Artificial Neural Network as a FPGA Trigger for a Detection of Very Inclined Air Showers

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Abstract—The observation of ultra-high energy neutrinos (UHE$\nu$s) has become a priority in experimental astroparticle physics. Neutrinos can interact in the atmosphere (downward-going $\nu$) or in the Earth crust (Earth-skimming $\nu$), producing air showers that can be observed with arrays of detectors at the ground. The surface detector array of the Pierre Auger Observatory can detect these types of cascades. The distinguishing signature for neutrino events is the presence of very inclined showers produced close to the ground (i.e., after having traversed a large amount of atmosphere). Up to now, the Pierre Auger Observatory did not find any candidate for a neutrino event. This imposes competitive limits to the diffuse flux of UHE$\nu$s.

A very low rate of events potentially generated by neutrinos is a significant challenge for a detection technique and requires both sophisticated algorithms and high-resolution hardware. We present a trigger based on a pipeline artificial neural network implemented in a large FPGA which after learning can recognize traces corresponding to special types of events.

The structure of an artificial neural network algorithm being developed on the MATLAB platform has been implemented into the fast logic of the biggest Cyclone® V FPGA used for the prototype of the Front-End Board for the Auger-Beyond-2015 effort. Several algorithms were tested, however, the Levenberg-Marquardt one (trainlm) seems to be the most efficient.

The network was taught: a) to recognize "old" showers (learning on a basis of real very inclined Auger showers (positive markers) and real standard showers especially triggered by Time over Threshold (negative marker), b) to recognize "young" showers (on the basis of simulated "young" events (positive markers) and standard Auger events as a negative reference). A three-layer neural network being taught by real very inclined Auger showers shows a good efficiency in pattern recognition of 16-point traces with profiles characteristic of "old" showers.

Nevertheless, preliminary simulations of showers with the CORSIKA shower simulation package and the response of the water Cherenkov tanks with the Offline data analyses and reconstruction package suggest that for neutrino showers starting a development deep in the atmosphere, and for relatively low initial energy $\sim 10^{18}$ eV, ADC traces are not too long, and a 16-point analysis should be sufficient for a recognition of "young" showers. The neural network algorithm can significantly support a detection for low energies, where a more intense neutrino interaction becomes more probable [14].

Index Terms—Pierre Auger Observatory, trigger, FPGA, DCT, neural network.

I. INTRODUCTION

ULTRA-high energy cosmic ray (UHECR) experiments in energy range of $10^{18} - 10^{20}$ eV are the inspiration for active development of theoretical astrophysics hypotheses [11]. The origin of the UHECRs, their production mechanism and composition still remain a mystery, as do hypothetical fluxes of ultrahigh energy neutrinos (UHE$\nu$s) [2].

Generally, we can classify astrophysical models as: "bottom-up" and "top-down". In the first case, protons and nuclei are accelerated in astrophysical shocks, while pions are produced by cosmic ray interactions with matter or radiation at the source [3]. The second scenario postulates that protons and neutrons are produced from quark and gluon fragmentation of very heavy particles, according to Grand Unified Theories or Super-symmetries, with a supremacy of pions over nucleons [4]. However, "top-down" models have been rather disfavored by the Pierre Auger Observatory due to relatively low photon limits [5]. Protons and nuclei also produce pions due to the Greisen-Zatsepin-Kuzmin (GZK) cutoff [6][7] seen by HiRes [8] and confirmed by the Pierre Auger Observatory [9][10].

For primary protons, decays of charged pions (as results of photo-pion production associated with the GZK effect) are expected to be the source of ultra-high energy neutrinos (UHE$\nu$s). However, their fluxes are still doubtful. If the primaries are heavy nuclei, the UHE$\nu$s should be significantly suppressed [11].

The observation of UHE$\nu$s should support an explanation of the origin of UHECRs [12]. Neutrinos indicate directly the source of their production due to the absence of any deflection in magnetic fields. Unlike photons, their unimpeded travel from the sources to the Earth may support a confirmation or rejection of production models. UHE$\nu$s can be detected with arrays of detectors at ground level that are currently being used to measure extensive showers produced by cosmic rays, e.g. the Pierre Auger Observatory [13]. The main challenge in this technique is the extraction of showers initiated by neutrinos from the "background" induced by regular cosmic rays.

Neutrinos have very small cross-sections. This implies a very low probability of interaction for any relatively thin target such as at small zenith angles of neutrino incidence, corresponding to a slant depth at the level of 1 kg/cm$^2$. Neutrinos can interact at any point along their trajectories. For a very inclined shower the slant depth increases to $\sim 31$ kg/cm$^2$ and neutrino interactions become more probable [14]. Protons, nuclei, or photons usually interact shortly after entering the atmosphere. For inclined showers they produce a narrow muonic pancake (only the muonic component survives), while for...
deeply interacting neutrinos the inclined showers contain also a significant electromagnetic contribution. Inclined showers that interact deep in the atmosphere may be a signature of neutrino events. The surface detector array (SD) of the Pierre Auger Observatory can detect both Earth-skimming and down-going showers [15]. The Earth skimming neutrino events are limited to a very narrow zenith range where the expected background of nucleonic showers is very small. For downward-going neutrino showers there is in principle a larger range of possible zenith angles, but with larger background contamination. This imposes specific algorithms allowing a separation of neutrino-induced showers from nucleonic ones.

In the downward-going channel neutrinos can be generated via both charged and neutral current interactions. Neutrinos of any flavor can induce extensive air showers along the entire path of their development in the atmosphere, also very close to the ground [16].

In the Earth-skimming channel showers can be induced by $\nu_\tau$, being a product of a $\tau$ lepton decaying after the propagation and interaction of an upward-going $\nu_\tau$ inside the Earth [17].

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II. ADC TRACES ANALYSIS

The surface detector array of the Pierre Auger Observatory is able to detect and identify UHE$\nu$s for $E \geq 10^{18}$ eV [18]. Due to a much larger first interaction cross-section for protons, heavier nuclei and even photons than for neutrinos, their showers usually appear shortly after entering the atmosphere. However, neutrinos can generate showers deeply into the atmosphere. Vertical showers initiated by protons or heavy nuclei have a considerable amount of electromagnetic component at the ground (“young” shower front). However, at high zenith angles ($\theta \geq 70^\circ$) (thicker than about three vertical atmospheres), UHECRs interacting high in the atmosphere generate shower fronts dominated by muons at the ground (an "old" shower front), which generate narrow signals (short ADC traces) spreading over typically tens of nano-seconds in practically all the stations of the event. These traces can be recognized with an algorithm of a 16-point discrete cosine transform (DCT) as well as with a 16-point input artificial neural network (ANN).

For a recognition of the very inclined "old" showers the DCT algorithm [19] was developed and tested on the SD test detector in Malargüe (Argentina) [20] [21]. The algorithm precisely recognized ADC traces of required shapes. Up to now it was tuned for "old" showers, however, it could be optimized also for shapes characteristic for "young" showers. The ANN algorithm is an alternative approach. The efficiency of both algorithms will be tested for both types of showers.

"Young" showers are spread in time over thousands of nano-seconds (Fig. 1) [15]. For the "old" showers practically only the muonic component survives. It gives a short bump in the SD. The "young" showers comprise also some electromagnetic component, which spread the ADC traces in time. However, the muonic component of "young" showers is ahead of the electromagnetic one and gives an early bump. The rising edge of the bump is not so sharp as for the "old" ones, but this signal is also relatively rapidly attenuated, until the electromagnetic component starts to provide its own contribution. The ANN approach can focus on the early bump, to select traces potentially generated by neutrinos.

On the other hand, independent simulations of showers in CORSIKA [22] and a calculation of a response of water Cherenkov detectors (WCDs) in OffLine [23] showed that for neutrino showers (initiated either by $\nu_\mu$ or $\nu_\tau$) for relatively large zenith angle (e.g. $70^\circ$) and low altitude (9 km) (to be treated as "young" showers before the maximum of development) there are relatively short ADC traces which can be analyzed also by 16-point pattern engines.

Fig. 1. Simulated ADC traces of stations at 1 km from the shower core for two real showers of 5 EeV. (a) Old extensive air shower ($\theta \sim 80^\circ$). (b) Shower arriving in the early stages of development (young shower) [15].

Fig. 2. Histogram of "fired" surface detectors for showers initiated by $\nu_\mu$ (left panel) and $\nu_\tau$ (right panel) neutrinos at an altitude of 9350 m.
Showers induced by relatively low-energy neutrinos (in the range of $10^{18}$ eV) (independently of flavor) can "fire" only a few surface detectors (Fig. 2). These showers may be ignored due to the Auger T3 trigger [24], although they can generate even saturated traces in a few surface detectors (Fig. 5).

Table I shows a fractional rate of simulated events giving 3-fold coincidences on the T1 threshold trigger [24]. For low energy neutrino showers a parallel trigger based on a pattern recognition (i.e. using an artificial neural network) can improve the probability of neutrino-induced shower detection.

Figs. 3 and 4 show that ignored events (which do not obey a condition of the T1 threshold trigger), especially for low energies, can be analyzed by the 16-point only algorithm, either the DCT or the ANN one.
### TABLE I

| Energy    | $\theta = 22^\circ$ | $\nu_\tau | 22^\circ$ | $\nu_\theta | 70^\circ$ | $\nu_\theta | 70^\circ$ |
|-----------|---------------------|------------|------------|------------|------------|
| $10^{18}$eV | 33 %                | 10 %       | 83 %       | 75 %       |
| $10^{19}$eV | 53 %                | 40 %       | 89 %       | 88 %       |
| $10^{20}$eV | 80 %                | 83 %       | 87 %       | 88 %       |

### III. MATLAB ANALYSIS

The main motivation of an ANN implementation as a shower trigger is the fact that up to now the entire array did not register any neutrino-induced event. The probable reasons are: a) a very low flux of neutrinos and b) amplitudes of ADC-traces that are small and probably below the threshold of the standard 3-fold coincidence trigger. The main idea is to use the ANN approach as a pattern recognition technique.

Several networks were tested (Fig. 6) to get a reasonable compromise between the efficiency of the pattern recognition and a resource occupancy in the FPGA. To train the network we created a database of real Auger inclined "old" showers (as positive marker) and "typical expected neutrino-like signal" (mostly vertical as negative markers). Table II shows results for various teaching configurations used for two networks. Only the Levenberg-Marquardt (Trainlm in MATLAB) algorithm was very efficient. The others showed unacceptable levels of error rates (Table II).

Theoretically, a more complicated network could provide a higher efficiency (Table III), however, it requires much more FPGA resources, especially DSP embedded multipliers. The biggest FPGA from the Cyclone® V E family - 5CEFA9F31I7 contains 342 fast DSP embedded multipliers. For 3 independent ANN (for 3 PMTs in the Auger surface detector) we can use 114 DSP blocks per channel. A single neuron (with sixteen 14-bit inputs and 14-bit coefficients) implemented with Altera® Multiply Adder v13.1 and PARALLEL_ADD Megafuntions requires 8 DSP blocks (Fig. 8). 114 DSP blocks allow an implementation of 14 neurons per PMT.

The database for training was built from real Auger ADC traces triggered by either Threshold trigger (T1 - 3-fold coincidences for a single time bin for simultaneous signals above 1.75 VEM) or by ToT trigger (at least 13 sub-triggers of any 2-fold coincidences in 120 µs interval, for signals 0.2 VEM above pedestal) [24]. Signals detected by the T1 are relatively strong. The fact that the Pierre Auger Observatory did not register up to now any event potentially generated by a neutrino suggests that the thresholds for standard triggers may be too high. So, we need to teach the network to recognize patterns with much lower amplitudes. We extended the database artificially by reducing the amplitude of real ADC traces (by factors 0.67, 0.5 and 0.25, respectively), keeping the same pedestals and shapes. Table III shows that all networks recognize traces with reduced amplitude pretty well.

The 12-10-1 network offers the best performance with a minimal resource occupation (Fig. 7) however it requires 23 neurons.

### TABLE II

| ANN | Total | 100 % | 67 % | 50 % | 25 % |
|-----|-------|-------|------|------|------|
| 16-12-6-1 | 0.0 % | 0.0 % | 0.0 % | 0.0 % | 0.0 % |
| 14-12-1 | 0.0 % | 0.0 % | 0.0 % | 0.0 % | 0.0 % |
| 14-10-1 | 0.0 % | 0.0 % | 0.0 % | 0.0 % | 0.0 % |
| 12-10-1 | 0.0 % | 0.0 % | 0.0 % | 0.0 % | 0.0 % |
| 12-8-1 | 1.56 % | 1.56 % | 1.56 % | 1.56 % | 1.56 % |
| 10-8-1 | 2.81 % | 3.70 % | 2.50 % | 1.25 % | 3.70 % |
| 10-6-1 | 1.56 % | 1.56 % | 1.56 % | 1.56 % | 1.56 % |
| 8-6-1 | 3.28 % | 3.75 % | 2.81 % | 2.81 % | 3.75 % |
| 8-4-1 | 6.71 % | 5.31 % | 5.61 % | 6.25 % | 9.68 % |

### TABLE III

| ANN | Total | 100 % | 67 % | 50 % | 25 % |
|-----|-------|-------|------|------|------|
| 16-12-6-1 | 0.0 % | 0.0 % | 0.0 % | 0.0 % | 0.0 % |
| 14-12-1 | 0.0 % | 0.0 % | 0.0 % | 0.0 % | 0.0 % |
| 14-10-1 | 0.0 % | 0.0 % | 0.0 % | 0.0 % | 0.0 % |
| 12-10-1 | 0.0 % | 0.0 % | 0.0 % | 0.0 % | 0.0 % |
| 12-8-1 | 1.56 % | 1.56 % | 1.56 % | 1.56 % | 1.56 % |
| 10-8-1 | 2.81 % | 3.70 % | 2.50 % | 1.25 % | 3.70 % |
| 10-6-1 | 1.56 % | 1.56 % | 1.56 % | 1.56 % | 1.56 % |
| 8-6-1 | 3.28 % | 3.75 % | 2.81 % | 2.81 % | 3.75 % |
| 8-4-1 | 6.71 % | 5.31 % | 5.61 % | 6.25 % | 9.68 % |

![Fig. 6](image-url) An example of the ANN structure used for an optimization in Neutral Network Training of the MATLAB toolbox.

![Fig. 7](image-url) Training performance for the 3-layer network 12-10-1.
Due to a limited amount of DSP blocks, we could use this network for a single PMT only. The Quartus® compiler allows a compilation with arbitrarily selected implementation of the multipliers: either in the DSP blocks or in logic elements only. An implementation of the multipliers in the Adaptive Logic Modules (ALMs) is much more resource-consuming (1247 ALMs instead of 107 ALMs + 8 DSP blocks), however such a selection allows an implementation of a more complicated network, which provides a similar performance (keeps approximately the same speed). The 3-channel 12-10-1 network needs 36 neurons (the 1st layer implemented in the DSP blocks) + 33 neurons implemented in 41151 ALMs (36.5% of 5CEFA9F31I7).

The network was trained using 160 inclined and normal ADC traces (768 samples per trace). This gives 2*122880 patterns. For 160 inclined traces the network 12-8-1 recognized 139 inclined showers and only 27 patterns from a reference set (this rate should have been zero). However, taking into account the number of all patterns the rate of missing traces is 0.017% and the rate of wrongly recognized patterns 0.022%.

The fundamental algorithm for each neuron is as follows:

\[
\text{Neuron}_{\text{out}} = \sum_{k=0}^{n-1} \text{ADC}_k \cdot C_{k,\text{layer}} + \text{bias}_{k,\text{layer}}
\]  

(1)

Neuron outputs are next scaled by a transfer function which is chosen to have a number of properties which either enhance or simplify the network containing the neuron. MATLAB offers the hyperbolic tangent sigmoid transfer (tansig) function. On-line calculation of the tansig in the FPGA is not necessary, it is enough to store in the ROM previously calculated values and to use the neuron output as addresses to the ROM. In order to keep a sufficient accuracy with a reasonable size of the embedded memory we used a 16384-word dual-port ROM with 14-bit output. For the network 12-8-1 we had to use 10 dual-port ROMs, which utilized 2240 kB of embedded memory (the output from the last layer was given directly to a comparator). Various parameterizations (Fig. 9) were tested for the best optimization. The best variant for the data used was with the scaling factor \( sf = 1536 \) which corresponds to the range of (-5.33, ..., +5.33) of the tansig argument (Fig. 9).

\[
f_{\text{index}} = \frac{2}{1 + e^{-2 \cdot \frac{\text{index} - 8192}{sf}} - 1}.
\]  

(2)

Fig. 9. Tested representations of the tansig function for the best optimization (Eq. 2).
ADC samples drive the 12-bit shift register whose output of sequential registers are connected to neuron inputs (Fig. 8). MATLAB provides a set of floating point coefficients obtained after a teaching process. In our practical implementation the FPGA uses the fixed point representation (FPR) to provide a fast enough registered performance and to utilize a reasonable amount of resources. There is no need to use floating point representation although Altera provides appropriate library procedures. For 12-bit input data at least 2 embedded DSP multipliers have to be used for a single multiplication in Eq. 1. The maximal width of the coefficients is 20-bit. However, we selected 18-bit coefficients to obtain a 32-bit width of neuron output (Fig. 8).

| Layer | SFS | SFL | SFX | SFB | SHP | SHN |
|-------|-----|-----|-----|-----|-----|-----|
| 1     | 2   | 131,072 | 8 | 524,288 | - | 6 |
| 2     | 4   | 32,768 | 8 | 32,768 | 14 | 1 |
| 3     | 2   | 32,768 | 2 | 32,768 | 13 | 1 |

All coefficients given by MATLAB have to be converted from a floating-point to fixed-point representation in two-component code. A simple conversion into two-component code is a multiplication of data by a fixed-point scaling factor (FPSF) and an addition of 2*FPSF for negative values. A condition is that the data must be in the (-1.0,...+1.0) range. Table IV shows all factors for scaling, suppressions and finally shifts of data. At first, coefficients (coeff and bias) calculated by MATLAB are suppressed (by factors SFS and SFX, respectively, to get a range (-1.0,...+1.0) (Eq. 3). Next, they are scaled by factors SFL and SFB, respectively (Eq. 4):

\[
coeff_{k,layer,\text{fixed-point}} = \frac{coeff_{k,layer}}{SFS} \times SFL
\]

\[
bias_{k,layer,\text{fixed-point}} = \frac{bias_{k,layer}}{SFX} \times SFB.
\]

The 32-bit signed output of the neuron (starting from the 2nd layer) is shifted right before a summation with bias due to very high values from the tansig transfer function (mostly either ~8192 or ~8191):

\[
P = \left( \sum_{k=0}^{k-1} ADC_k \cdot C_{k,layer} \right) >> SHP.
\]

Addresses for the tansig function are additionally optimized to use the most sensitive function response region:

\[
address_{k,layer} = (P >> SHN) + 8192.
\]

The highest bits from the neuron (Eq. 1) are neglected as irrelevant for a big argument of the tansig transfer function. Addresses are cropped to the range < 0, ..., 16383 >.

In order to save some amount of memory we used Altera® library RAM: 3-port (as dual output ROM) with an initiation file, and blocked writing to the left port. The library function ROM: 2-port unfortunately failed. The same coefficient array is used for two independent addresses and gives two independent tansig coefficients. The RAM: 3-port saves twice embedded M9K memory blocks in comparison to a simple implementation of the ROM: 1-port library function.

An analysis of differences between the output data from neurons shows that differences reach a maximal value of only 1 ADC-unit. However, due to the relatively sharp slope of the tansig function in the central range, an error of 1 ADC-unit generates an output error of up to 6 ADC-units for the next (2nd) layer and even 10 ADC-units from the 2nd to the 3rd layer (Fig. 11). Nevertheless, the final error is negligible. A comparison of registered patterns for inclined showers (161/160) or spuriously recognized patterns for reference traces (39/160) shows that they are exactly the same as for the exact calculation (with double precision representation) and for the FPGA calculation in fixed-point representation with optimized bus and coefficients widths.

V. Simulations

The structure of the neuron network has been implemented in several FPGA families: Cyclone® III, Stratix® III and
implemented in the logic cells due to a lack of DSP embedded blocks. This reduced the speed below our requirements. The middle-size FPGA EP3SL150F780C2 was a perfect chip for Quartus® simulation. We decided to make simulations using a relatively old tool: the Quartus® simulator as a much faster tool than the currently recommended ModelSim.

Figs. 12 and 13 show results of simulations for inclined (positive marker) and reference (negative marker) traces. For trained patterns the recognition is almost perfect. On 160 events with positive markers (totally 122,760 samples) 161 patterns were recognized by the 12-8-1 network (only a single false event - Fig. 12). On 160 reference events (with negative markers) 39 spurious events were registered, however, 12 of which had very high amplitude, which would have been also registered by the standard trigger.

Results of simulations confirm that the noise is perfectly rejected. On the output of the 3rd layer, the simple comparator was used instead of the tansig procedure (with an embedded memory).

VI. LABORATORY TESTS

The surface detector electronics is being improved from 10-bit 40 MSps to at least 12-bit 120/160 MSps ADCs. The University of Łódź has been developing the new Front-End Board based on the Altera® Cyclone® V 5CEFA9F31I7 and 8 channels supported by the ADS4249 (Texas Instr. 2-channel, 14-bits 250MSps ADCs) [25]. It can fully test the developing ANN also under real environmental conditions in the Argentinean pampas.

Before the field tests we were running laboratory tests based on the Altera development kit DK-DEV-5CEA7N driven via HSMC-ADC-BRIDGE from the ADS4249 Evaluation Module (EVM). The ADC on the EVM is driven from the two channel arbitrary function generator Tektronix AFG3252. The first channel generates patterns corresponding to the "old" showers (marker "+"), the second one generates reference traces (marker ",-"), Channels are uncorrelated, they run with different frequencies and duty cycles (Fig. 14).

The FPGA trigger (either simple T1 or DCT based) freezes incoming traces and sends their output via the UART in NIOS to the PC. The virtual processor stores several hundred patterns in the RAM (both the developed FEB and the development kit contain a large enough external SDRAM). Thus, it starts the learning process with the algorithm extracted from the MATLAB package. Calculated coefficients are sequentially sent to the temporary D registers in the FPGA fast logic and are next simultaneously (in a single clock cycle) reloaded to the final registers driving the multipliers. Trigger rates for positively vs. negatively marked patterns agreed with our theoretical simulations.

VII. CONCLUSION

A huge amount of progress in electronics allows an introduction of new, much more powerful FPGAs and an implementation of much more sophisticated mathematical algorithms for real time processes. Neutrino physics is one of the discipline where new developments, in both hardware, and
software, can significantly improve the efficiency of rare event detection. It is especially interesting where theories estimate neutrino fluxes over a very wide range.

The spectral trigger based on the Discrete Cosine Transform, offering a pattern recognition technique, has been already implemented in a test Front-End Board and tested in a test detector in Malargüe (Argentina). The new electronics developed according to the Auger-Beyond-2015 task in the Pierre Auger upgrade project allows an implementation of both DCT and ANN algorithms.

The Technical Board of the Pierre Auger Collaboration selected 8 surface detectors (a hexagon + twin in the center for an investigation of possible GPS jitter) in a north-west region of the SD array for tests of the new FEB on the Cyclone® V platform with 3-4 times higher sampling and 14-bit resolution with a cooperation of the SPMT and possibly other detectors. Simultaneously, the DCT triggers will be implemented in parallel with the standard ones to verify the detection of very inclined showers based on an on-line analysis of a shape of signals in the frequency domain. This platform is appropriate also for tests of artificial neural networks. The biggest FPGA chip 5CEFA9F31I7N in the new Front-End allows an implementation of two 12-8-1 networks with multipliers fully embedded in DSP blocks. Three PMTs require 3 networks. The FPGA is big enough to implement mixed DSP/fast logic multipliers for 3 networks.

We run CORSIKA [22] simulation for proton, iron, $\nu_\mu$ and $\nu_\tau$ primaries. Output data collected at 1450 m (the level of the Pierre Auger Observatory) was an input for Offline [23] providing the ADC response in the WCDs. The obtained ADC traces were thus used to train the 12-8-1 neural network implemented already in the 5CEFA7F31I7 FPGA on the Cyclone® V development kit. This FPGA is a smaller version of the chip being designed for the Front-End Board for the Auger-Beyond-2015 task. Preliminary results show that the 16-point ANN algorithm can detect neutrino events currently neglected by the standard Auger triggers and can support a recognition of neutrino-induced very inclined showers when ADC traces are relatively short and the muonic bump is better separated from the electromagnetic component.

![Fig. 14. Experimental setup with arbitrary pattern generators Tektronix AFG3252C and Agilent 33250A, Altera® Cyclone® V E development kit, Altera® HSMC-ADC-BRIDGE and Texas Instr. ADS4249EVM.](image)

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