Self-Trigger for Radio Detection of UHCR

A. Schmidt[‡], H. Gemmeke[‡], W.D. Apel[*], J.C. Arteaga[†,xiv], T. Asch[‡], F. Badea[*], L. Bähren[§], K. Bekk[*], M. Bertaina[¶], P.L. Biermann[‖], J. Blümer[*,†], H. Bozdog[*] I.M. Brancus[**], M. Brüggemann[††], P. Buchholz[††], S. Buitink[§], E. Cantoni[¶,‡‡], A. Chiavassa[¶], F. Cossavella[†], K. Daumiller[*], V. de Souza[†,xv], F. Di Pierro[¶], P. Doll[*], R. Engel[*], H. Falcke[§,x], M. Finger[*], D. Fuhrmann[xi], P.L. Ghia[‡‡], R. Glasstetter[xi], C. Grupen[††], A. Haungs[*], D. Heck[*], J.R. Hörandel[§], A. Horneffer[§], T. Huege[*], P.G. Isar[*], K.-H. Kampert[xi], D. Kang[†], D. Kickelbick[††], O. Krömer[‡], J. Kuijpers[§], S. Lafebre[§], P. Łuczak[xii], M. Ludwig[†], H.J. Mathes[*], H.J. Mayer[*], M. Melissas[†], B. Mitrica[**], C. Morello[‡‡], G. Navarra[¶], S. Nehls[*], A. Nigl[§], J. Oehlschläger[*], S. Over[††], N. Palmieri[†], M. Petcu[**], T. Pierog[*], J. Rautenberg[xi], H. Rebel[*], M. Roth[*], A. Saftoiu[**], H. Schieler[*], F. Schröder[*], O. Sima[xiii], K. Singh[‡‡,xvi], G. Toma[**], G.C. Trinchero[‡‡], H. Ulrich[*], A. Weindl[*], J. Wochele[*], M. Wommer[*], J. Zabierowski[xii], J.A. Zensus[‖]

[*] *Institut für Kernphysik, Forschungszentrum Karlsruhe, Germany*
[†] *Institut für Experimentelle Kernphysik, Universität Karlsruhe, Germany*
[‡] *IPE, Forschungszentrum Karlsruhe, Germany*
[§] *Department of Astrophysics, Radboud University Nijmegen, The Netherlands*
[¶] *Dipartimento di Fisica Generale dell' Universita Torino, Italy*
[‖] *Max-Planck-Institut für Radioastronomie Bonn, Germany*
[**] *National Institute of Physics and Nuclear Engineering, Bucharest, Romania*
[††] *Fachbereich Physik, Universität Siegen, Germany*
[‡‡] *Istituto di Fisica dello Spazio Interplanetario, INAF Torino, Italy*
[x] *ASTRON, Dwingeloo, The Netherlands*
[xi] *Fachbereich Physik, Universität Wuppertal, Germany*
[xii] *Soltan Institute for Nuclear Studies, Lodz, Poland*
[xiii] *Department of Physics, University of Bucharest, Bucharest, Romania*
[xiv] *now at: Universidad Michoacana, Morelia, Mexico*
[xv] *now at: Universidade de São Paulo, Instituto de Fîsica de São Carlos, Brasil*
[xvi] *now at: KVI, University of Groningen, The Netherlands*

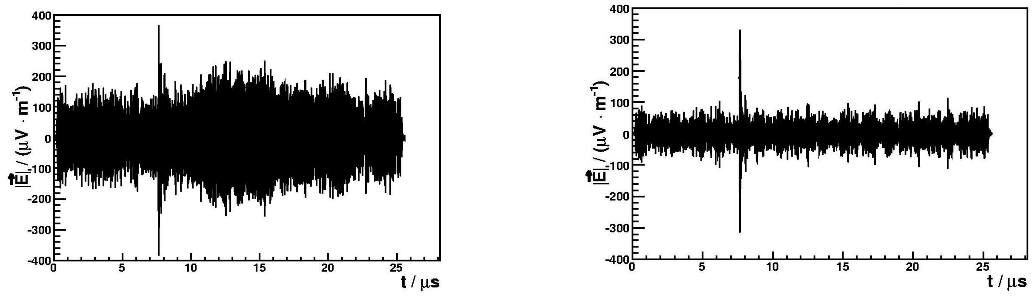
Abstract. **In a large scale antenna array for the radio detection of cosmic rays the trigger mechanism is one of the key features. While calling for a low trigger threshold for best event acceptance, the trigger rate of each station must be low enough to allow for the limited capacity of wireless communications. Additionally a low power consumption is required, as the stations will be solar powered.**
We have developed a trigger algorithm realized in FPGA-hardware which provides an RFI-suppression by Fourier transforming the radio signal live to frequency domain, eliminating mono-frequent carriers and transforming back to time domain. This improves the signal to noise ratio by a factor of 2. Then a threshold is applied and cuts on particular pulse shape parameters are performed to further reduce the trigger rate. Finally the coincidence between neighboring antennas is built, and the event is read out. The current status of the hardware development and first results of test measurements with 3 prototype antennas is presented.

***Keywords*: extensive air shower, radio emission, self trigger**

I. INTRODUCTION

After the first radio measurements of extensive air showers (EAS) with the ground-breaking LOPES experiment [1], the next generation radio detector should show its advantages compared to established detection methods. Similar to a fluorescence detector it measures the integrated energy deposit of the shower along its axis, instead of a single snapshot at ground level, which also improves the acceptance of very inclined showers. At the same time a radio detector has the advantage of a high duty cycle close to 100 % like a particle detector array. To establish radio emission as a new self contained standard detecting method, a self trigger mechanism is essential. Some of the advantages of radio detection, like the expected better acceptance of very inclined air showers are only valid for a self triggered radio array.

The radio signal of an extensive air shower of a given energy shows a steeply falling lateral distribution [2]. This requires the field strength threshold of the trigger to be as low as possible to allow for a reasonable antenna grid spacing. Because of these large distances between antenna stations, the communication and data transfer must be done wireless, which strongly limits the possible data load and asks for a low false trigger rate. As the



(a) Before RFI-suppression (b) After RFI-suppression

Fig. 1: Enhancement of an example shower event by applying the RFI-suppression.

radio band is traditionally contaminated with plenty of man made noise, only a sophisticated trigger mechanism can meet these requirements. The trigger algorithm must mainly focus on the antenna station level to reduce the amount of readout data as far as possible. Due to the solar power supply of the antenna stations a low power consumption of the trigger implementation is also required.

II. Trigger Approach

To learn about the environmental trigger conditions, LOPES$^{\mathrm{STAR}}$ (LOPES **S**elf-**T**riggered **A**rray of **R**adio detectors) was developed. This detector consists of antennas arranged in equilateral triangles on the site of the Forschungszentrum Karlsruhe (FZK), triggered by the KASCADE-Grande [3] experiment. The taken data was used to develop a suitable trigger strategy [4].

According to monte carlo simulations [5] radio emission takes place in the frequency range from few MHz up to 100 MHz. Due to radio frequency interference (RFI), the detection of this emission is only applicable above the strongly used short wave band going up to 30 MHz and below the FM radio band starting beyond 80 MHz.

However we also find lesser radio sources in the used frequency band in between. As a first step to improve the trigger situation we filter these mono-frequent carriers. Therefore we Fast Fourier transform (FFT) into frequency domain, where the carriers can easily be removed by replacing the spectrum by its median. A short pulse created by an air shower is not affected by this median filter, as it is distributed widely over all frequencies. After transforming the median filtered spectrum back to time domain, the signal to noise ratio of the pulse is improved by a factor of 2 under fair conditions, the gain under the heavily industrialized radio-loud environment on the site of FZK is much higher (s. fig. 1). In particular this RFI-suppression provides a comparable situation for the subsequent trigger, as independent as possible from the initial recording situation.

As the RFI-suppression performs two FFTs continuously at full sampling rate before the first trigger level, it requires high calculation power and the implementation in a low power system is tricky: The incoming continuous data stream must be divided into blocks first to perform the FFT. To avoid leakage effect and signal jumps at the block edges, a trapezoid window function is applied, fading in and out the signal over the first and last eighth of each block. After transforming into frequency domain and back, the affected first and last eighth of each block are dumped before glueing the blocks together again. To conserve a continuous data stream without gaps, the block division is done with one quarter overlap, and the FFTs are calculated for a factor of $^4/_3$ more data (s. fig. 2).

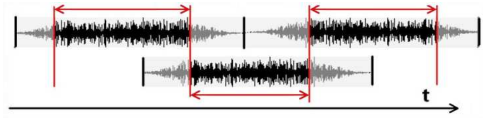


Fig. 2: Illustration of the used block windowing.

The next task is to identify pulses on the such enhanced data. Therefore a dynamic threshold is applied. The threshold is kept to a fixed factor above the RMS which is calculated over a time period of some seconds. The threshold variation is important to avoid unreasonable trigger rates due to strong background noise variations over the day, caused by the change of the ionospheric reflectivity and the rise and descent of the galaxies as a dominant radio noise source.

To further reduce the trigger rate, the pulse shape is characterized by particular parameters to discriminate shower pulses from background noise pulses. For example measurements in combination with the KASCADE-Grande detector show that EAS-induced pulses seem to be shorter than 125 ns (FWHM) and have a faster signal fall-off after the maximum than background transients [6]. Anyhow final reliable pulse shape cuts require careful further work, as the radio emission mechanism of EAS is not completely understood yet. Of course the measured pulse height and shape are strongly affected by dispersion along the analogue signal path including antenna and filters, which must be taken into account for the trigger decision. Fortunately our trigger approach in principle makes it easily feasible to deconvolve such a frequency response before triggering, as the needed

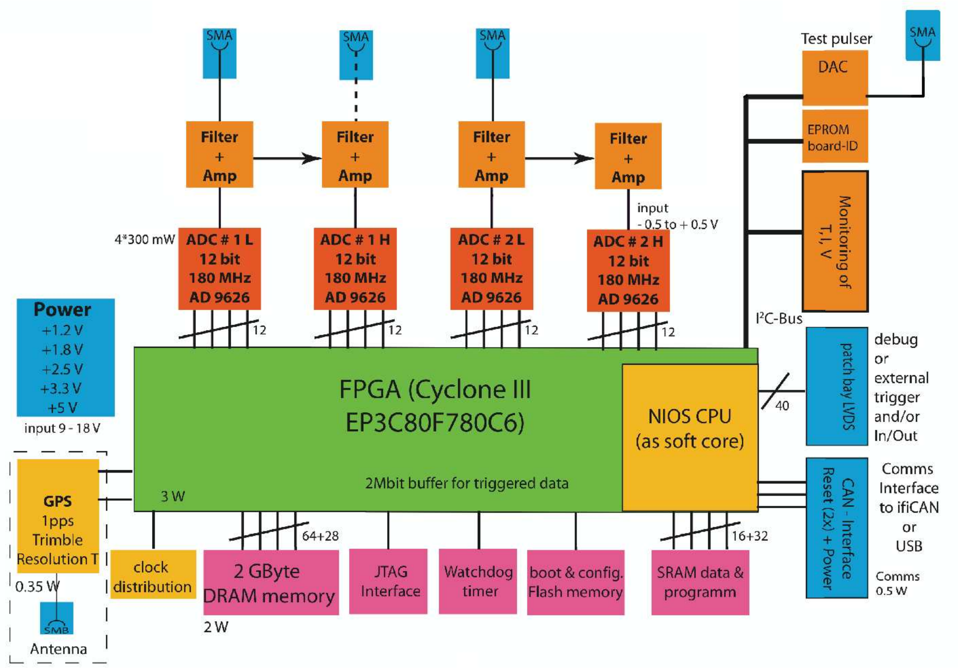


Fig. 3: Block diagram of new electronics design

FFTs are already implemented.

If three adjacent antennas trigger within the coincidence time, the event is finally accepted, read out and stored. By varying the required maximum coincidence time the accepted zenith-angle is set: A vertical shower will trigger the antennas simultaneously, the maximum trigger time difference is the antenna spacing over the speed of light and caused by horizontal events.

III. Prototype electronics

To verify the real-time feasibility of our trigger algorithm, we used existent hardware offering 10 bit ADCs at a sampling rate of 80 MHz connected to a Stratix I FPGA with 40'000 logic elements. As a first step we only use these prototype electronics to create a trigger signal replacing the external trigger from KASCADE-Grande. The data taking is done by our field-tested DAQ-System.

Because of the low sampling rate, we take sub-sampled data of the limited radio band between 40 and 80 MHz in the second Nyquist domain. Sub-sampling still conserves full signal information, the RFI-suppression algorithm is not even affected, the frequency spectrum appears just mirrored. Before pulse finding, the signal must be up-sampled to get back the original pulse shape. With this prototype hardware we could well prove the functionality and stability of our sophisticated algorithm in laboratory.

However we did not find any 3-fold coincidences corresponding to an air shower neither during three weeks of measurement at the KASCADE-Grande detector nor during four months of data taking at the Pierre Auger Observatory in Argentina. This is due to different problems:

- The ADC-resolution is too low: When the analogue amplification is high enough to guarantee numerical stability for the background analysis, many pulses get saturated, which renders the pulse shape analysis useless.
- Our elaborate algorithm leads to about 10 W power consumption in the FPGA. Especially during Argentinian summer inside an enclosed container the heat dissipation was underestimated, which lead to longer dead time of the remote stations.
- Because of the high power consumption of our prototype setup, we depend on a power line. This increases the radio background, in particular it introduces plenty of radio spikes.

Nevertheless we continue measurements with the prototype hardware, try different trigger variations and improve our understanding of the radio background. For the development of a trigger which reduced the data rate by more than a factor of 10^5 from permanent recording down to less than one event per second, rare background events can play an important role. Offline analysis of randomly recorded background data hardly helps with such rare background, a live test is essential.

IV. New electronics development

Learning about the problems of our prototype, we currently develop new electronics (s. fig. 3).

To improve dynamic range, we use two 12 bit Flash-ADCs for each antenna polarization. One ADC operating with high analogue gain, the other at low gain, they deliver an effective 18 bit resolution in a cost- and power efficient way. A dedicated test pulser is used to calibrate the analogue signal path. The time resolution is improved by a high sampling rate of 180 MHz. Sampling in first Nyquist domain not only eases the requirements on the band filter, which can now be optimized for a smooth phase response, but also enables data taking in the whole available radio band from 30 MHz to 80 MHz. This should improve the signal to noise ratio, as air shower simulations predict a more dominant radio emission at lower frequencies [5].

The ADCs are connected to a large Cyclone III FPGA with 80'000 logic elements. The new chip with 65 nm structure together with a reduced core voltage delivers a lower power consumption compared to the 130 nm prototype. In spite of the higher clock frequency, simulations predict a consumption of only 3 W. However we pay highest attention to a decent heat management under the rough ambient conditions in the Argentinian pampa.

These low power needs are very important for the projected $20\,\mathrm{km}^2$ array with 100 antennas, as all stations will be solar powered. The expected advantage of this remoteness is a strongly reduced interference by transients from power lines or passing cars.

Besides the actual trigger-task, the second major topic is the wireless communication between the antenna and the central readout station. For each pulse detected by the antenna's trigger, its timestamp evaluated by a GPS-clock is sent to the central station. This task is fulfilled by a processor implemented as soft core on the FPGA. If the central station finds a coincidence between adjacent antennas, it requests a readout of the event trace from all involved antenna stations. For an improved usage of the communication bandwidth and to avoid collisions, we will use a time division multiple access method (TDMA), where each station only transmits during its particular time slice each second. This approach is for example used for the surface detector of the Pierre Auger Observatory. It optimizes the throughput, but also increases the latency up to a few seconds.

As we are still learning about the radio emission mechanism and its triggering, we want event data as complete as possible. This includes data of antennas that did not trigger, thus the outer ring of an event, where the radio pulse was to faint to trigger on. Anyhow this low pulse contains valuable information, and even if there is no visible pulse at all, it is possible to extract additional information by means of interferometry with several antennas.

The possibility of reading out untriggered data is therefore an important key-feature. Because of the high latency of the communication, this requires a huge buffer memory. With a ring buffer of 2 GByte we get a buffer time of 2 s for raw data or 3 – 4 s including a half-decent online compression. The large buffer in principle also enables external triggering of the radio detector by a regular surface detector to form a new type of hybrid detection.

V. Conclusion

A sophisticated algorithm to trigger the radio emission of extensive air showers was developed on shower data recorded with an external trigger from KASCADE-Grande. At first interfering carrier frequencies are removed from the radio signal by Fourier transforming into frequency domain, replacing the spectrum by its median and transforming back into time domain. This improves the signal to noise ratio by a factor of 2, and compensates for different environments. For each signal pulse exceeding a dynamic threshold the pulse shape parameters are calculated resulting in a trigger decision. If at least three neighboring antennas show an accepted pulse within a certain coincidence time, the radio event is finally accepted and read out.

The real-time feasibility of this trigger mechanism was proven on prototype hardware, single design problems were identified, and the improvements are incorporated into the design of the next generation electronics.

The approach of fully reconfigurable hardware with decent power reserves in buffer memory and FPGA resources permits to continue the advancement of the trigger logic not only during development, but also after some time of data taking, when the radio detection properties are better understood.

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