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16-point discrete Fourier transform based on the Radix-2 FFT algorithm implemented into cyclone FPGA as the UHECR trigger for horizontal air showers in the Pierre Auger Observatory

Z. Szadkowski*,[1]

Physics Department, Bergische Universität Wuppertal, 42097 Wuppertal, Germany

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Abstract

Extremely rare flux of UHERC requires sophisticated detection techniques. Standard methods oriented on the typical events may not be sensitive enough to capture rare events, crucial to fix a discrepancy in the current data or to confirm/reject some new hypothesis. Currently used triggers in water Cherenkov tanks in the Pierre Auger surface detector, which select events above some amplitude thresholds or investigate a length of traces are not optimized to the horizontal and very inclined showers, interesting as potentially generated by neutrinos. Those showers could be triggered using their signatures: i.e. a curvature of the shower front, transformed on the rise time of traces or muon component giving early peak for "old" showers. Currently available powerful and cost-effective FPGAs provide sufficient resources to implement new triggers not available in the past. The paper describes the implementation proposal of 16-point discrete Fourier transform based on the Radix-2 FFT algorithm into Altera Cyclone FPGA, used in the 3rd generation of the surface detector trigger. All complex coefficients are calculated online in heavy pipelined routines. The register performance ~200 MHz and relatively low resources occupancy ~2000 logic elements/channel for 10-bit resolution provide a powerful tool to trigger the events on the traces characteristic in the frequency domain. The FFT code has been successively merged to the code of the 1st surface selector level trigger of the Pierre Auger Observatory and is planned to be tested in real pampas environment.

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1. Introduction

Extensive Air Showers are investigated in several experiments utilizing different detection techniques (scintilators, water Cherenkov and fluorescence detectors). Signals in the detectors depend on several parameters such as the energy, the type of the primary particle, distance from the core, the angle of registered shower, etc.

Usually the triggering conditions are chosen such as to detect as wide as possible classes of events. However, sometimes the standard trigger conditions are not optimized for the specific class of events, which are either not registered at all or for which the registration efficiency is poor.

In experiments utilizing water Cherenkov detectors, signals from photo-multipliers are usually digitized in Flash ADCs and next processed by often-sophisticated electronics. In order to increase the signal/noise ratio coincidence techniques are widely used. Typically signals from PMTs are analyzed online in both amplitude and time domains. Strong signals in all PMT channels, corresponding to energetic showers detected near the core, are

*Tel.: +49 202 439 3736; fax: +49 202 439 2662.
E-mail address: zszadkow@physik.uni-wuppertal.de.
[1]On leave from University of Łódź, Pomorska 151, 90-236 Łódź, Poland.

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registered because of many-fold coincidence single bin trigger with a fixed thresholds. Showers detected far from the core give much lower signals usually spread in time. Such events are detected by the other type of trigger investigating the structure of signal in some period (in a sliding time window).

Both types of triggers do not seem to be optimized for very inclined or horizontal showers, also generated by neutrinos. The signals from that type of showers are usually too low to be detected by the single bin trigger. On the other hand, the signals could be too short to provide sufficient occupancy to be detected by a Time over Threshold trigger (ToT) [1].

2. Deep showers

The structure of signals detected in water Cherenkov tanks and generated by horizontal showers depend strongly on the point of the EAS initialization. "Old" showers (see Fig. 1) generated by hadrons early in the atmosphere give flat muonic front; showers generated by deeply interacting neutrinos are characterized by a curved front (radius of curvature of a few km), a large electromagnetic component and with particles spread over a few microseconds interval [2]. In both cases muonic front produces a bump, which can be a starting signature of horizontal showers. The bump for the "old" showers is shorter and sharper than for the "young" ones and results in a larger contribution in higher Fourier coefficients. For "young" showers, with relatively smooth shape of a signal profile, the lower Fourier components should dominate. The online analysis of the Fourier components may trigger specific events.

The existing software procedures, available as commercial IP routines, can calculate Fourier coefficients effectively utilizing a FFT algorithm. However the software implementation is too slow to be able to trigger events in the real time. Online triggering requires the hardware implementation calculating multipoint DFT with a sufficient speed. Modern powerful FPGAs can do this job, however, the resource requirement increases dramatically with the number of points. The analysis time interval should be a reasonable compromise between a time resolution and the resources occupancy in the FPGA.

3. General algorithm

Let us consider a DFT $\bar{X}$ of dimension N [3]

$$\bar{X}_k = \sum_{m=0}^{N-1} x_m W^{mk} \tag{1}$$

where $W = e^{-j2\pi/N}$ and $k = 0, \ldots, N-1$.

If N is the product of two factors, with $N = N_1 N_2$, the indices m and k we can redefined as follows: $m = N_1 m_2 + m_1$,

where $m_2 = 0, \ldots, N_2 - 1$ and $m_1 = 0, \ldots, N_1 - 1$,
$k = N_2 k_1 + k_2$, $k_2 = 0, \ldots, N_2 - 1$
and $k_1 = 0, \ldots, N_1 - 1$

$$\bar{X}_{N_2 k_1 + k_2} = \sum_{m_1=0}^{N_1-1} W^{N_2 m_1 k_1} W^{m_1 k_2} \times \sum_{m_2=0}^{N_2-1} x_{N_1 m_2 + m_1} W^{N_1 m_2 k_2}. \tag{2}$$

For the Radix-2 algorithm: $N = 2^t$, $N_1 = 2$ and $N_2 = 2^{t-1} = N/2$. Hence,

$$\bar{X}_k = \sum_{m=0}^{N/2-1} (x_{2m} + W^k x_{2m+1}) W^{2mk}. \tag{3}$$

If we split the sum as follows

$$\bar{X}_k = \sum_{m=0}^{N/4-1} x_{2m} W^{2mk} + \sum_{m=N/4}^{N/2-1} x_{2m} W^{2mk} + \sum_{m=0}^{N/4-1} x_{2m+1} W^{2mk} + \sum_{m=N/4}^{N/2-1} x_{2m+1} W^{2mk} \tag{4}$$

and afterwards, if we redefine indices and group the sums, we get,

$$\bar{X}_k = \sum_{m=0}^{N/4-1} (x_{2m} + (-1)^k x_{2(m+N/4)}) W^{2mk} + W^k \left(\sum_{m=0}^{N/4-1} (x_{2m+1} + (-1)^k x_{2(m+N/4)+1} \right) W^{2mk}. \tag{5}$$

We can introduce the new set of variables defined for $m = 0, \ldots, N/4 - 1$ as follows:

$$A_{2m} = x_{2m} + x_{2m+N/2} \tag{6}$$

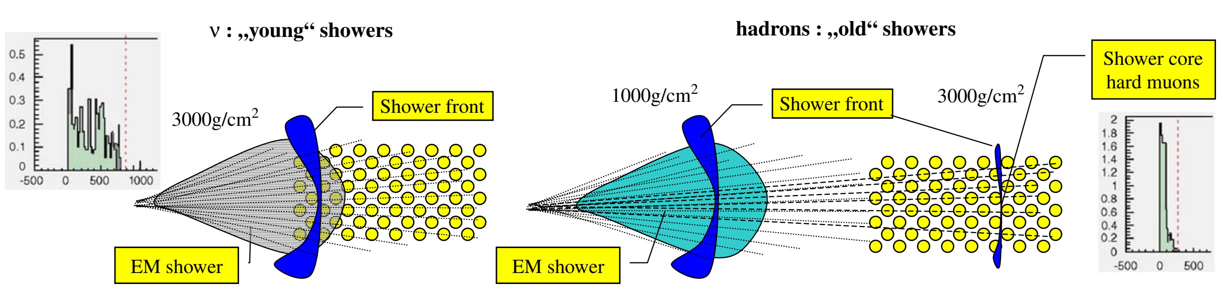

Fig. 1. Development of showers generated deeply and early in the atmosphere.