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Terrestrial Gamma-Ray Flashes at the Pierre Auger Observatory

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Abstract. The Pierre Auger Observatory is designed to measure the highest energy cosmic rays. However, the surface detector, covering 3000 km^2, is also sensitive to events associated with atmospheric electricity. These events can be distinguished from normal cosmic-ray events in both temporal and spatial structure. With signals lasting around 10 µs, they are about an order of magnitude longer than cosmic-ray events. Their circular footprints on the ground are also different and larger than those of typical cosmic-ray showers. Due to their association with thunderstorms and topology, these events are candidates for downward-going terrestrial gamma-ray flashes (TGFs). We show a detailed analysis of the effects that the data-taking system has on recording of TGF candidate events. Furthermore, we present a recently implemented special trigger algorithm aimed at increasing the data-taking efficiency for TGF candidates.

1. Introduction

The Pierre Auger Observatory [1] is designed to detect extensive air showers produced by ultra-high energy cosmic rays in the atmosphere. Nonetheless, it also proved efficient at observing transient phenomena related to atmospheric electricity. The fluorescence detector was built to record the longitudinal evolution of showers in the atmosphere. However, it also records peculiar events, associated with ELVES [2], a type of transient luminous events occurring in the upper atmosphere above thunderstorms. The second large detector component of the Pierre Auger Observatory, the surface detector (SD), is made up by 1660 water-Cherenkov detectors used to sample shower particles like electrons, photons, and muons, and covers about 3000 km^2. In the SD, peculiar events have been discovered during thunderstorms as well [3]. These events exhibit features, in footprints and signals, that are very different from those produced by the highest-energy cosmic rays [3, 4].

In Fig. 1, we show several footprints of such events with their characteristic circular shape. The missing centre was shown to be an artefact of the data-taking system [5] that is optimised for cosmic-ray events with durations on a very different time-scale, and there is firm evidence of a closed footprint [4]. The difference in time-scales of the signals is evident from the comparison of example traces in Fig. 2. In panels *a*-*c*, we show example traces of cosmic ray events. In panel *d*, we show a typical RF-noise picked-up in the PMT cables. The signals in panels *e* and *f* are clearly different and extend beyond what the electronics were designed to cover, hence they were dubbed “long-signals”. Since the data taking period starting in 2004, 23 such events of high-quality have been identified that are also correlated to reconstructed lightning strikes from the World Wide Lightning Location Network (WWLLN) [4].

In these events, the energy density deposited in the detectors is comparable to that in NaI-scintillators [9] at 650 m from the source [4] and the events are similar in size and length to events found

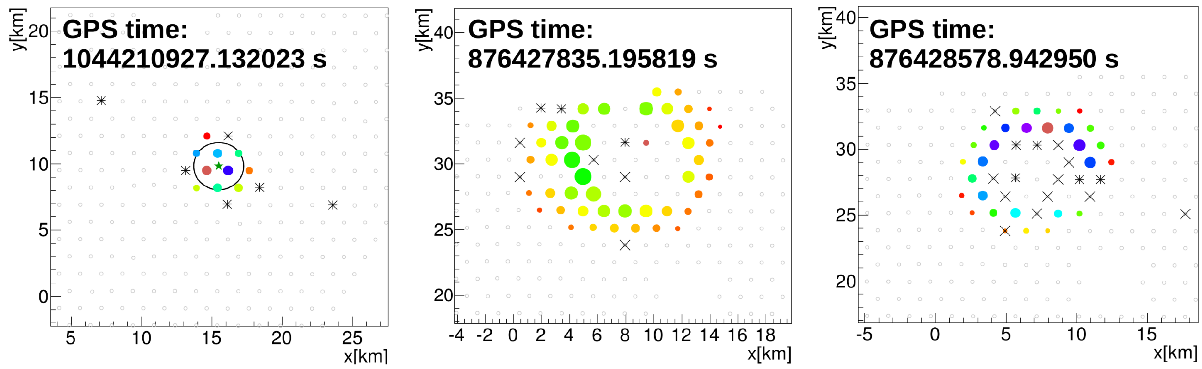


Figure 1. Footprints of example peculiar events observed in the SD. Circles mark stations with long-signals (cf. Fig. 2 e and f) with the marker size corresponding to the signal size and the colour representing time (blue early, red late). Stations recording RF noise from lightning activity are marked with stars and stations with muon-like signals with crosses. A ring-like shape for these events is evident, in the left panel it is highlighted with a black circle that originates from a fit. For smaller events, the ring is filled [4].

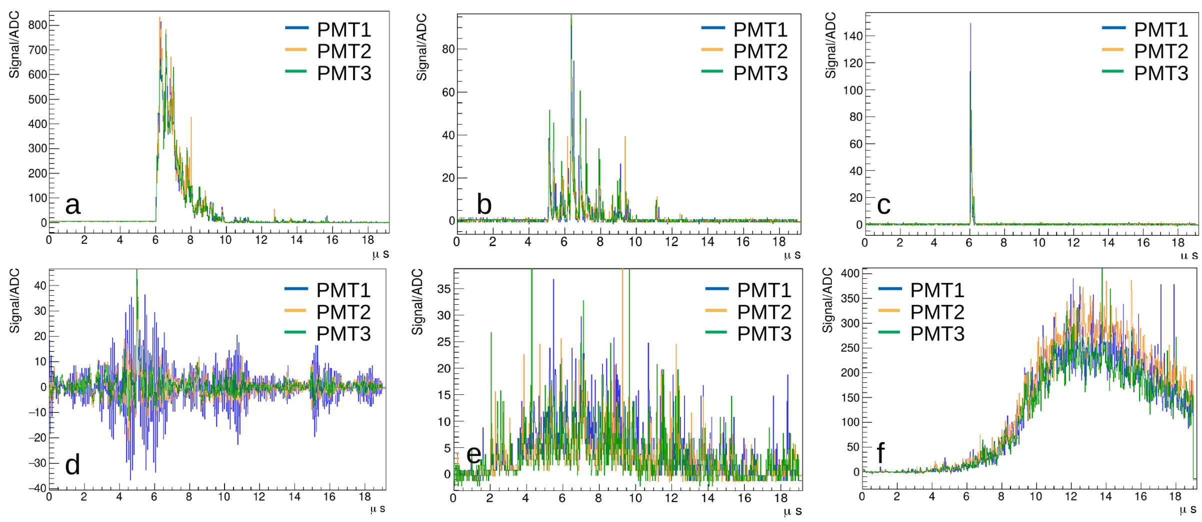


Figure 2. Illustration of typical signals in the surface detectors: Panels a-c are signals from cosmic-ray showers at different distances to the core. Panel d is a typical example trace caused by RF noise picked up in the PMT cables during lightning activity. Panel e and f show examples of the so-called "long-signals" observed in TGF candidates. The two latter examples differ in amplitude but are thought to be originating from the same type of events [3].

by Telescope Array [6, 7, 8]. We thus can conclude that there is evidence that these events are downward-going Terrestrial Gamma-ray Flashes (TGFs) and we will thus refer to the events in the following as TGF candidates.

In this contribution we recapitulate the capabilities and limitations of the Pierre Auger Observatory data-taking system with respect to TGF candidates and highlight recently added capabilities aimed at improving the SD sensitivity.

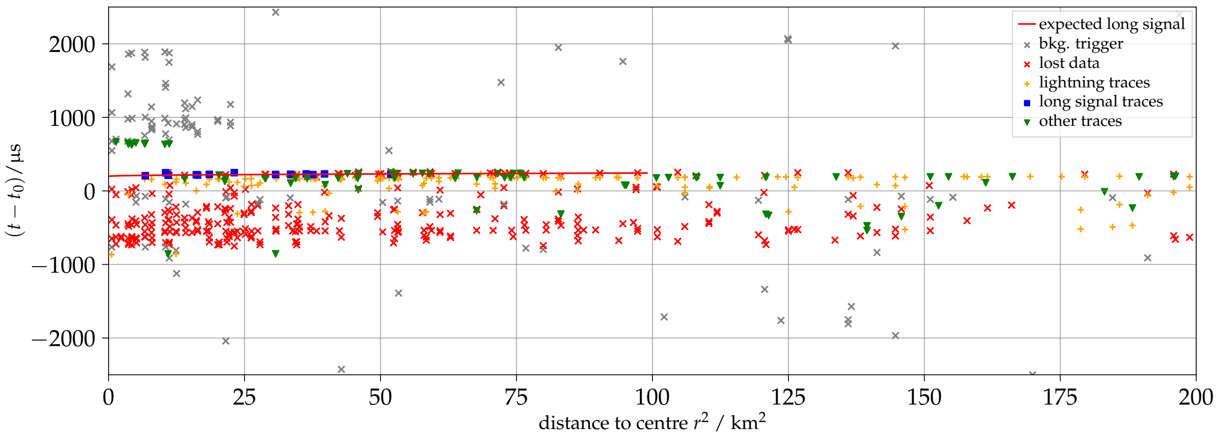


Figure 3. Illustration of the station triggers during the period of a TGF-candidate event. We show the trigger time (with respect to a event time t_0) as function of squared distance to the estimated centre r^2 because in r^2 the density of SD stations on ground is constant. Crosses indicate station triggers for which no trace information is available because either the event could not be transmitted (red) or the trace was not requested (gray). The TGF-candidate signals are marked with blue squares.

2. The Auger-SD Data Acquisition

The task of the data-taking system of surface detector at the Pierre Auger Observatory is to ensure recording of event data from ultra-high energy cosmic-ray events under the constraints of the available bandwidth. This means that in the data taking chain from detector to event level, most of the suppression of the random background has to happen on the local station level. During normal conditions, the rate of signals in a detector station is dominated by atmospheric muons that hit a single station with a rate of about 2 kHz. The rate of triggers per station have to be reduced to about 100 Hz of signals from events (level-1 triggers) that can be requested by the central data acquisition system (CDAS) and are buffered on the station. The radio link between stations allows about 20 Hz of level-2 triggers to be sent to the CDAS to form coincidences and request events. Forming coincidences of three or four stations in geometrically compact formations, the CDAS achieves full efficiency above energies of $10^{18.5}$ eV [5]. The rate of such events across the whole SD array is about 0.1 Hz. This means that having more than a single event per GPS second – that are used to synchronise the communications between CDAS and the stations – is a rare occasion.

In contrast to these regular conditions, the rate of coincidences and thus event requests during thunderstorms can change massively. While such periods can be identified and are excluded for cosmic-ray analyses, they are of particular interest in the study of TGF candidates presented here. To highlight this difference, we show all level-2 triggers from ± 2.5 ms around a TGF candidate recorded in May 2017 in Fig. 3. In the first millisecond the normal rate of background triggers can be inferred from the occurrence of a handful of random triggers. With the beginning of the lightning activity a period of very high (level-2) trigger activity starts that ends with the TGF candidate (blue markers).

This high number of triggers leads to a high rate of coincidences and thus event requests. In this case, 11 separate events are formed and the data is requested from the stations. Fig. 4 shows the same triggers as Fig. 3, now associated with these different event requests. It is clearly visible that the capacity of the CDAS – designed for less than one event per second – can only cope with five to six consecutive events before most data is lost.

These limitations imply that, if TGF candidates are accompanied by lightning activity, the chance of recording the interesting events with the current CDAS is impaired by the excessive rate of event triggers. To compensate this, a new trigger scheme is designed that can increase the efficiency of data taking for TGF candidates [4]. We describe this concept and the implemented changes in detail in the next Section.

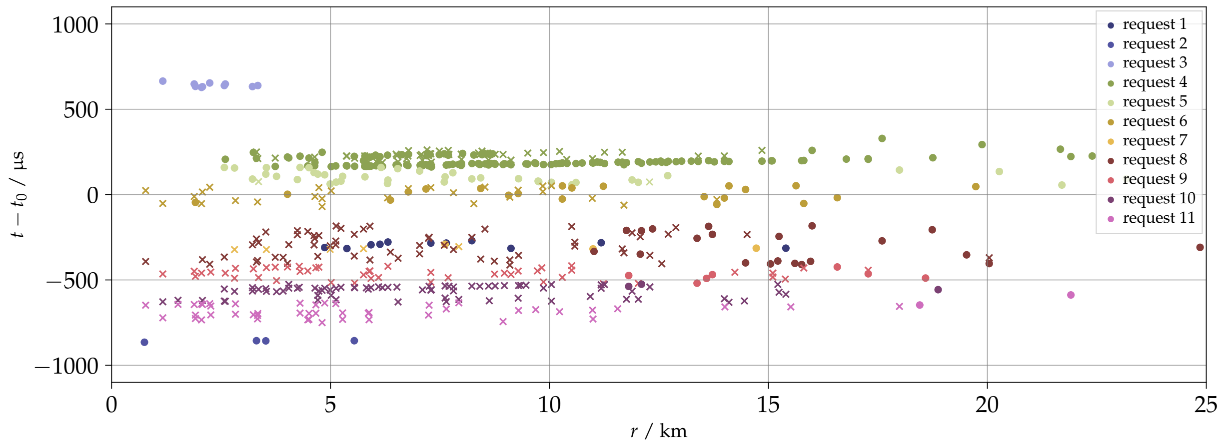


Figure 4. Visualisation of how the CDAS requested the data from the stations in the TGF-candidate event shown in Fig. 3. We use a linear-r scale here to highlight the speed-of-light compatibility. Circles indicate successful returned data, while crosses represent lost data. The TGF-candidate traces are recorded in the event requests 4 and 5.

3. New Trigger Scheme

The basic idea to increase the read-out efficiency of TGF candidates without compromising normal data taking is to request events with interesting traces first, i.e. as "request 1" in Fig. 4 instead of request 4 or 5. Such an arrangement has no effect on normal data taking even in the case of false positive identifications because a reordering of singular requests – as expected from the event rate – does not change the result.

The challenging task in this concept is the design of an algorithm that can identify the interesting signals, e.g. traces like *e* and *f* in Fig. 2, and be robust against background. In light of the excess triggers from lightning activity, having traces similar to panel *d* of Fig. 2, this background is the most important to suppress. An additional challenge is the requirement to be run on the local-station controller, as the computational power is limited. We tested several algorithms on already recorded data and chose the best-performing one that reaches a true positive efficiency of more than 70% on single station basis when low false positive rates of less than one station per GPS second of interest are required. In the following, we present this algorithm as it is implemented in the stations in the surface detectors since November 2021.

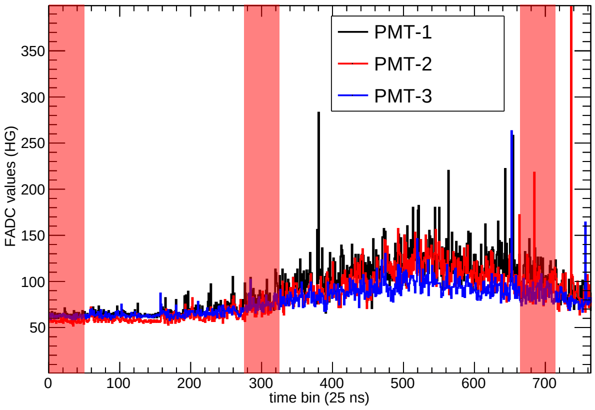
We use the fact that lightning noise, as shown in trace *d* of Fig. 2, is high-frequency bipolar noise so it cancels if a sufficiently long time interval of the trace is integrated. In this algorithm, we use an integration window of 50 bins ($= 1.25\,\mu$s), highlighted as red boxes in the examples of Fig. 5. To identify the characteristic "long-signals", we use the trigger bin (bin 250 in Fig. 5) as a reference point and place one integration window after the trigger bin, as it can be seen in the right panel of Fig. 5. The other two windows are placed at the beginning and end of the trace at a distance that allows to capture the baseline in at least one of them.

Given a trace t, we define the accumulated signal in the i^{th} window as

$$S_i = \sum_{j=a_i}^{b_i} t(j), \tag{1}$$

where a_i and b_i are the limits of the window. Then the algorithm triggers on the long-signal candidates if the condition

$$\sum_{i=2}^{3} |S_i - S_1| > x_{\text{thr}}, \tag{2}$$



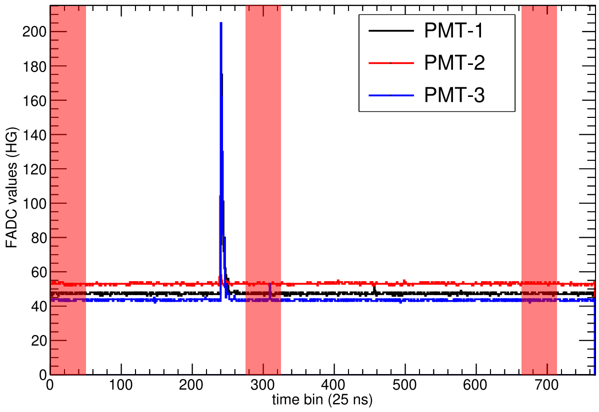


Figure 5. Example traces with illustration of the implemented algorithm (cf. text). *Left:* A trace from a TGF-candidate event with signal contributions picked up in the windows two and three. *Right:* A small cosmic-ray signal. Clearly no signal is present in the integration windows.

is fulfilled. Here, $x_{\rm thr}$ is a threshold tuned to achieve the highest possible efficiency without tagging lighting events during known TGF-candidate periods. The integration windows are fixed to positions optimised on the available sample of TGF-candidate traces.

Fig. 5 shows that the choice of intervals covers the beginning and end of the long-signals (in the left panel) and that a normal cosmic-ray shower is not tagged due to the choice of intervals (right panel).

4. Conclusions and Outlook

We showed that the limiting factor for recording TGF-candidate events at the Pierre Auger Observatory is the high event rate associated with lightning activity accompanying the TGF candidates that the SD data taking system is not designed for. With the implementation of the dedicated trigger algorithm in November 2021 this bottleneck can be circumvented in the future because it allows the prioritised selection of TGF-like events during thunderstorm periods. A detailed study of the performance during the lightning season is currently on-going and we will use the gained knowledge to improve the data taking even further.

Especially in light of the on-going upgrade of the Pierre Auger Observatory, called AugerPrime [10], the additional insight into data during thunderstorms can be very valuable. The key part in the further development and analysis of TGF-like events is the upgrade of the station electronics with the Upgraded Unified Board (UUB) [11]. It will provide more memory, buffers, and CPU power to allow the implementation of more analysis algorithms on the station level. Additional triggers, or data taking beyond the about 20 µs of the current traces are also among the possibilities that can be explored. The upgraded trigger system presented in this work can provide first clues into how further improvements are possible.

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