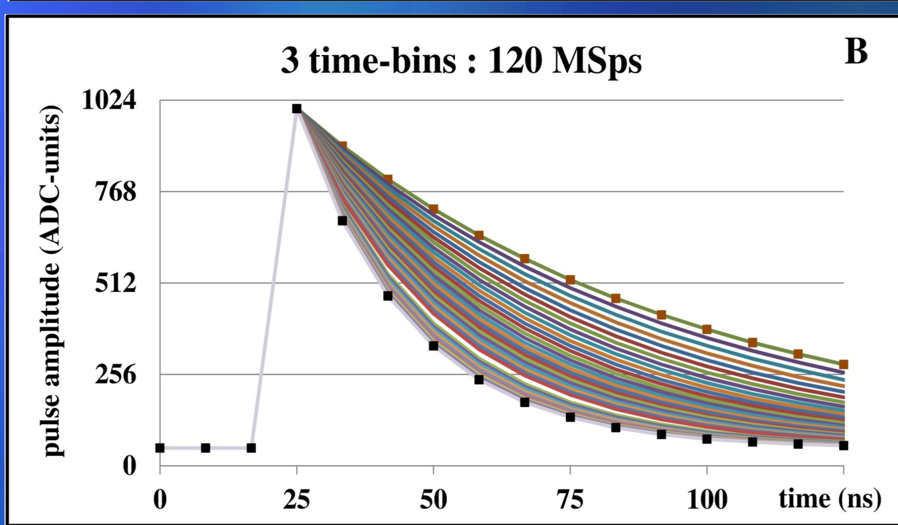
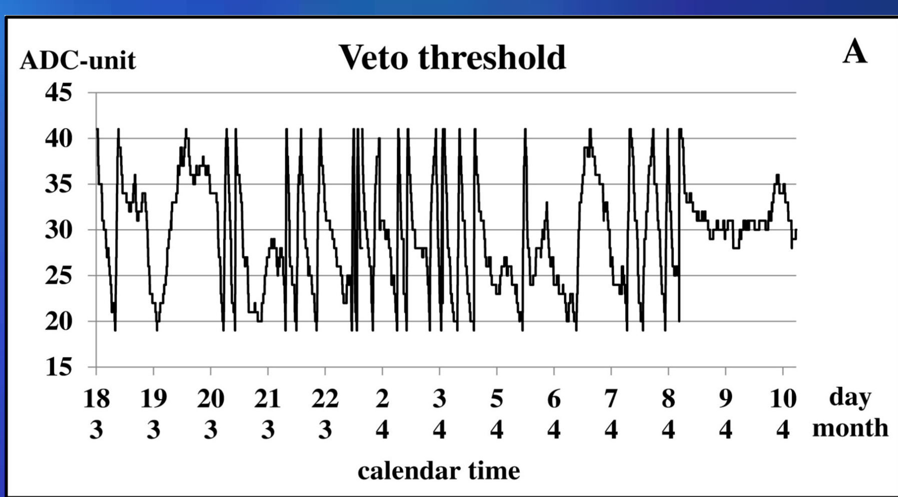
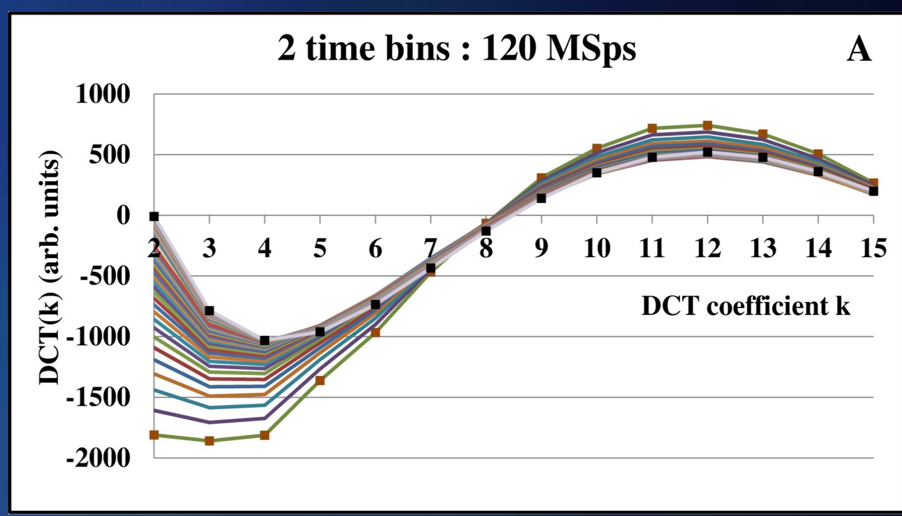
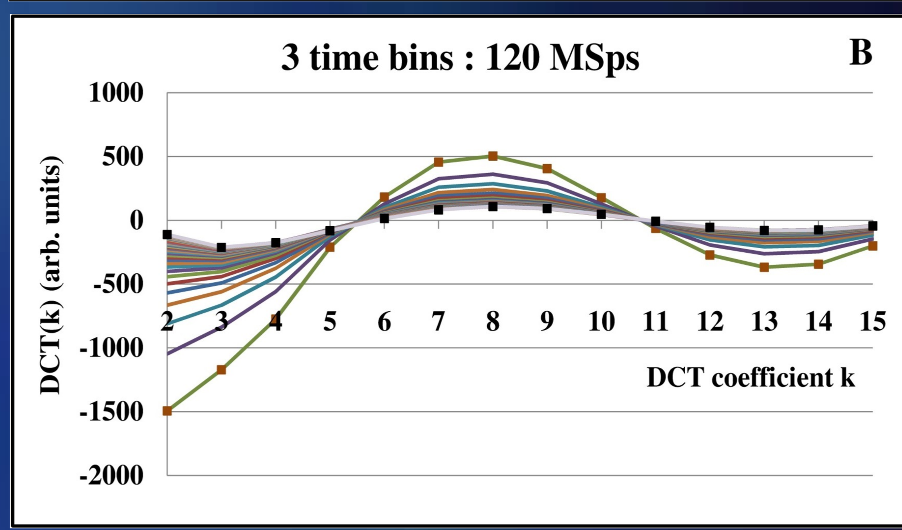




**Fig. 3** – Shapes of signal waveforms giving the DCT trigger. Graphs correspond to shapes, where jumps appear in the 2nd or 3rd time bins.



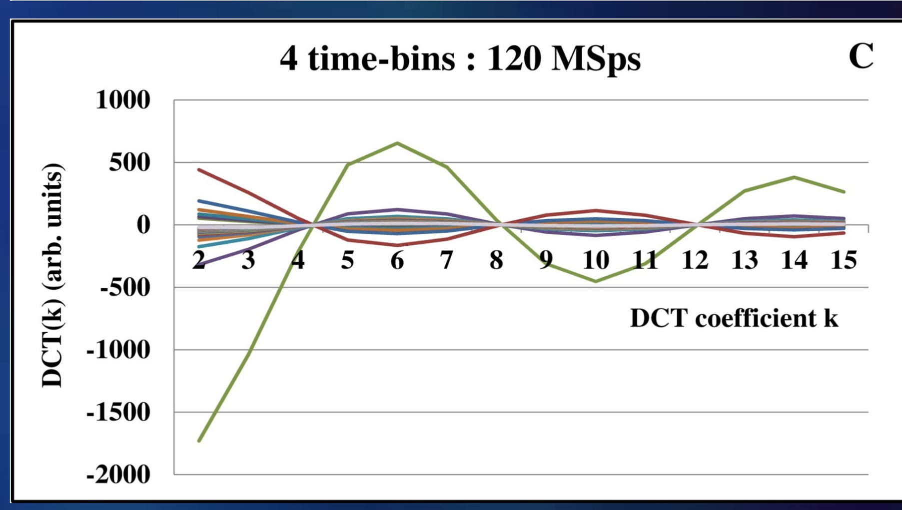
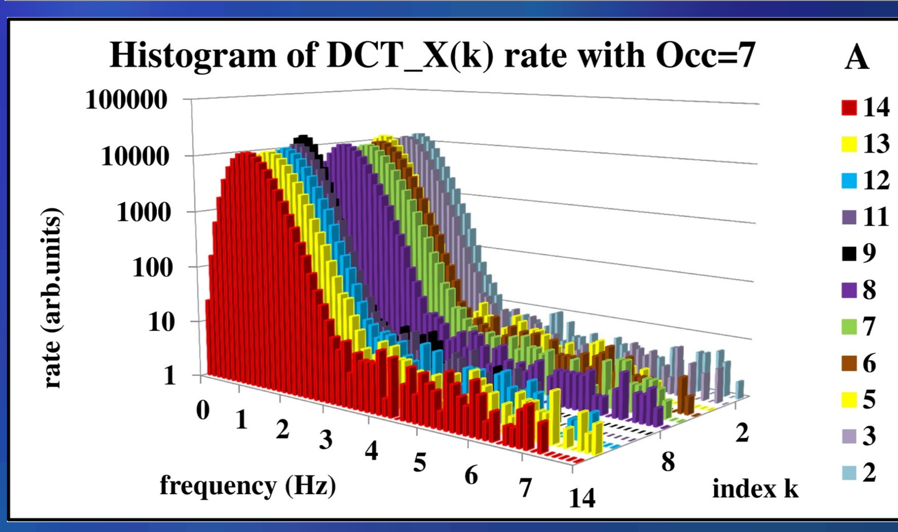
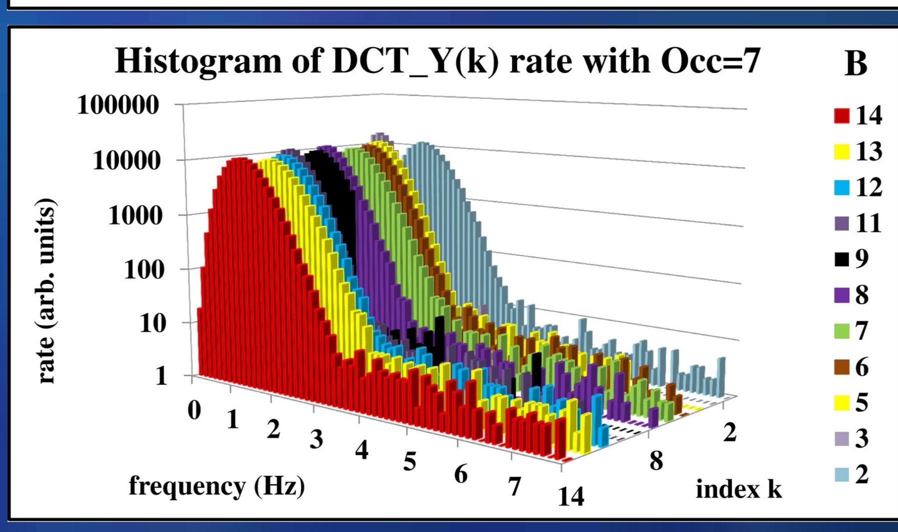




**Fig. 6** – Coefficients giving the DCT trigger. Graphs correspond to shapes, where a jump appears in the 2nd ,3rd and 4th time bins.



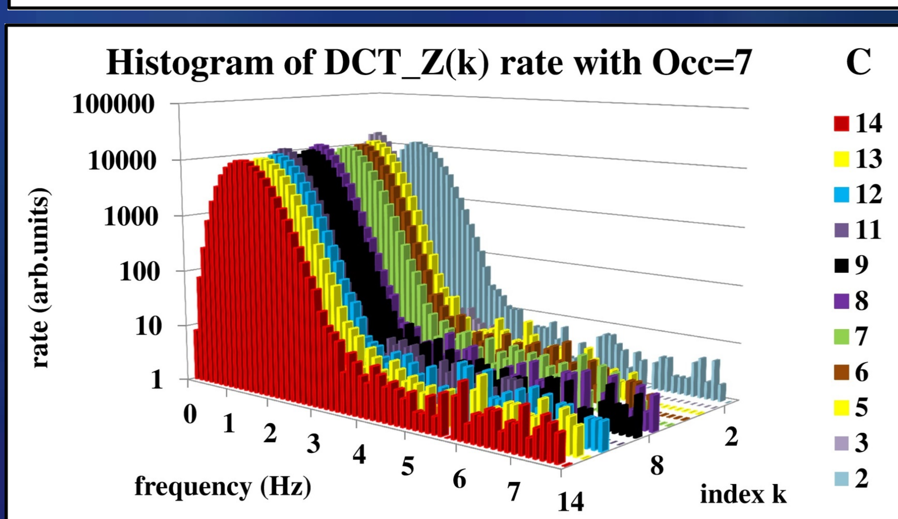
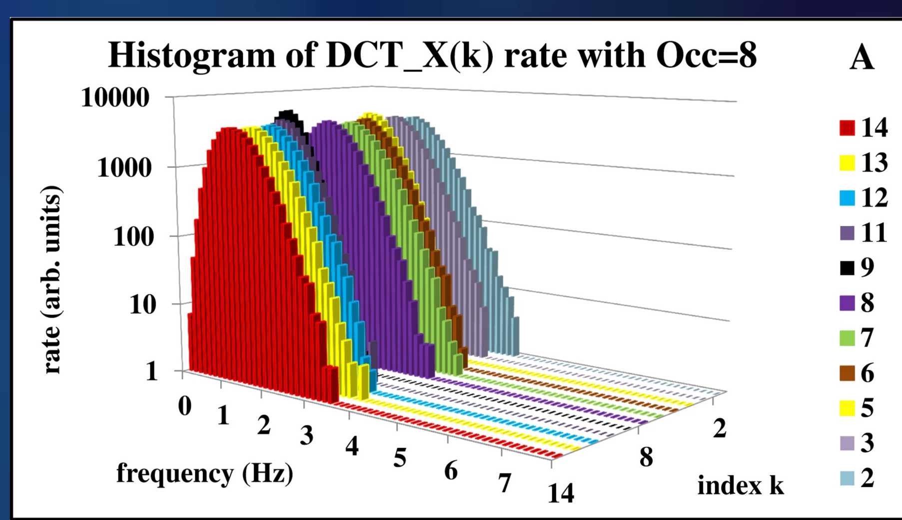
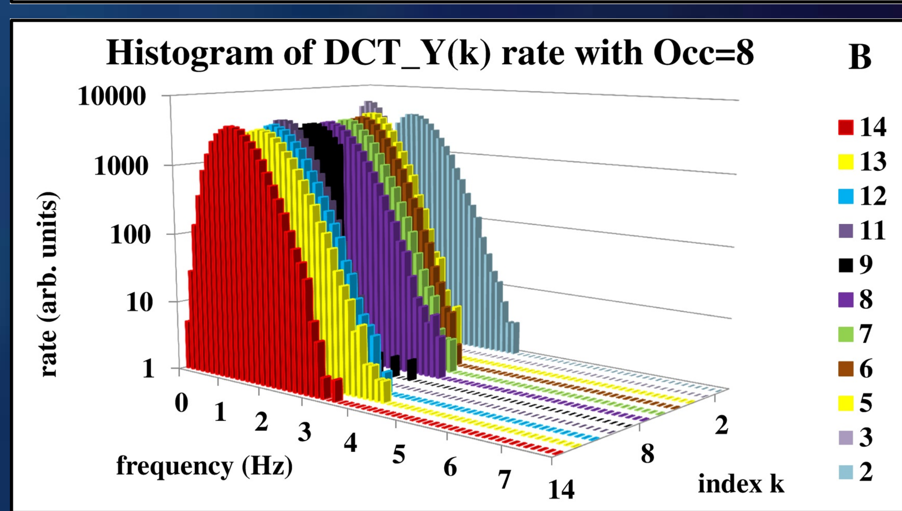




**Fig. 6** – Internal structure of an FPGA neural network.



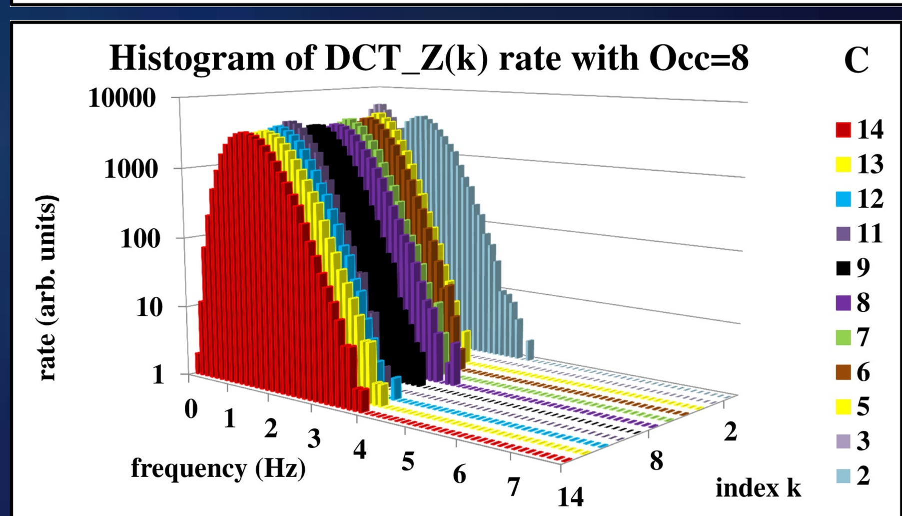




**Fig. 7** – DCT rates for DAQ test sessions with Occ = 8


[1] Pierre Auger Collaboration, A. Aab et al., *The Pierre Auger Cosmic Ray Observatory, Nucl. Instrum. Meth.* **A 798** (2015) 172.
[2] Pierre Auger Collaboration, P. Abreu et al., *Search for ultrahigh energy neutrinos in highly inclined events at the Pierre Auger Observatory, Phys. Rev.* **D 84** Issue 12 (2011) 122005.
[3] Pierre Auger Collaboration, P. Abreu et al., *Search for point-like sources of ultra-high energy neutrinos at the Pierre Auger Observatory and improved limit on the diffuse flux of tau neutrinos, Astrophys. Journal Lett.* **755** Issue 1 (2012) L4.
[4] Z. Szadkowski, *A spectral 1st level FPGA trigger for detection of very inclined showers based on a 16-point Discrete Cosine Transform for the Pierre Auger Observatory, Nucl. Instrum. Meth.* **A 606** (2009) 330.
[5] Z. Szadkowski, *Trigger Board for the Auger Surface Detector with 100 MHz Sampling and Discrete Cosine Transform, IEEE Trans. on Nucl. Science* **58** (2011) 1692.
[6] Z. Szadkowski, Z. Szadkowski, *Optimization of the Detection of Very Inclined Showers Using a Spectral DCT Trigger in Arrays of Surface Detectors, IEEE Trans. on Nucl. Science* **60** (2013) 3647.


**CONCLUSIONS**

Tests on the „Jamie" surface detector allowed an optimization of DCT trigger parameters to get a stable DAQ with simultaneous T1 and DCT triggers for 120 MHz sampling on the new Front-End Board equipped with the Cyclone® FPGA. The parameters Occ = 8 and $Thr_{veto}$ in a wide range of 20-48 ADC-units provide stable DAQ conditions over. The „Jamie" detector located close to the Assembly Building of the Pierre Auger Observatory was not equipped with a solar panel but instead with a standard power supply. This allowed a continuous operation with a power consumption at a level of 19 W (the solar panel provides ~10 W only). Data collecting on a local PC were next transferred via remote link to the University of Łódź, Poland. Seven Front-End Boards have already been deployed over a hexagon of surface detectors in the Pierre Auger Test Array in November 2015. However, they were not equipped with the DCT trigger yet. Due to a higher power consumption than available with solar cells, the surface detectors equipped with Cyclone®V FPGA will have to be working in an interrupted mode. Field tests of the DCT trigger have been temporarily postponed until the near future, when the power budget is better optimized.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