Multiple ELVES and other Transient Luminous Events at the Pierre Auger Observatory

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Abstract. In the last ten years, the Pierre Auger Observatory has exploited a dedicated trigger and extended readout, and its very high time resolution, to record the world's largest sample of multiple ELVES. By comparing the time gaps between flashes with waveforms recorded by the antennas of the ENTLN network, we observe the correlation expected by models for what concerns double ELVES. On the contrary, using a large sample of triple ELVES, from four different thunderstorms, we refute the ground reflection mechanism. In the same data sample, we could observe another type of TLE, the halo, a few hundred microseconds after some ELVES. This has motivated the installation, in December 2023, of new cameras, to complement the observations done with our Fluorescence Detector. Preliminary results, including the first observation of sprites in Auger, will be shown.

1. Introduction

The Pierre Auger Observatory is the world's largest infrastructure for the study of ultra-high energy cosmic rays. Besides its main activity, the Observatory has started a program of cosmo geophysics studies, which exploit some of the unique features of its detectors. ELVES (Emission of Light and Very low-frequency perturbations due to Electromagnetic pulse Sources) are transient luminous events occurring at the base of the ionosphere when a strong electromagnetic pulse (EMP) is emitted by lightning. This phenomenon, theoretically predicted a few years before [1], was photographed for the first time in 1990 from the Space Shuttle [2].

ELVES appear as rapidly expanding rings, smoothly fading towards the horizon, and can trigger our fluorescence detector (FD) [3] when the source is at a distance farther than 250 km, so that the earth's curvature prevents the direct light from reaching our sensors. Since 2013, we have implemented a dedicated trigger and readout scheme to study these events using the twenty-four FD Telescopes [4]. Since 2017, we have extended the length of recorded traces to up to 0.9 ms, to study a larger fraction of the doughnut-shaped region of maximum emission. Such an upgrade has been only partially successful, as the broadening of the traces from distant pixels significantly reduced the first-level trigger efficiency. In turn, much brighter and longer signals were observed in the lowest rows of pixels: these are other types of Transient Luminous Events (TLEs from now on), named halos, and will be reported in Section 3.

In December 2023, in the proximity of the FD site of Coihueco, we installed a Sony α7-III camera, to complement our FD observations, with images with longer integration times, and better spatial resolution. A second CMOS sensor, ZWO ASI294MC, was added in March 2024. A short report on the first events observed by this new instrument will be given in Section 4.

2. Multiple ELVES and ENTLN waveforms

The time resolution of the Auger Observatory, coupled with its 2D imaging capability, allows us to study in detail the fine structure of the light emission in ELVES events, often characterised by two or more distinct flashes. While double ELVES have been reported many times in the literature [5,6,7], Auger has been the first experiment to report the observation of a triple ELVES event [8]. In this paper, we report results from a dataset of the four thunderstorms with the largest fractions of multiple ELVES in 2014-2020: statistics are shown in Fig.1.

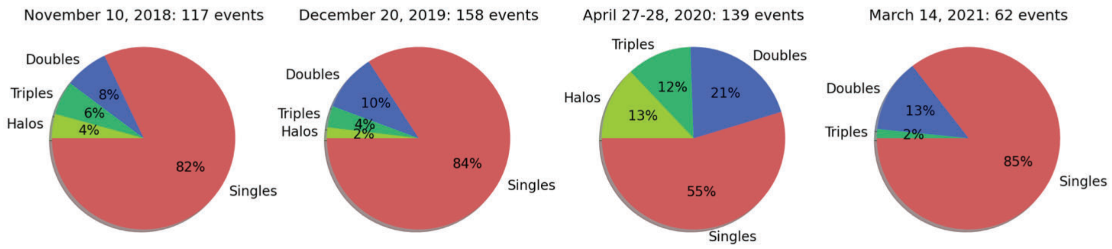

Figure 1 Fractions of multiple events and statistics of the four storms described in this work.

The strong electromagnetic pulse (EMP) that produces the ELVES can also be detected by networks of radio antennas; the EMP propagates towards the antennas either following the surface of the earth (with a shorter attenuation length) or repeatedly bouncing between the base of the ionosphere and the ground, as in a resonant cavity. By comparing the radio waveforms with the UV light emissions of the ELVES, we can study the mechanism underlying the production of multiple ELVES.

The Earth Networks Lightning Network (ENTLN) has installed more than 35 antennas in Argentina during the austral summer 2018-9 [9]. Each antenna has a bandwidth of up to 24 MHz. Besides lightning location, timing, energy, and polarisation, ENTLN can provide waveforms for each antenna. Using lightning longitude and latitude provided by our ELVES reconstruction algorithm to calculate the time offset between the antenna traces, we observe that signals align consistently. By sorting the signals with the distance of the antenna from the lightning source, one can distinguish the surface wave, the first sky wave, directly related to the ELVES emission, and even the second sky wave. The waveforms of the first sky wave observed with antennas located between 300 and 400 km from the ELVES source were used to measure the EMP durations [10], and correlate them to the time gaps between two or three flashes. While single ELVES have significantly shorter pulse durations (red histogram), double and triple ELVES have very similar pulse durations (grey and green histograms), as can be seen in Fig.2.

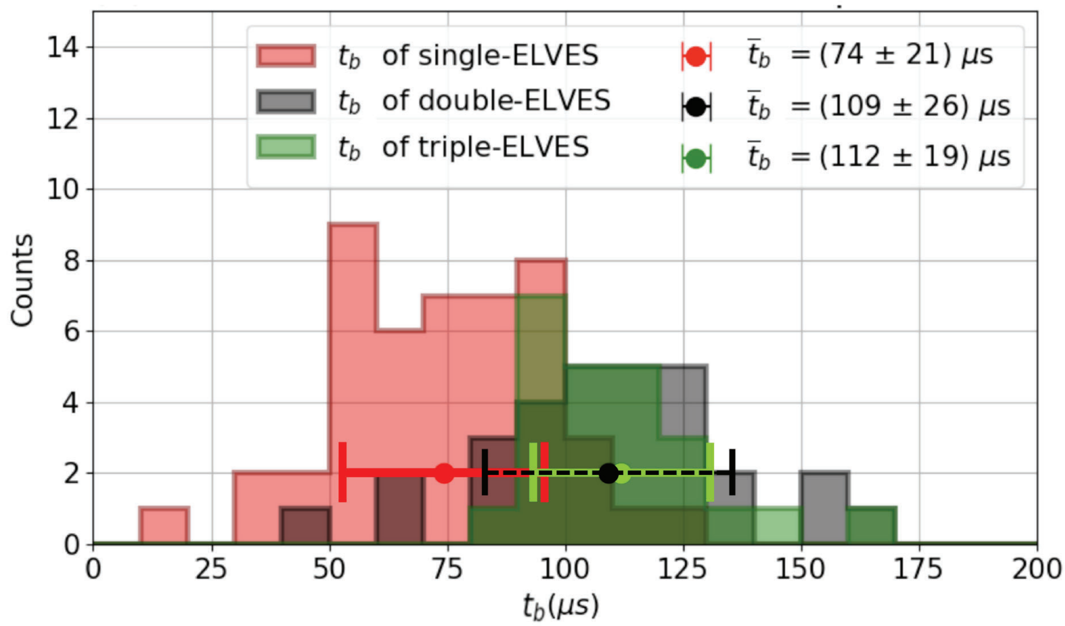

Figure 2 Distributions of pulse durations of single(red), double(grey) , and triple(green) ELVES.

A second feature emerging from these samples is the linear correlation between time gaps larger than 60 μs and base times in double ELVES, as shown in Fig.3, left. Triple ELVES always feature one long and one short time gap; the longer is again linearly correlated with the waveform pulse duration, as shown in Fig.3 right.

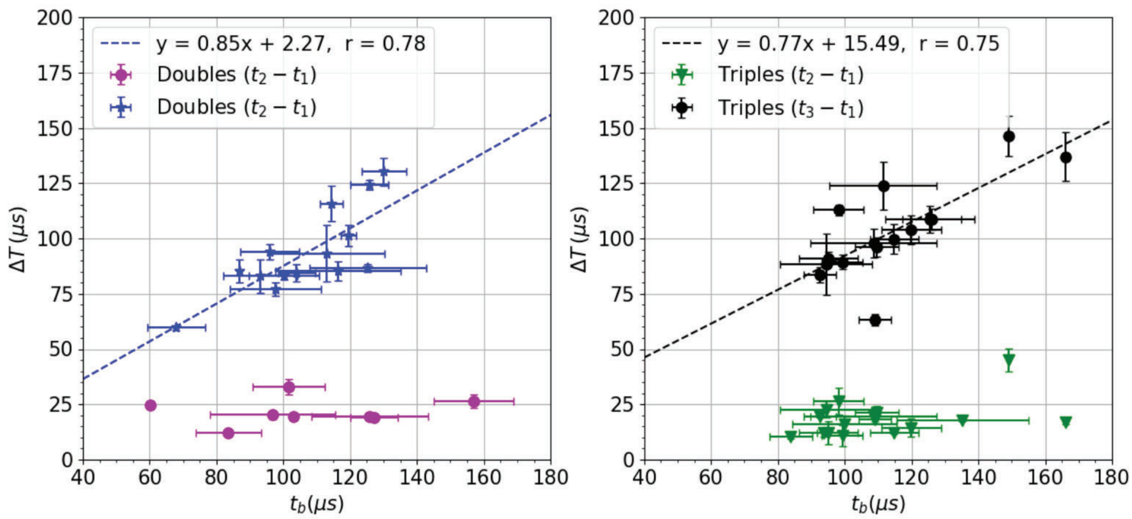

Figure 3 Time gap vs pulse duration correlations for double (left), and triple (right) ELVES.

The origin of the short time gaps is a controversial issue: according to [7], they should be associated with ground reflections of the EMP from a source at the top of the cloud. We have strong evidence, based on the analysis of GOES-16 data on cloud heights, that almost all ELVES are generated from altitudes above 10 km. Multiple ELVES are expected to be related [11] to another process, the Terrestrial Gamma Ray Flash (TGF), which results from plasma acceleration to relativistic energies of electrons inside thunderstorm clouds [12]. In [11] the presence of triple and even quadruple ELVES is explained as a consequence of the ground reflection of the EMP. This analysis, based on a sample of ~30 triple elves, from three storms, does not find compelling evidence of the bounce mechanism. A few bounce candidate events shown in the previous edition of this workshop [10] were rejected thanks to an improved reconstruction algorithm. In Fig. 4, we show the time gaps measured during the storm with the largest number of multiple ELVES in the period 2014-2021: all the pixels with the same colour belong to the same event. None of the events has time gaps decreasing with the great-circle distance ArcR (blank dots show the expected trends with a source at 5,10,20 km altitude), as predicted by the EMP bounce model.

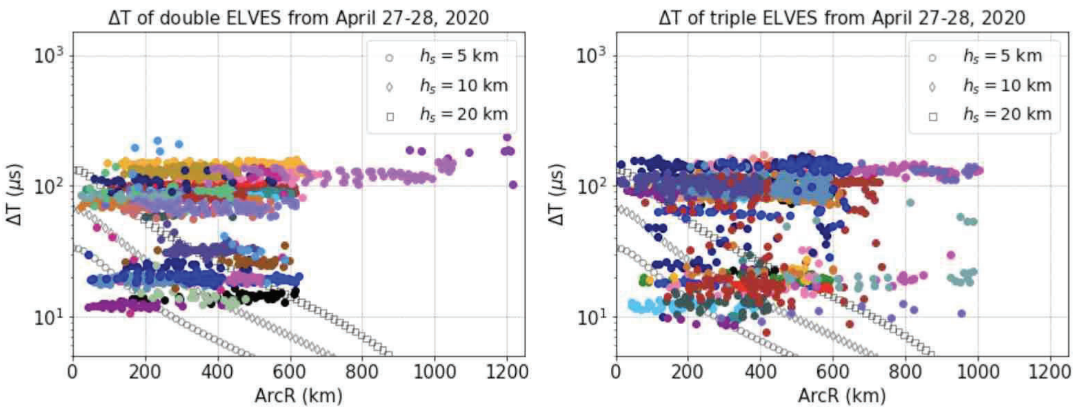

Figure 4 Time gaps for double (left) and triple (right, two entries per pixel) ELVES observed in the night between April 27 and 28, 2020. Points with the same colour belong to the same event. Circle, diamond and square dots indicate the expected trends with source altitudes at 5,10,20 km respectively.

3. Halos observation and modelling

Since 2017, the ELVES triggers in Auger are acquired with trace lengths up to 900 μs, in order to study the region of maximum emission around the vertical of the lightning source. This study is challenged by two factors: (a) the farthest part of the ring is significantly attenuated by the distance, and (b) the light pulse in a given pixel is naturally much broader and, therefore, may fail to meet the conditions for the first level trigger [4]. Nevertheless, this allowed us to detect other TLEs correlated with ELVES but brighter, such as the halos. Halos are produced by the quasi-static component of the EMP which produces the ELVES, at heights ~20 km lower than the base of the ionosphere. Halos are typically brighter than ELVES and have diameters around 80 km. Halos, which are ten times less frequent than ELVES[13], are often followed by sprites when the originating lightning leader has a positive charge. Halos can be easily distinguished from ELVES after correcting the traces of each pixel for the time delay of the full light path from source to the FD site [14].

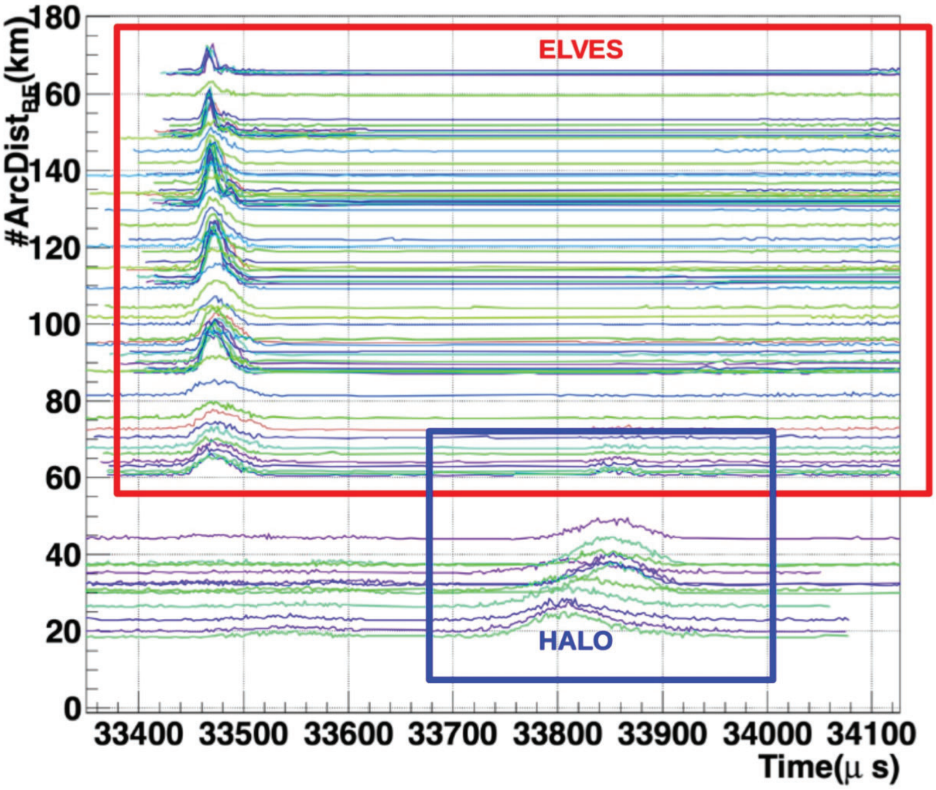

Figure 5 Traces from an ELVES followed by halo, observed on April 28,2020.

A typical event is shown in Fig.5: the traces with a distance of 60 to 160 km peaking about time 33480 μs form the ELVES ring. The bump closer to the lightning centre is the halo, occurring about 400 μs later. The traces are corrected for the time propagation of the pulse from the source to the ionosphere and then to the FD. The slight misalignment between the peaks related to the halo is due to the different altitudes of the light emission from the halo. The traces containing the halo peak are to be rejected from the reconstruction of the source location. The limited spatial extension of the halo prevents us from triggering these kinds of events independently from ELVES, therefore we can study only a biased sample of such phenomena. The extended readout allowed us to observe that other types of light emission follow the ELVES, stimulating the installation of more instruments to complement our FD.

4. TLE cameras for observation of sprites and blue jets

The main drawback of the high time resolution of the FD is the limit on the recordable trace length, which cannot exceed 1 ms without introducing large dead time on the DAQ for cosmic ray observations (a 0.9 ms event requires 9 seconds to be written to disk). A second limitation comes from the memory depth of the first-level trigger, which can take up to 64 consecutive traces, i.e. 6.4 microseconds. In a significant fraction of ELVES triggers, we observed full saturation of the first level memory buffers, implying extended emission of light from the horizon. In most cases, despite the top of the thunderstorm cloud being below the horizon, multiple scattered light from the bolt can reach our sensors a few ms after the ELVES.

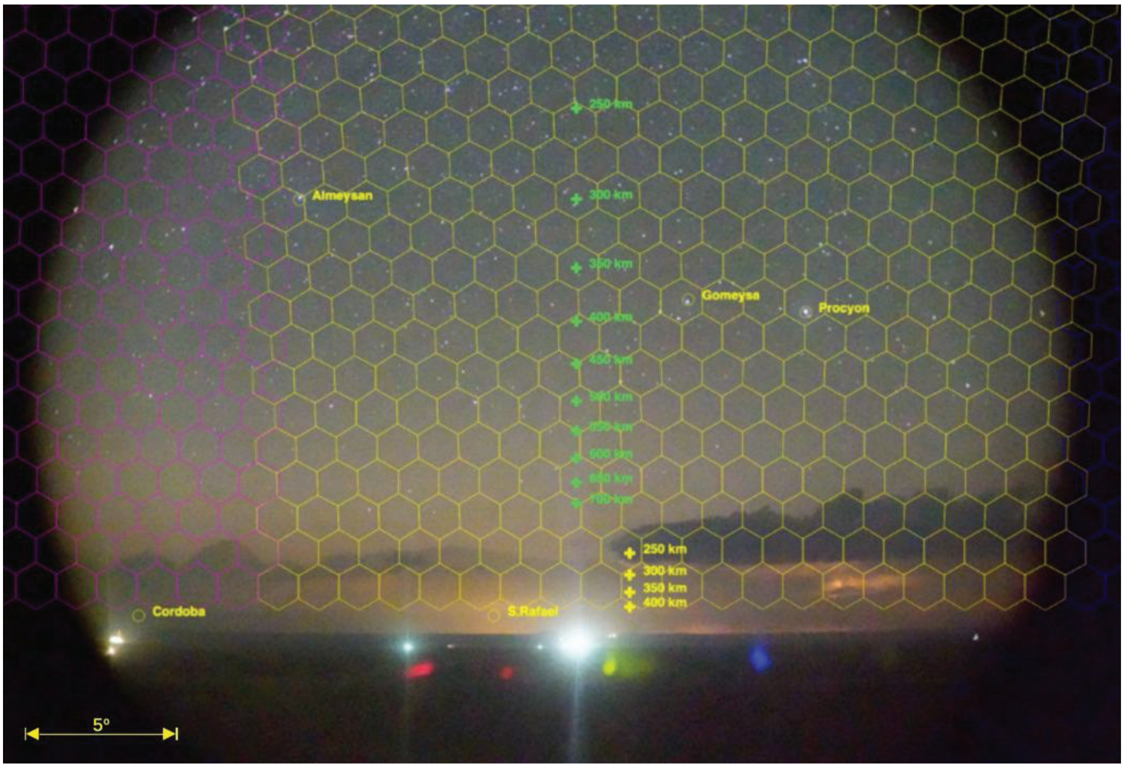

Figure 6 Field of view of the FD telescopes aligned with that of the Sony camera.

More interesting types of "transient luminous events" (TLEs) can indeed occur after the ELVES: besides halos, we can expect to detect sprites or blue jets. Sprites were theoretically predicted by CTR Wilson in 1925 [15], to occur under strong thunderstorms, when a positive cloud-to-ground strike is taking place. Sprites, discovered in 1989 [16], are intense discharges moving both upwards and downwards from 70 to 40 km altitude, with widths of about 0.1 km, occurring from about 1 ms up to 10 ms after the lightning strike. Such discharges can appear almost simultaneously over a horizontal distance of several km, have peculiar shapes (similar to jellyfish or carrots), and are significantly brighter than the ELVES. Blue and gigantic jets [17] last even longer than sprites, start from the top of high thunderstorm clouds, can last a few tenths of a second, and can reach the base of the ionosphere.

In order to complement the FD observations of ELVES and halos, we installed, in the proximity of the FD site at Coihueco, two cameras with high photon sensitivity, good space resolution, a field of view comparable with that of each FD telescope, capable of recording video sequences at speeds of up to 100 fps. The specifications of these two cameras are summarised in Table 1. Both cameras are read by an Intel NUC PC via USB-3 ports.

The Sony camera (named TLEcam-1) was installed in December 2023, so that it could take data during the winter 2023-4. The ZWO camera (named TLEcam-2) was installed in April 2024: since then, no storms have yet occurred in its field of view. Both cameras are mounted in the same enclosure, which can be remotely controlled, to rotate azimuthally over a range of ~90 degrees centred in the NE direction, looking towards the city of Cordoba. Synchronisation between FD observations and TLE events is at present not better than 100 ms. The alignment between the two cameras and the field of view of the FD telescopes has been performed using the brightest stars, as shown in Fig.6, which also shows the elevation of an ELVES center (green crosses) and of a fifteen-km high cloud top (yellow crosses) as a function of its distance.

Camera/Sensor	Npixels	Sensor Size	Objective
Sony α7-III	6000x4000	852 mm^2	7 artisans 50 mm f/0.95
ZWO ASI294 MC	4144x2822	248 mm^2	Sigma 20 mm f/1.4

Table 1. Specifications of the cameras installed in the proximity of the Coihueco site.

Here, we report a summary of the first events recorded by the Sony camera during the commissioning phase, which started on Dec.9, 2023. During this period, the TLEcam was manually controlled, aiming at the thunderstorms producing ELVES events. TLEcam-1 records 40 ms frames in 5-minute files. During a storm occurring on the morning of December 13, we observed a few ELVES triggers with our FD, and the first four sprites events. Only one sprite was correlated with the ELVES within 0.1 s. On the contrary, the observation of five sprites in closer time coincidence with ELVES events on January 7, 2024 indicates that the causal connection between these two types of TLE may depend on the type of thunderstorm. Fig.7 shows one of these events, overlapping the sprite profile with the light profile recorded by the FD pixels at the same time, after the ELVES. As this event occurred at an estimated distance of 650 km, the light of the ELVES (much dimmer than the one of the sprite) is not visible in the video recorded by the Sony camera. Another storm on March 9, 2024 yielded seven sprites observations, none of which was in time coincidence with ELVES.

5. Conclusions

More than thirty years have passed since the discovery of the first ELVES, but many aspects of their phenomenology, e.g. the origin of multiple ELVES, are still an open field of research. We here report on the analysis of the largest triple ELVES data sample collected so far, from which we do find clear evidence of a correlation between the time gaps and the EMP waveform baseline as recorded by radio antennas, and no evidence of multiple ELVES due to ground reflection of the EMP. Moreover, we are developing a reconstruction algorithm to resolve halos from multiple ELVES, and we have installed new cameras to do more systematic studies of the correlations between different types of TLEs. Commissioning is in progress: we have observed the first coincidences between ELVES and sprites in January 2024, and we'll exploit the next storm season to improve operational efficiency and automatization of these new instruments.

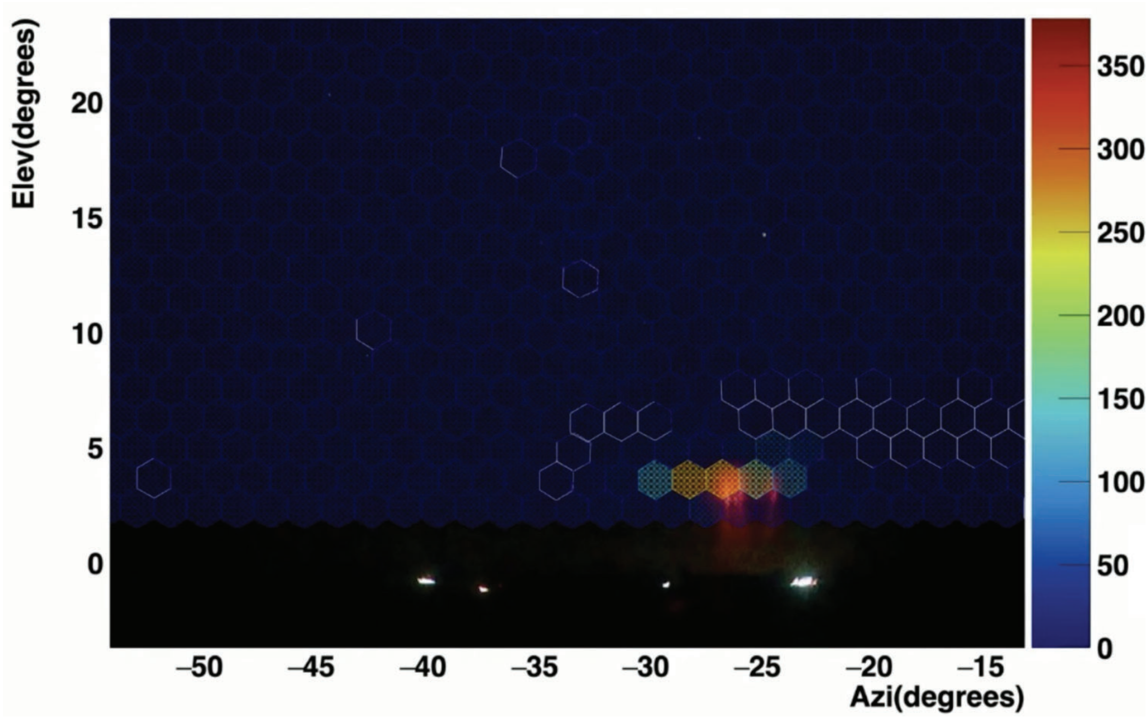

Fig.7 Event observed by both FD and TLEcam-1 on January 7, 2024 at 06:19:36 UTC. The five pixels in the second row see an increasing light signal after the passage of the ELVES light front, close to the vertical of the ELVES source location.

References

[1] U. S. Inan, T. F. Bell, J. V. Rodriguez, Geophys. Res. Lett. **18**, (1991) 705
[2] W. L. Boeck *et al.*, Geophys. Res. Lett. **19**, (1992) 99
[3] J. Abraham *et al.* [Pierre Auger Coll.], Nucl. Instrum. Meth. A **620** (2010) 227
[4] A.Tonachini *et al.*, Proc ICRC 2013 (2013), 0676
[5] R. T. Newsome, U. S. Inan, J. Geophys. Res.**115**, (2010) A00E41
[6] R. A. Marshall, J. Geophys. Res.**117** (2012) A03316
[7] R. A. Marshall *et al.*, Geophys. Res. Lett.**42**(2015) 6112.
[8] A. Aab *et al.* [Pierre Auger Coll.], Earth Space Sci. **7** (2020) 4, e2019EA000582
[9] Y. Zhu *et al.* , Remote Sens.**14** (2021) 2209.
[10] R.Mussa, A.Vasquez *et al.* [Pierre Auger Coll.], J.Phys.Conf.Ser. 2398 (2022)012006
[11] N.Liu *et al.*, J.Geophys.Res.**122** (2019) 10563
[12] G. J. Fishman *et al.*, Science **264** (1994) 1313
[13] A. B. Chen *et al.*, J.Geophys.Res.113(2008) A08306
[14] A. Abdul Halim *et al.* [Pierre Auger Coll.], Proc.ICRC 2023 (2023) 372
[15] C. T. R. Wilson, Proc. Phys. Soc. London (1925) 37, 32D
[16] R. C. Franz *et al.*, Science **249** (1990) 48
[17] H. T. Su *et al.*, Nature **423** (2003) 974