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Trigger and data filtering approaches in the Askaryan Radio Array

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Abstract: The Askaryan Radio Array (ARA) is one of the future neutrino observatories focusing on the detection of neutrinos with energies beyond 10^{17} eV. In this energy regime, the GZK-neutrino flux is expected as a result of the interaction between Ultra-High Energy Cosmic Rays (UHECR) and the Cosmic Microwave Background (CMB). This interaction is a possible explanation of the cut-off seen in the cosmic ray spectrum on Earth at around $10^{19.5}$ eV by experiments like the Pierre Auger Observatory and the TA experiment. Observing GZK-neutrinos is especially interesting because it is the only way to investigate the CR-spectrum beyond the observed cut-off. The GZK-neutrinos produce particle cascades in different media like ice and rock salt which emit radio waves through the Askaryan effect. ARA is currently in the building phase and will be optimized to detect the radio emission from neutrino-induced cascades with primary energies greater than 10^{17} eV. A grid of 37 antenna clusters, spaced by 2 km, is planned to be deployed in the South Pole ice, at a depth of 200 m. The full ARA detector will cover an instrumented area of about 100 km^2 and as-built will be the most cost-effective neutrino detector in the energy range between 10^{17} eV and 10^{19} eV. Three ARA-stations, each consisting of 16 in-ice antennas and 4 surface antennas, and one prototype station are already deployed in the ice. All of them are functioning as single detectors each with full detection and reconstruction capabilities. With the first stations deployed, optimized data-taking and filtering becomes one of the collaborations working priorities. This presentation will give insights in the development of a data filter algorithm as well as some ideas for hardware triggers to use in the currently deployed stations.

Keywords: Neutrino telescope, radio-Cherenkov emission, data filter.

1 Introduction

The detection of ultra-high energy neutrinos produced in the GZK-mechanism is becoming more and more interesting for the investigation of Ultra-High Energy Cosmic Rays (UHECR). The GZK-mechanism, as postulated by Greisen, Zatsepin and Kuzmin in 1966, predicts a cut-off in the cosmic ray spectrum at an energy around 10^{20} eV, due to a resonance in the cross-section for the interaction between cosmic rays and the cosmic microwave background [1, 2]. A neutrino flux, resulting from the decay of such produced pions was predicted shortly afterwards [3]. Recently, strong evidence for this effect has been found in the cut-off of the cosmic ray spectrum, by the Pierre Auger Observatory and the TA experiment [4, 5]. Given this cut-off, most information about cosmic rays beyond those energies can exclusively be achieved by investigating the predicted neutrino flux. The Askaryan Radio Array (ARA) is currently being constructed as a ground based experiment to detect ultra-high energy neutrinos via the radio-Cherenkov emission from neutrino induced cascades, as it was predicted by Askaryan in 1962 and measured at the SLAC beam in 2007 [6, 7].

1.1 The project

This section will give a short overview about the general setup of the ARA detector as it is planned to be built within the next years. More details can be found in [8].
The baseline design for the ARA detector are 37 antenna clusters, so-called stations, spread over the South Pole ice in a hexagonal grid with distances of 2 km between each other (see figure 1). Each station is composed of 16 in-ice antennas, operating in a frequency range between 150 and 850 MHz and 4 surface antennas, operating in a frequency range between 30 and 900 MHz. The in-ice antennas are deployed on four strings at a depth of 200 m, forming a cubical structure with edge lengths of some 10 m. On each string four antennas are mounted, two horizontally polarized antennas (**hpol**) and two vertically polarized antennas (**vpol**). These provide sensitivity to the polarization of the incoming radio wave, which is crucial for neutrino reconstruction. Depth and distance of the ARA stations are chosen to maximize the effective volume of the detector.

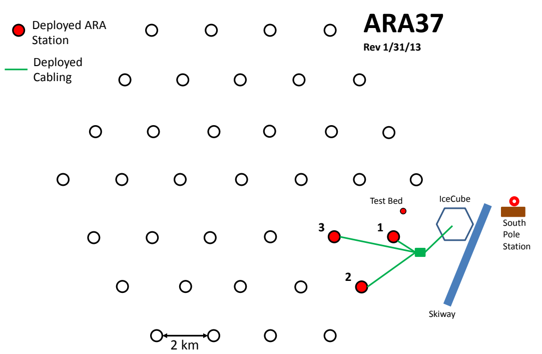

Figure 1: A top view on the South Pole area, with the planned and currently deployed parts of the ARA detector.

The Askaryan Radio Array, when finished, will cover

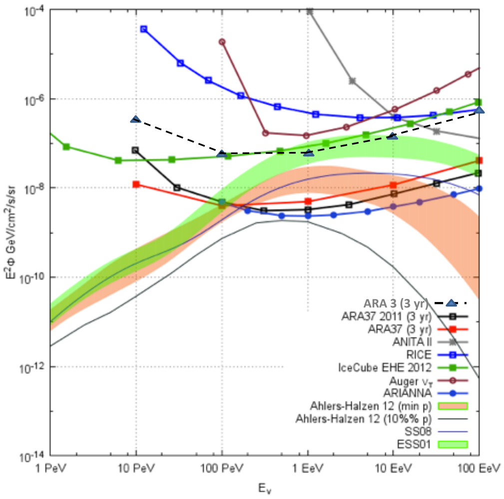

Figure 2: The expected ARA sensitivity in different configurations, compared to previously set limits and different possible flux models.

an area of about 100 km^2 and its sensitivity will surpass the current detectors by more than a factor of ten in the optimized range between 10^{17} eV and 10^{19} eV (see figure 2).

1.2 The current detector setup

After having determined measurement conditions and tested different detector setups in a station prototype, which was deployed in 2010 – 2011 [9], three of the 37 ARA-stations have been put into place with the final baseline design in the last two years, taking data continuously. Their positions are shown in figure 1. Given drilling problems in the first deployment season, ARA station one is deployed at a shallower depth of 100 m, which results in a slightly lower sensitivity. ARA stations two and three were deployed at the final depth of 200 m. An expected detector sensitivity for these three stations is plotted in figure 2.

2 The ARA trigger system

The focus of this article is to discuss recent trigger and data-filter developments for ARA. The basic understanding of the current trigger setup is crucial to investigate further possibilities.
While power consumption and building costs are an important issue for the ARA detector, data readout at radio frequencies with highly synchronized measurement channels is challenging. In the ARA stations, antenna waveforms are amplified through low noise amplifiers (LNA's) and transmitted analog to the ice surface via optical fiber cables. There, the waveforms are split into two paths, the IRS2 (Ice Radio Sampler) chip and the trigger system. The IRS2 chip is a custom ASIC, built to read and digitize signals at radio frequencies with relatively low power consumption. It buffers up to 10 µs of the incoming data samples and reads and digitizes them in case of an asserted trigger.
The station trigger system consists of an integrating tunnel-diode which enhances radio signals from thermal noise by integrating the signal power over a few nanoseconds. In this way, trigger pulses are also broadened to be detectable for the connected electronics. The tunnel-diode output is

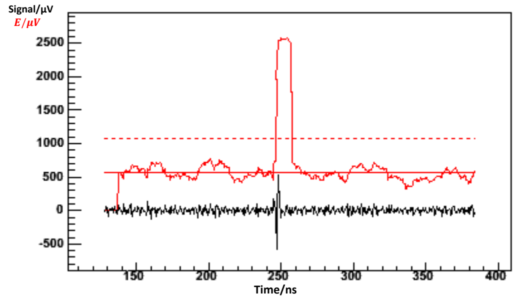

Figure 3: A typical signal waveform with the square root of the integrated power in red. The red solid line represents the average value, the red dashed line is the threshold, set to generate a hit pattern.

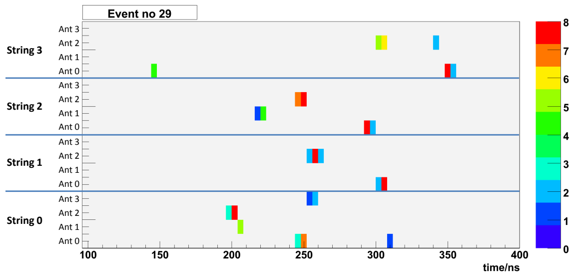

Figure 4: A generated hit pattern. The 16 in-ice antenna channels are displayed on the y-axis.

fed into a TDA (Trigger Daughterboard for ARA), where it is run through a band filter and amplified, before being used in the trigger logic. As soon as a signal crosses a certain trigger threshold, a logic signal is set high for 110 ns, the present trigger window. As soon as 3 out of 8 hpol or vpol antennas trigger, a global trigger signal is sent out and corresponding data is read and digitized. The adjustable parameters in this system are the power threshold, which can be set individually for each channel, the length of the trigger window and the trigger logic, which handles the processing of upcoming channel triggers. These parameters are chosen to reduce the event rate to roughly 10 Hz to prevent data loss during the transfer to the storage system. A more detailed description of the trigger system can be found in [8].

3 The current filter status

Due to a limited satellite transfer budget of 1.5 GB, only less than 1% of the currently produced data from the ARA stations, approximately 100 GB per day, can be transferred north, where it is accessible for data analysers.The biggest part of the data must be hand carried back at the end of each season, during the austral summer. To enhance the sensitivity of analyses done on the data transferred by satellite link, selective data filter algorithms have to be installed, which reduce the amount of transferred data sufficiently while passing ultra-high energy neutrino signal events with high efficiency.
The algorithm discussed here is based on hit patterns generated from the recorded event waveforms. To enhance the signal to noise ratio, the signal power is integrated over a fixed amount of time, as it is done in the tunnel-diode. For

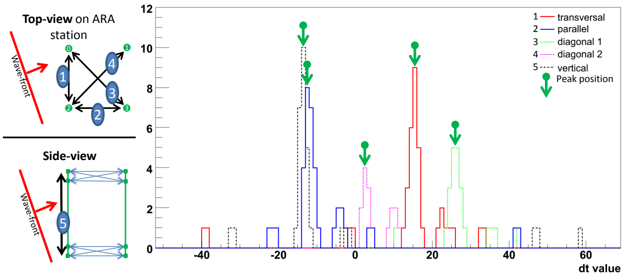

Figure 5: The histograms from the filter algorithm for a signal pattern. The five different curves show the histogrammed time differences for hit pairs with directions shown on the left.

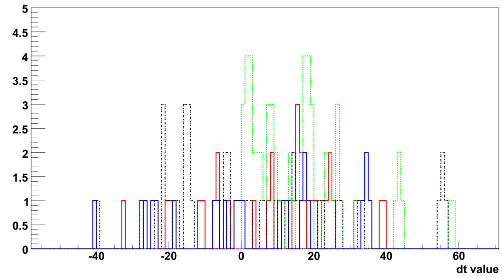

Figure 6: The histograms from the filter algorithm applied on a noise pattern.

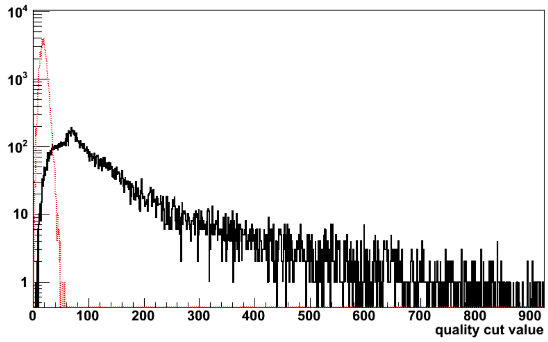

Figure 7: Histograms of the quality parameter for 16000 signal patterns generated with a primary energy of 10^{17} eV **(black)** and 47000 noise patterns **(red)**.

the resulting energy waveform, average and standard deviation are determined as a base for a threshold value (figure 3). The hit patterns are then generated by recording all times with energy beyond the chosen threshold level (see figure 4). This threshold as well as the integration time can have a big influence on the performance of an applied filter algorithm. Therefore, in the finalization of the filter, a parameter scan over the two values will be performed, to optimize the filter efficiency.

In the investigated algorithm, pairs are formed from all hits that appear in a pattern. Time differences are expected to be nearly identical between hit pairs along a common axis if produced by an incoming radio wave. The algorithm uses only vertical and horizontal (or nearly horizontal) hit pairs; vertically diagonal hit pairs are not included. For each hit-pair, the time difference is calculated and divided by the distance between the two antennas. The resulting number is histogrammed. As shown in figure 5, pairs can have 5 different orientations relative to the incoming wave which is why they are all counted separately. Examples of histograms from patterns with roughly the same hit count can be seen in figure 5 for signal, in figure 6 for noise. The histograms for the signal pattern show much stronger peaks than those for noise, which is expected for an incoming plane wave as opposed to thermal noise. The maximal bin counts of all histograms can be summed and used as a quality parameter for each pattern.

This filter algorithm has been tested on simulated data provided by the standard ARA simulation [10]. It is very difficult to create a statistically significant sample of noise waveforms in simulations, which corresponds to the triggering data. The reason for that is the high threshold which has to be set to achieve a manageable trigger rate in the experiment. Therefore, triggering noise waveforms are generated at two different lower thresholds. The goal is to extract a possible extrapolation to the behavior at higher thresholds from the differences between the low-threshold data samples. Signal waveforms can be generated very well with the current detector settings. In this approach, the filter performance presented in the following has to be regarded as slightly too optimistic, but there is evidence, that the finally triggering noise will not decrease the performance strongly.

The quality parameter for a set of signal and noise patterns, generated with a primary energy of 10^{17} eV, is plotted in figure 7. It is nicely visible that noise events can strongly be reduced while keeping more than 90% of the signal. Also the azimuthal behavior of the cut appears approximately isotropic, when compared to the angular distribution that triggered the detector. By using the positions of the maximum bin count for each distribution in figure 5 and applying some simple angular relations, a value for the speed of light can be calculated for each pattern (see figure 8). As expected, the light speed values extracted from noise patterns are randomly distributed, tending towards smaller numbers while the results from signal patterns strongly peak at $1.7 \cdot 10^8$ m/s, which is the speed of light in the ice around the stations. A combined cut on the two values can be very robust, providing a strong noise reduction and a good signal passing rate. The expected effective volume before and after filtering is plotted in figure 9.

4 Future plans on triggering

Apart from improving the data, which is transferred to the northern hemisphere, the development of efficient online triggers is very important since they can increase the general sensitivity of the detector remarkably. The currently used multiplicity trigger is based on setting a threshold to the tunnel-diode power and checking the number of hits in a time window. The goal of new trigger developments is to find an algorithm that cuts noise more efficiently than the simple multiplicity condition. In that way, the trigger threshold can be lowered, i.e. the sensitivity risen, while keeping the output event rate constant. Since the predicted neutrino flux is rapidly falling with rising energy, even small changes in the threshold can make a big difference in the detector efficiency. But before efficiency, simplicity is the most important feature of such an algorithm because of the limited calculation capabilities of the used FPGAs (Field Programmable Gate Array) in which they have to be implemented. The basic principle of some possible trigger

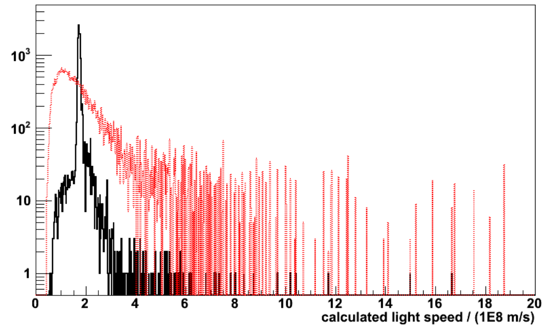

Figure 8: The speed of light, calculated for the events shown in figure 7 with signal **(black)** and noise **(red)**.

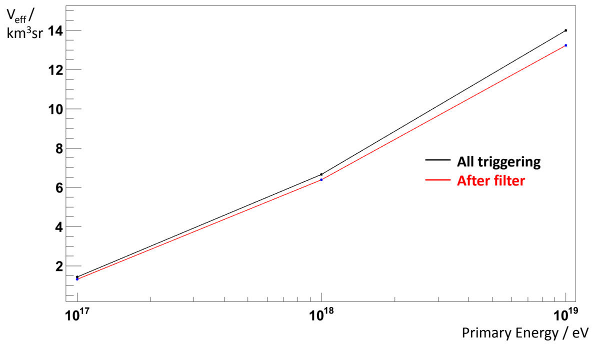

Figure 9: The expected effective volume of 1 ARA station for different energies for all triggering events **(black)**, for events that passed the data-filter **(red)**.

methods, all based on the recognition of an incoming plane wave are presented in the following.

- **The track engine algorithm** as it was developed for the IceCube detector [11], uses all hits in a certain time window, forms all possible pairs and calculates the direction of the wave movement. Antenna positions are used to calculate a directional vector for each pair i, then the maximum physically possible time difference $\Delta t_{max,i}$ is calculated. This corresponds to a wave travelling parallel to the pair vector. This maximum time value is used as a cut, rejecting all time differences which are larger. For the time differences not rejected, Δt_i, a weight is calculated, $w_i = \Delta t_i / \Delta t_{max,i}$. This weight is multiplied with the given vector of the antenna pair. The length of the sum of all weighted vectors is the quality parameter of this algorithm. Since noise is mostly expected to be thermal, hits are assumed to appear randomly in time. Therefore, weights should become small and random for all the vectors, whereas for the signal some directions should have strong weights. Thus, the final noise vector should typically be much shorter than the signal vector. Apart from being promising as a quality cut between signal and noise, this algorithm would perform a first very simple directional reconstruction.

- **The time sequence algorithm** is similar to the presented filter algorithm in section 3, but simplified and exclusively uses vertical hit pairs, i.e. hits on the same string. It forms pairs from antennas that are hit consecutively in time and calculates two numbers for each pair that are histogrammed:

  – The antenna hit sequence: Each antenna gets a number $(0,1,2,3)$ according to its vertical position on a string (see figure 4). With an incoming plane wave, the antennas are expected to be hit in a monotonously rising or falling sequence. The sequence is calculated for each pair of consecutive hits and histogrammed.

  – The hit time difference: One more number that should be regular for an incoming plane wave is the time difference between hit antenna pairs. Here the algorithm works exactly as the presented filter. Accounting for the actual antenna position on the string, the measured time difference between the hits is divided by the distance between the antennas and histogrammed as well. In that way, they are projected onto the same number, independently from the direction of the incoming wave.

  Again in both values there is a peak expected for the signal and a rather flat distribution of numbers for the noise. This structure is used to separate signal and noise, by using the highest bin count in the histogram as a quality parameter from this algorithm.

These algorithms are currently under investigation, using the ARA simulation, to understand if they can enhance the sensitivity compared to the current trigger settings and in which way they can be implemented, to be most efficient.

5 Conclusions

While the trigger algorithms still have to be verified in greater details on simulation, a promising data-filter for ARA has been tested on simulation and shows evidence for a strong improvement in the selection of data that arrive in the north. This algorithm is now to be checked on real data, to calculate reliable values for its efficiency.

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