PROCEEDINGS OF SCIENCE

Simulation Study of the Detection of Inclined Photon Air Showers with the AugerPrime Radio Detector

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The Pierre Auger Observatory is the largest Cosmic Ray (CR) observatory with a size of $\approx 3000\,\mathrm{km}^2$. Its size makes it feasible to not only look for CRs but also for presumably rare primaries like photons at energies larger than 1 EeV. Strong upper limits on the diffuse photon flux have been set in the past using the Surface Detector (SD). Additionally, air showers with photon-like properties were detected. For these photon candidate events, however, an uncertainty remains regarding whether they are of photon origin or possibly misinterpreted hadrons. With the AugerPrime upgrade, the SD is complemented by the Radio Detector (RD). The combination of both detectors yields new information about air showers and will improve primary identification. Here, inclined photon showers are of special interest as they have a negligible particle footprint but strong radio emission. This is in contrast to hadronic primaries, where a strong particle footprint is expected for inclined air showers as well. The difference is investigated in simulation studies to determine the primary discrimination power of the AugerPrime detector with a given trigger concept. We will quantify the discrimination power and introduce parameters for the photon-hadron-separation. We will present an outlook on future prospects of the analysis.

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1. Introduction

The detection of *ultra high-energy photons* (UHE-γ) is one of the most relevant and often discussed topics in astrophysics. Various analysis [1–4] from different collaborations set upper limits on the UHE-γ flux and most recent investigations result in photon candidates in the data set of the Pierre Auger Collaboration [5]. In a study on the hadronic background, the number of observed photon candidates could not be explained by miss-interpreted hadrons [6].

Nonetheless, the identification of photons in the data set remains uncertain due to the limited discrimination power of the water Cherenkov detectors (WCD). Especially for inclined photon air showers, particle detectors are not sensitive due to the absorbed electromagnetic (EM) and reduced muonic component of the photon air shower. The increasing importance of radio detection techniques for ground based experiments can solve this issue. Even though the EM component is absorbed in the atmosphere, the radio emission is strong at ground and can be detected [7].

The AugerPrime upgrade of the Pierre Auger Observatory includes the installation of the Radio Detector (RD). Each WCD is complemented by an antenna, sensitive in the frequency range of 30 to 80 MHz. The detection of strong radio signals in the absence of large particle footprints then indicates the air shower to be of photon origin.

2. Trigger system and data acquisition of the Pierre Auger Observatory

The current trigger system is designed for an array of WCDs, hence, the new components of the upgrade are not taken into account. Therefore, the RD only sends the data to the central data acquisition system (CDAS) if the WCD triggered the station, thus in case of a significant particle footprint. This is challenging for air showers of photon primaries as their particle contribution might not be large enough to result in a trigger. Hence, we will present the design of a RD trigger to increase the detection rate of UHE-γ and other exotic primaries as neutrinos.

We shortly line out the local triggering of the Surface Detector (SD) stations and how the data is collected to form a recorded event by CDAS. The so-called T1 is processed on the digitized samples of the WCD PMTs [8]. A T1 triggers the local storage of the data in the station electronics where it can be requested up to 10 seconds. Two original and another two new triggers added in June 2013 can result in a T1. On the station level the T2 is formed, which is in most cases identical to the T1. Only for the WCD threshold trigger, stricter requirements are given. Only the T2 is then sent to CDAS which decides on forming a T3 trigger. In case of a T3, CDAS sends out the request to all stations of a quadrant to collect all data available, which includes local T1 fulfilling timing requirements. In the design of local station-trigger we need to differentiate between a T1, which is required to collect data from a station, and the T2, which is required by a T3 and the event-readout by CDAS. Especially, creating a T2 trigger is a challenging topic as the T2 rate is very limited. The current operating has a T1 rate at the station of ≈ 104 Hz compared to a T2 rate of ≈ 22 Hz with a possible extension of only 1 to 2 Hz due to limited network bandwidth. Hence, the new RD trigger can add only a small trigger rate and has to be carefully designed to result in limited rates for all radio-background conditions.

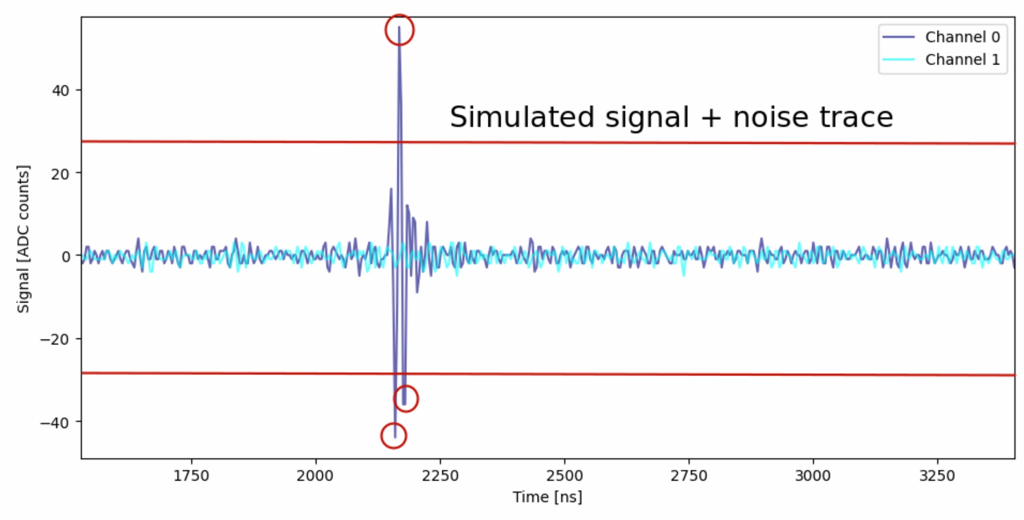

Figure 1: Simulated signal with added measured noise for the two different channels (blue colors). The red lines show an exemplary threshold for a trigger, while the circles mark triggering bins.

3. Concept of a RD trigger

The RD trigger mainly needs to fulfil the following aspects:

1.) **Increase of photon detection rate:** Most important, the new trigger should increase the trigger efficiency of photon air showers significantly.

2.) **Compatibility with the limited bandwidth:** The T2 trigger messages and the T3 event readout are bandwidth limited and close to the maximum bandwidth. The design of a new trigger cannot increase the trigger rates largely, or it would require a reduction of the existing trigger-rates. The new trigger should not trigger on low energy or vertical hadronic shower that due to their small footprint produce a strong radio signal only in single stations at the shower core, but will not be reconstructable with only a single signal station. Additionally, high energy hadrons are triggered already by the particle detectors and do not profit from a additional trigger.

3.) **Trigger purity:** The trigger threshold should be above the noise level. This will secure the purity of our data and limit the required bandwidth.

As a trigger design, a simple threshold trigger was chosen. This is depicted in Fig. 1, where three peaks of a simulated signal are observed, that trigger in case of the chosen threshold of 25 ADC counts. More complicated trigger concepts are not feasible as the FPGA, which carries out the calculations, has a limited number of bits. A significant fraction of bits is used for a FFT, which is needed. Hence, only minor calculations like counting of bins is possible. Furthermore, the simple threshold trigger allows to veto noise due to the different shapes as we will show in Sec. 4.

In the following sections we will show that the trigger concept is compatible with all of the mentioned requirements. The noise investigation in Chap. 4 uses measured noise traces of RD prototype stations, the remaining analysis is done with CORSIKA simulations [9].

4. Noise level at the Pierre Auger Observatory

The RD trigger threshold (RDTT) should be large enough that it is not triggered by regular noise (regular noise = noise that is ubiquitous, i.e. excluding lightning etc.). We tested possible RDTT with data that was measured on the 15th of March 2022. This data was taken outside the normal acquisition, so periodically triggered over one day. The data set includes traces of both channels from four stations arranged in a parallelogram. They are part of the engineering array, which is known to be radio quiet. In the following, we will show results from one station only as the results are similar for all stations.

Each station measured 4,000,000 events for a time of 8M traces (two polarization per event) with lengths of approximately 8 μs. Hence, we have a total of more than 4 minutes of noise, which is sufficient for a statistically significant analysis. The Feldman Cousins 95 % C.L. in case of no event over a given threshold is $\approx 9 \cdot 10^{-2}$ Hz for each station compared to triggering frequencies in the order of Hz.

A good way to see specific features of the noise traces is to look at the average of many traces. This is shown on the left of Fig. 2, where we took 5,000 randomly selected traces. One observes a flat baseline which is shifted by around two ADC counts between the channels. Additionally, one feature is a peak at around 4,400 ns. This is expected to be noise coming from the station, most probably communication of the data saving. This feature can also be seen in the real event data, but it is not a cause for concern, as the peak occurs several hundred nanoseconds after the initial signal. Also, the magnitude of the noise is acceptable and is anyway not seen by a potential RD trigger (as we save the data only after a trigger). Besides the writing noise, no irregularity can be observed in the average trace.

The majority of traces are not conflicting for the RD trigger. In order to find traces that are more conflicting for our trigger, we look at the maximum absolute value for each trace. This yields the ratio of noise traces, which amplitudes would exceed our RDTT and therefore contributes to the triggering frequency. The distribution of the maximum values is shown in Fig. 2 on the right. One observes a splitting of traces into two categories. The majority of traces can be found in distribution **A** with values below 55 ADC counts and a peak at 10 ADC counts. These traces consist of fluctuations of a few ADC counts with values below the the RDTT. The second and more interesting distribution starts at around 55 ADC counts and shows a rise in the curve after the decline of distribution **A**.

The main part of distribution **B** arises from citizens-band (CB) radio (people talking over walkie-talkie next to the station). An exemplary noise trace with its FFT spectrum is depicted on the left of Fig. 3. The noise is strong for both channels and ubiquitous over the whole trace. Additionally, these traces were found to be consecutive. For one station for example, hundreds of these traces were consecutively recorded. The frequency spectrum shows a clear peak at approximately 27 MHz, which is known to be the common frequency of CB radio. We also found these kind of traces to vary in amplitude and polarization, which also indicates that people are walking around the tank with the walkie-talkie. These traces can also be found at the right edge of distribution **A**, shown on the right of Fig. 3. Traces effected by CB-radio have in common that they

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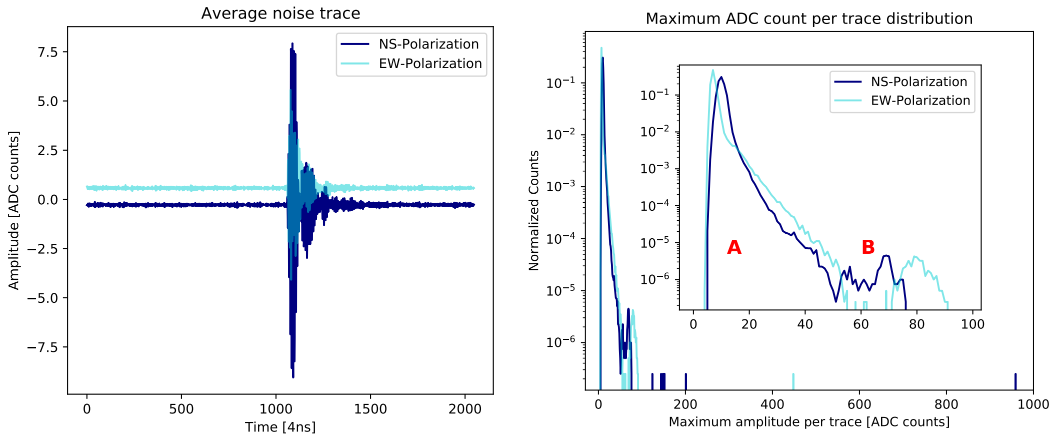

Figure 2: Left: Average trace of 5,000 randomly selected traces. Right: Distribution of the maximum absolute value of the noise traces.

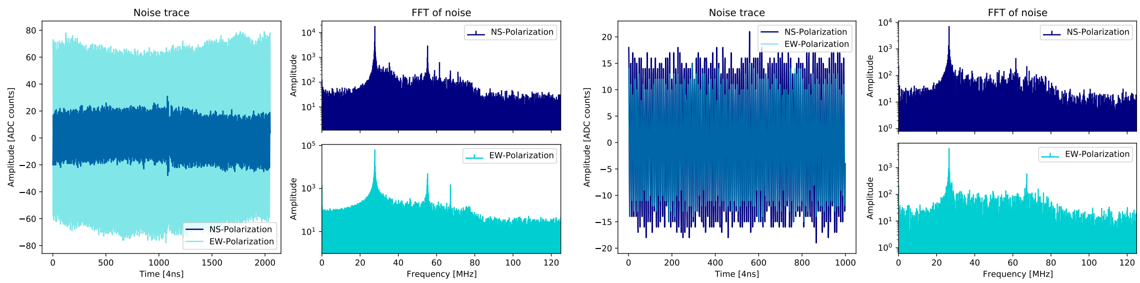

Figure 3: Left: Noise trace with large amplitudes and its FFT caused by CB radio. Right: Noise trace with small amplitudes and its FFT caused by CB radio.

differ significantly in terms of pulse lengths from signals of air showers. Hence, we can reject these traces already on the trigger level based on their pulse length. A filter can be used, that rejects traces which have more than 15 bins with amplitudes above 30 ADC counts. It should be mentioned, that these values are selected to validate the concept and the exact values will be studied later. The filter is able to reject traces with large amplitudes but fails to filter traces with amplitudes smaller than 30 ADC counts. Lowering the rejection threshold would increase the risk of filtering real signal events.

It is important to point out the time variation of noise. Noise like CB-radio is not expected to occur at night as there are normally no people in the array at this time. This can exemplary be seen in Fig. 4 on the left. One observes the averaged time variation over the day for one station. A peak around 250 is visible, afterwards the noise level is significantly lower. Hence, one should analyse the noise distribution for the noise periods separately. This is shown in Fig. 4 on the right depicting the integrated distribution of the maximum amplitudes. As reference, the grey lines show different trigger frequencies and the green solid line indicates the distribution for all traces. The plot shows the importance of filtering on trigger level and the necessity of a variable trigger threshold. Here, one can reduce the applicable trigger threshold (1 Hz line as reference) from ≈ 90 ADC counts to 40 ADC counts when using the filter and even down to 25 ADC counts for noise quiet times. In the

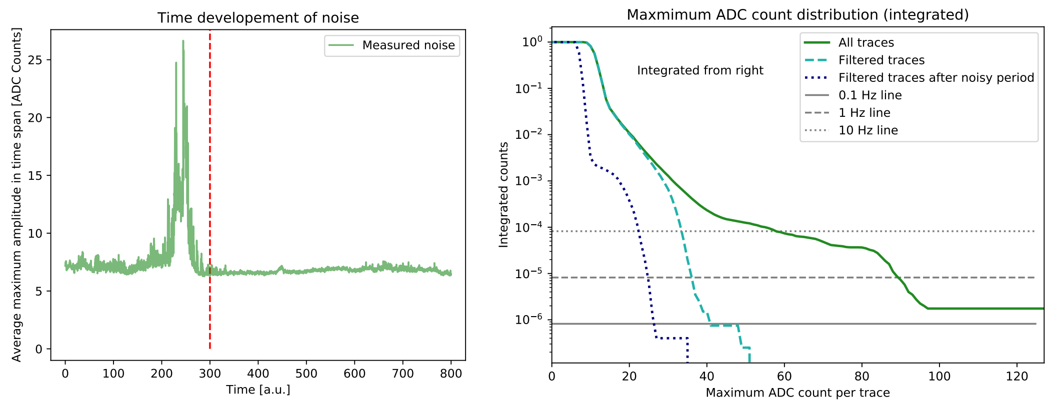

Figure 4: Left: Time development of the noise. The red dashed line marks the beginning of a noise quiet period. Exact timestamps are not known. Right: Integrated distribution of the maximum absolute value for all traces (green solid line), filtered traces (dashed light blue line) and filtered traces after the noisy period (dotted dark blue line). The grey lines indicate corresponding the resulting trigger frequencies of 0.1, 1 and 10 Hz.

end, a variable threshold is required to keep the T2 rate constant. Hence, one can use the lowest possible trigger threshold at all times while being compatible with the limited bandwidth

5. Increase of the photon trigger rate

The next important aspect for the trigger is the increase in the photon trigger rate. We used 800 CORSIKA simulations with energies ranging from $10^{18.4}$ eV to $10^{20.4}$ eV and zenith angles from 65 ° to 85 °. A reconstruction of these shower with our analysis framework was done. Here, new parts were designed to simulate the functionalities of an RD trigger. The output was used to analyze the data set on important aspects like trigger and reconstruction rate. Figure 5 shows the increase of trigger rate for different energies and zenith angle ranges. On the left a conservative trigger threshold of 60 ADC counts is applied. One obtains an increase for all zenith angle ranges compared to the case without RD trigger (black dashed line). Still, the triggering only gets really efficient for energies larger than 10 EeV. The zenith angle and energy weighted trigger rate doubles from 12 to 25 %. On the right of the figure, the case of a threshold of 25 ADC counts is depicted. For the zenith angle range of 65 ° to 70 ° no significant change to the previous case can be observed. The footprint is too small on ground that also a smaller RDTT does not improve the triggering. For more inclined showers, the triggering significantly improves and is nearly 100 % efficient for zenith angles larger than 75 ° and energies greater than $10^{18.6}$ eV. The zenith angle and energy weighted trigger rate increases from 12 to 46 %.

The new trigger should not only be characterized by the amount of gained events but should also be evaluated by the gain in discrimination power. Particle surface detectors lack of information about the EM component of the air shower. The RD trigger also enables to detect events which consist nearly completely of EM particles. These events can then almost certainly be characterized as photon air showers. This can be seen in Fig. 6. The trigger composition is shown for protons and photons. Events where all stations have a particle trigger are shown on the left side, events with

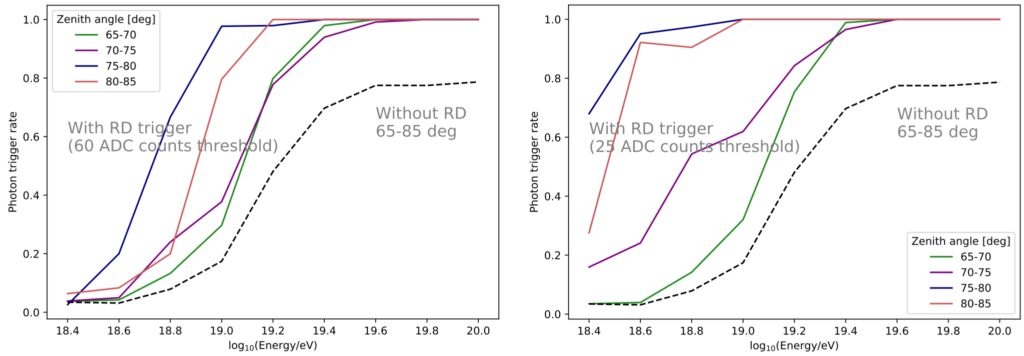

Figure 5: Left: Increase of the photon trigger rate for different energies and different zenith angle ranges (solid lines) for a trigger threshold of 60 ADC counts. The dashed black line shows the case without RD trigger. Right: Same as on the left but with a trigger threshold of 25 ADC counts.

only RD triggers on the right side. Events with only RD triggers can be seen on the right edge. A good separation of the two primaries is observed and many photon events can be seen with only RD triggers, while no protons events can be observed.

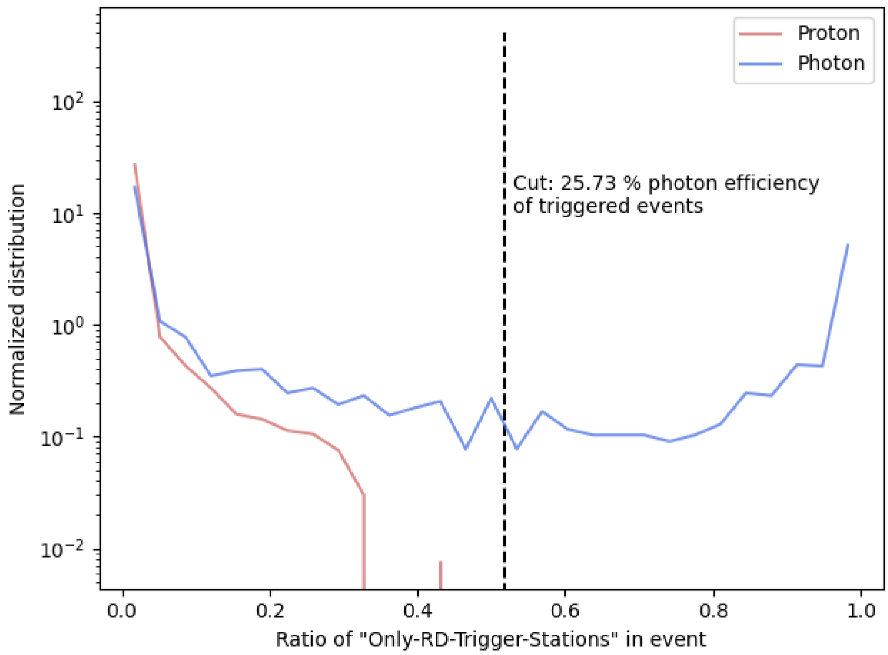

Figure 6: Ratio of stations which have no particle trigger but a RD trigger within an event for photons (blue) and protons (red).

6. Summary and Outlook

We showed that the concept of an RD trigger leads to a significant increase of triggered photon events while being compatible with the limited bandwidth. A variable trigger threshold enables the lowest possible trigger threshold at all times while not interfering with the measured noise level. We also determined the irreducible noise level and have shown a way to reject artifacts from our noise data set. Additionally, we can evaluate the trigger concept by the discrimination power between photons and hadrons. Already with basic parameters like the trigger composition, one gets a significant separation of the two distributions. Future analyses will concentrate on the different signals in the detectors and will make use of more advanced parameters than the trigger composition. Multivariate analyses can also increase the efficiency of discrimination cuts.

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