

Earth and Space Science



RESEARCH ARTICLE

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Quasi-Constant Time Gap in Multiple Rings of Elves

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Key Points:

- Exploiting a 100 ns time resolution multi-elves are shown to be very frequent, approximately 23% of the total
- Observations of multi-elves in Argentina challenge the model attributing their origin to reflection of electromagnetic pulses at the ground
- The multiple peaks observed in elves appear to be more closely linked to the lightning waveform than to its source altitude

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract We present evidence that the time delay between the multiple rings of elves is not caused by the ground reflection of the electromagnetic pulse produced by intracloud lightning. To investigate temporal differences of multi-elves, we analyzed data from four storms occurring at various times and distances from the Pierre Auger Observatory in Malargüe, Argentina. The Auger fluorescence detector's high temporal resolution of 100 ns enabled the frequent observation of multi-elves, accounting for approximately 23% of the events. By examining the traces of 70 double and 24 triple elves, we demonstrate that the time delay between the rings remains relatively constant regardless of the arc distance to the lightning. These results deviate from the trend expected from the electromagnetic pulse (EMP) ground reflection model, which predicts a decreasing time delay with increasing arc distance from an intracloud lightning at a given height. The first emission ring is due to a direct path of the EMP to the ionosphere, with the reflected EMP creating the second ring. Simulations conducted with this model demonstrate that short energetic in-cloud pulses can generate four-peak elves, and a temporal resolution of at least 25 μ s is required to separate them. Therefore, temporal resolution is crucial in the study of multi-elves. Our observations in the Córdoba province, central Argentina, indicate that the current understanding of the mechanism generating these phenomena may be incomplete, and further studies are needed to assess whether multi-elves are more likely related to the waveform shape of the lightning than to its altitude.

1. Introduction

ELVES (Emission of Light and Very Low-Frequency perturbations due to Electromagnetic Pulse Sources) is a type of transient luminous event (TLE-elves, sprites, halos, blue jets), occurring when the electromagnetic pulse (EMP) from an intense lightning strike reaches the lower ionosphere, causing the ionospheric electrons to heat up and produce secondary ionization and optical emissions (Fukunishi et al., 1996; Inan et al., 1991; Taranenko et al., 1993). Evidence shows that elves mainly originated from negative cloud-to-ground (CG) lightning (Barrington-Leigh & Inan, 1999; Newsome & Inan, 2010), as opposed to sprites which are usually triggered by positive CG. Elves are the most common type of TLE, occurring globally at a rate of 35 elves/min, while sprites and halos occur at 1 event/min (Chen et al., 2008).

The elves emission pulses usually last about 1 ms, and several authors (Aab et al., 2020; Barrington-Leigh & Inan, 1999; Lyu et al., 2015; Newsome & Inan, 2010) have reported cases where two of the pulses appear close together in time, sometimes only tens or a few hundred microseconds apart. These pulses, often called elve doublets, are thought to be associated with the same event because they are too close to be caused by multiple return strokes since the interstroke period is around 60 ms, and to be observed, detectors need resolutions better than a few tens of microseconds.

The origin of the multiple elves phenomenon remains under investigation. R. A. Marshall et al. (2015) suggested that multiple elves may be generated by compact intracloud lightning discharges (CIDs), with the time difference, ΔT , between the rings of a doublet being directly related to the height of the source. Using the maximum value of the ΔT detected among the vertical and horizontal channels of the Photometric Imager of Precipitated Electron Radiation (PIPER) (R. Marshall et al., 2008), R. A. Marshall et al. (2015) calculated the lightning height and confirmed observationally that ΔT correlates with high-altitude CIDs. From these observations, they also suggest that many simple elves labeled as CG-lightning generated are CIDs, but the temporal resolution of the PIPER (40 μ s) is not sufficient to separate the peaks of these elves.

Liu et al. (2017) used this approach to simulate the emissions in the ionosphere produced by energetic intracloud pulses (EIPs) and linked to terrestrial gamma-ray flashes. Results from the simulations of EIPs producing elves doublets suggest that at least 50 μ s time resolution is needed to differentiate the two peaks. They also show that very short EIPs (33.6 μ s) can produce elves quadruplets, and the minimum time resolution to separate the peaks is about 25 μ s. Therefore, time resolution is crucial for the study of multi-elves.

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On the other hand, R. A. Marshall (2012) showed that CGs with a very long rise time of the current waveform could produce double elves. However, R. A. Marshall et al. (2015) noted that those rise times are unrealistically long but the possibility of a fraction of double elves originating from CG discharges remains open.

Since 2013, the fluorescence detector (FD) at the Pierre Auger Observatory (The Pierre Auger Collaboration, 2015) in the Mendoza province-Argentina has been catching elves using a dedicated trigger (Mussa et al., 2012). The FD is well-suited for elves detection due to the optimization of its telescope parameters for recording faint light in the 300–420 nm band (Abraham et al., 2010). The elves' observation footprint covers an area of $3 \times 10^6 \text{ km}^2$ (Aab et al., 2020), including the Córdoba province where large thunderstorms often occur (Witze, 2018).

Furthermore, the FD telescopes offer an exceptional time resolution of 100 ns, surpassing other TLE detection systems such as the Imager of Sprites and Upper Atmospheric Lightning onboard the FORMOSAT-2 satellite (ISUAL), which has a 200 μs time resolution (Chern et al., 2003), PIPER with 40 μs (R. Marshall et al., 2008), the Multiwavelength Imaging New Instrument for the Extreme Universe Space Observatory (Mini-EUSO) with 2.5 μs (Capel et al., 2018), and the Atmosphere-Space Interactions Monitor (ASIM) with 10 μs (Neubert et al., 2020). This feature enables unprecedented precision in capturing the internal structure of elves. The Auger FD has successfully identified not only two-ring elves but also three-ring events, as evidenced by the first reported elve with three peaks in its traces (Aab et al., 2020).

In this paper, we analyzed the traces of double and triple elves detected at the Auger Observatory, finding that the time delay between the peaks is relatively constant with the arc distance to the lightning source. This behavior persists in the multi-elves of four storms at different distances from the observatory. These findings do not fit the proposed model in reference R. A. Marshall et al. (2015) that predicts the time delay should decrease as the arc distance to the source increases, leading us to question the EMP reflection model as an explanation for the origin of multiple elves.

2. Multi-Elves Data From the Auger Observatory

The Pierre Auger Observatory is a ground-based cosmic-ray observatory that measures the properties of the most energetic particles in the universe and aims to discover their sources. These high-energy particles interact with the Earth's atmosphere creating extended air showers. The observatory uses a surface array of 1,600 water-Cherenkov detectors and FDs to measure air showers over 3,000 km^2 (Abraham et al., 2010).

The FD (Abraham et al., 2010) comprises 24 telescopes at four sites, namely Los Leones (LL), Los Morados (LM), Loma Amarilla (LA) and Coihueco (CO). Each building accommodates six telescopes, whose fields of view are 30° in azimuth $\times$ 28° in elevation. The UV optical filters have a bandwidth of 300–420 nm, and the photomultiplier tubes of the cameras—440 per telescope—have a quantum efficiency of 30% within this range, limiting the red and infrared light detection from all TLEs. The readout system includes a 28 μs pedestal and, in 2017, its time window was extended from 300 μs to 900 μs to fully observe the high light intensity region for most of the elves. Although the viewing distances range from 3 to 30 km for cosmic rays, due to its high sensitivity to light, the Auger FD has detected elves at 250–1,000 km (details in Figure 1 of Aab et al. (2020)). The FD is operational during locally clear nights with low background light and clear local conditions, accumulating about 1,200 hr of on-time over 12 months, equivalent to almost 15% duty cycle. In addition, the observatory employs lasers, lidars, and infrared cloud cameras to measure the optical transparency of the atmosphere over the array.

An additional fluorescence detector, the High Elevation Auger Telescopes (HEAT) (Abraham et al., 2010) consisting of three telescopes set at a 45-degree elevation, is also part of the observatory. While the primary objective of HEAT is to detect low-energy cosmic ray showers, it also enables the detection of elves. The elves detected in HEAT originate from storms closer to the observatory, within a range of approximately 50–150 km. In December 2020, we implemented the elves detection trigger in HEAT, resulting in fascinating nearby events available for analysis.

As reported by Aab et al. (2020), during 2013–16, most of the events detected in the Auger FD occurred during the southern summer, with production showing minimal variation between June and August. We identified April 27–28, 2020, as the night with the highest number of multi-elves between 2014 and 2020. Accordingly, we selected these dates along with two other thunderstorms from 10 November 2018, and 20 December 2019. Additionally,

Table 1

Total Numbers of Single, Double, and Triple Elves Detected Across Four Storms at Various Dates and Distances From the Auger FD Are Reported

Storm date	Total	Singles	Doubles	Triples	Halos	% ME
10 November 2018 (01:26:46–07:49:03) UTC	114	96	11	3	4	16%
20 December 2019 (01:56:40–06:14:18) UTC	156	134	16	3	3	14%
April 27–28, 2020 (23:36:58–09:36:05) UTC	137	77	35	17	8	44%
14 March 2021 (00:51:03–06:34:07) UTC	71	62	8	1	0	13%
Total events analyzed	478	369	70	24	15	23%

Note. Multi-elves with halos are denoted as “Halos.” The percentage of multi-elves relative to the total (% ME) varies for each storm. Overall, multi-elves account for 23% of the total detected across the four storms.

we included the events detected by HEAT on 14 March 2021, to examine multi-elves occurring closer to the observatory.

The total number of events from these four storms is 478, as shown in Table 1, of which 369 are single and 109 are multi-elves. The occurrence of multi-elves over the total events (%ME) is 23%, consisting of 70 double, 24 triple elves, and 15 multi-elves occurring with halos labeled as “Halos.” These events can be detected simultaneously within the 900 μ s time window of the FD readout system. To avoid introducing biases in the analysis of the time delay between multi-elves peaks, we handle them separately, focusing on the multi-elves traces and disregarding the associated halo emissions. A new dedicated camera is currently capturing such events, which will be analyzed in detail in forthcoming publications.

The number of single and multi-elves within different storms display notable variability. In the November and December storms, %ME is about 16% and 14%, respectively, whereas, in April, this proportion significantly increases to 44%. Within the HEAT observations conducted in March, the percentage of multi-elves is 13%. These findings highlight the prevalence of multi-elves phenomena within the analyzed data, indicating that they often appear during the storms that the Auger Observatory can investigate.

3. Multi-Elves Traces Analysis

The Auger FD employs a multi-level trigger system for event selection, and elves are primarily detected by the third-level trigger originally developed as a lightning veto. The algorithm searches for events with a radially expanding light front. It identifies the first triggered pixel in the camera and requires adjacent pixels' pulse start times to show monotonic growth. At least three neighboring pixels on both sides of the first signal (or one side if near the camera edge) and three above and below must satisfy the described cut (Aab et al., 2020). The left panel of Figure 1 shows an example of pixels triggered by the light of a single elve on 28 April 2020, at 04:08:13 UTC in two FD cameras. This plot shows the time corresponding to the peak of the light pulse at each pixel (t_{FD}), with the typical time for elves around 300 μ s.

Using the traces of elves, we can determine the location and timing of the lightning source from the first triggered pixel (details in reference (Aab et al., 2020)). The right panel in Figure 1 shows the projection of the light of the single elve onto the ionosphere (at a height of 92 km) spreading concentrically outward from the source lightning located at 36.57° S latitude and 64.54° W longitude. We correlated this single elve event with the Earth Networks Total Lightning Network (ENTLN) data, and the plot shows that the reported location (36.64° S and 64.53° W) is consistent with the one we obtained (Auger bolt location).

With the lightning location determined, we can analyze the time differences between the multiple rings of an event and its source. This process begins with identifying the most prominent peaks in the elve traces, labeled as t_1 , t_2 , and t_3 . Figure 2 illustrates in the top panel the temporal evolution of the first light pulse in a double elve (left) and a triple elve (right). The camera pixels are indexed according to the row number (from 1 to 22), which increases from bottom to top in elevation, and the column number (from 1 to 20), which increases from right to left in azimuth. We selected row 16 of the double-peak event occurring on 28 April 2020, at 03:09:17 UTC, to illustrate in the middle panel examples of determining t_1 and t_2 . For the triple-peak event occurring at 02:07:17

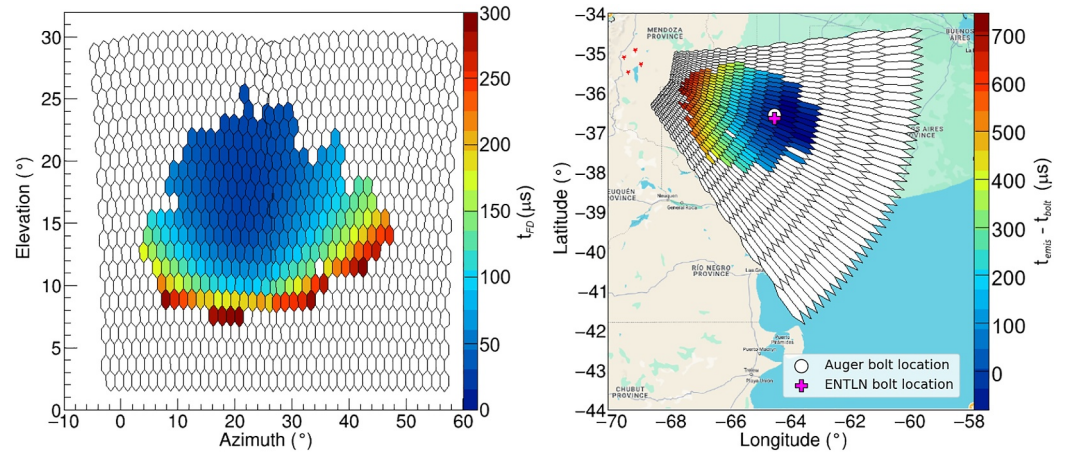


Figure 1. Left panel: pixels of two FD cameras triggered by a typical single elve. This event was detected on 28 April 2020, at 04:08:13 UTC. The colors show the time evolution of the light as seen in the FD cameras, which usually lasts around 300 μ s. Right panel: time evolution of the event as projected at the base of the ionosphere fixed at an altitude of 92 km. After correcting for the transit time from the emission layer to the FD, we observe the concentric spread of light from the source lightning at 36.57° S and 64.54° W (Auger bolt location). The Earth Networks (ENTNLN) lightning location correlated with this event, 36.64° S and 64.53° W, aligns with our determined location. The red stars indicate the locations of the four FD buildings.

UTC, we show t_1 , t_2 , and t_3 in row 8. In both cases, the characteristic parabolic shapes of the elves are evident (t_1 fit, t_2 fit and t_3 fit).

It is important to note that, not all pixels in a multi-elve event will exhibit the distinct peaks required for the algorithm to differentiate them based on their prominence and width. For example, in the triple elve event in row 8, columns 4 and 5, t_1 is not distinguishable, whereas t_2 and t_3 are identifiable. This issue is not attributable to the inefficiency of our algorithm, which has demonstrated effectiveness in resolving separate peaks with a precision of approximately 7 μ s. Instead, this limitation is primarily due to the relatively low prominence of t_1 compared to t_2 and t_3 in some pixels.

After finding the peaks, we perform the corresponding Gaussian fitting (single, double, or triple) using t_1 , t_2 and t_3 as the initial parameters. We select the fit that minimizes the error relative to the signal data, from which we obtain the values for the times (t_1 , t_2 , and t_3), amplitudes (a_1 , a_2 , and a_3), and peak widths (σ_1 , σ_2 , and σ_3) of the pulses. The bottom panel in Figure 2 provides examples of Gaussian functions fitted to the data for one pixel of each event. On the left, a double Gaussian fit corresponds to the signal of the double elve in column 11 and row 16, while on the right, a triple Gaussian fit corresponds to the signal of the triple elve in column 7 and row 8. The amplitude of these signals is expressed in the number of photons.

Finally, we calculate the time difference between the peaks of double elves ($\Delta T_d = t_2 - t_1$), and for triple elves, we determine both ΔT_d and $\Delta T_t = t_3 - t_1$.

4. Time Delay of Double and Triple Elves

To analyze the behavior of the time delay of the multi-elves with the distance to the lightning source, we recall the model proposed by R. A. Marshall et al. (2015) where the occurrence of two-peaked elves can be attributed to intracloud lightning strokes at a height denoted as h_s . In this model, the first peak in the elve trace is created by the electromagnetic pulse taking a direct path to the ionosphere. The second peak is generated by the ground reflection of the EMP, which reaches the ionosphere with a time delay (ΔT).

$$d_{2,1}^2 = (R_E \pm h_s)^2 + (R_E + h_{\text{iono}})^2 - 2(R_E \pm h_s)(R_E + h_{\text{iono}}) \cos\left(\frac{D_{\text{arc}}}{R_E + h_{\text{iono}}}\right), \quad (1)$$

$$\Delta T = \frac{d_2 - d_1}{c}. \quad (2)$$

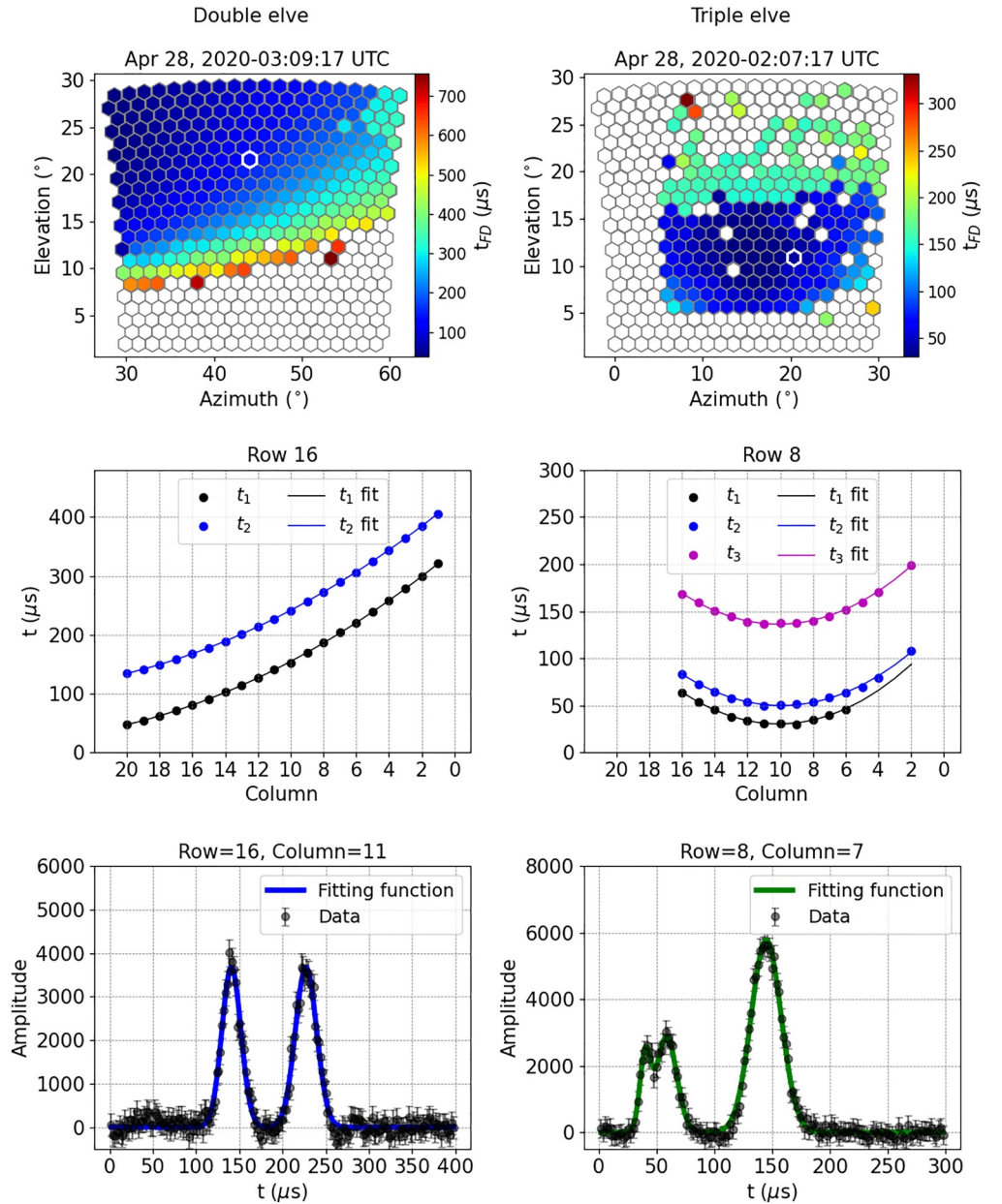


Figure 2. Top panel: time evolution of the first peak of a double elve event detected by an FD telescope on 28 April 2020, at 03:09:17 UTC (left), and a triple elve event at 02:07:17 UTC (right). The highlighted pixel in each camera was selected to illustrate typical double-peak and triple-peak signals. Middle panel: examples of prominent peaks t_1 and t_2 for the double elve in row 16 pixels, and t_1 , t_2 , t_3 for the triple elve in row 8 pixels. Row numbers increase with pixel elevation, and column numbers decrease with azimuth, as shown in the top panel. The distinct parabolic patterns of the elves emission are visible in both cases (t_1 fit, t_2 fit and t_3 fit). Bottom panel: examples of Gaussian fitting for the double elve signal in row 16, column 11, and the triple elve signal in row 8, column 7.

Equations 1 and 2 describe the relationship between ΔT and h_s . In these equations, d_2 and d_1 represent the distances traveled by the EMP in the direct-to-source and ground reflection paths, respectively. Additional parameters include R_E , the Earth's radius; h_{iono} , the height of the ionosphere; and D_{arc} , the arc distance between the emission point P in the ionosphere and the lightning location, as illustrated schematically in panel a of Figure 3.

Each FD camera has 440 pixels that individually collect a part of the elve light ring. We obtain the position of point P (Lat_{pix} , Lon_{pix}) by projecting the position of a camera pixel onto the ionosphere, based on its elevation, azimuth and

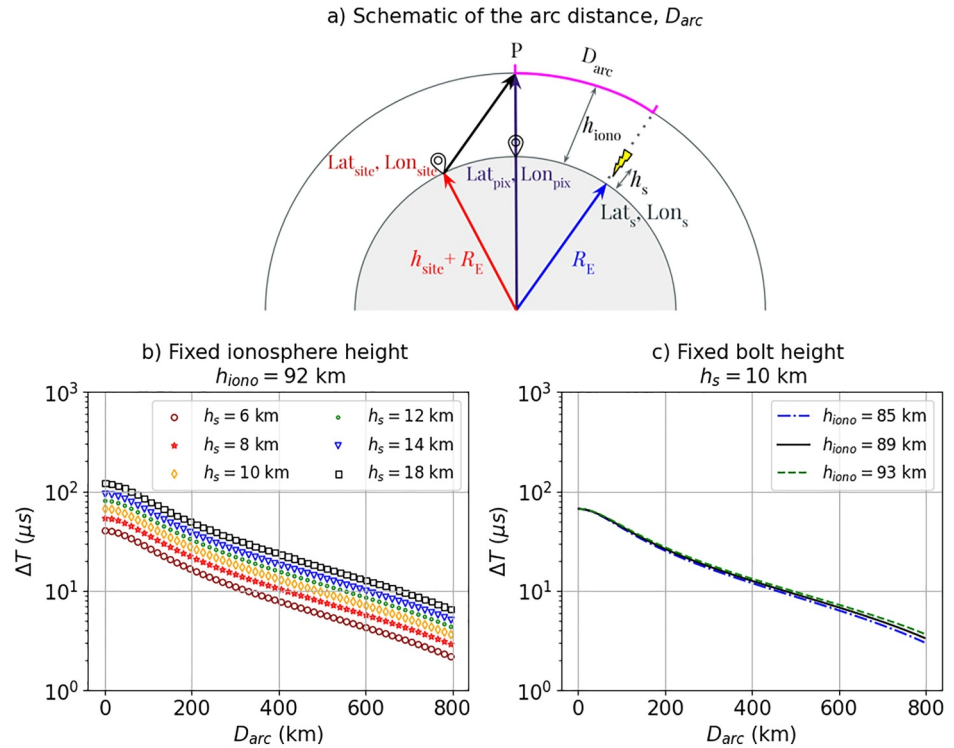


Figure 3. (a) Schematic of the arc distance (D_{arc}) between the lightning source (Lat_s, Lon_s) and the emission point at the ionosphere P. We determine the position of point P (Lat_{pix}, Lon_{pix}) by projecting a camera pixel's position onto the ionosphere, using the associated site coordinates (Lat_{site}, Lon_{site}). Additionally, we calculate the lightning location (Lat_s, Lon_s) based on the observed light-time distributions of recorded elves. (b) Time delay between two peaks of an elfe, given by the Equations 1 and 2, with the ionosphere height fixed at 92 km and various values of lightning height (h_s). (c) Varying the ionosphere height does not significantly change the functionality of the curves of ΔT with distance D_{arc} .

the coordinates of the site where the elfe is detected (Lat_{site}, Lon_{site}). As mentioned earlier, we reconstruct the location of the lightning (Lat_s, Lon_s) from the measured light-time distributions of the recorded elfe.

Using Equations 1 and 2, we can determine how ΔT varies with the arc distance, D_{arc} . For instance, a lightning source at a height of $h_s = 6$ km can generate a double elfe event with a maximum time delay of 40 μs , assuming the ionosphere is at a fixed height of 92 km. This behavior is illustrated in panel b of Figure 3, where the dependence of ΔT on D_{arc} is shown for various lightning heights (h_s). Changes in ionosphere height do not affect the functional form of the curves describing the relationship between ΔT and D_{arc} distance, as shown in panel c.

This model has been used to explain the wide time separation between the peaks of double elves, observationally confirmed to correlate with high altitude compact intracloud lightning discharges (R. A. Marshall et al., 2015). However, some authors report multi-elves with temporal differences that appear too large to be associated with realistic lightning heights. For example, Newsome and Inan (2010) reported a set of 40 double elves with ΔT between 80 μs and 160 μs detected by the PIPER with a time resolution of 40 μs . They argued that these events are unlikely to be caused due to a ground reflection mechanism, which implies an altitude of the source above 18 km, nor are they caused by multiple return strokes, which would be further separated in time.

Thanks to the temporal resolution of the FD, we report events over a wider range, with the smallest ΔT observed being 7 μs . The ΔT of a multi-elfe must follow a behavior given by the function in Equation 1 to consider that its origin is the EMP bounce mechanism. However, we have not found double elfe events with this characteristic in the Auger data, since the ΔT_d tends to be constant with the arc distance D_{arc} . We also observe this behavior in the ΔT_d and ΔT_t values of triple elves.

In panel a of Figure 4, we present all traces of the double elfe event from Figure 2, aligning the first peak with the time of the lightning source. This plot shows that the time difference between the first and second peaks remains constant as the arc distance, D_{arc} , increases. Panel b shows the calculation of $\Delta T_d = t_2 - t_1$ for these traces,

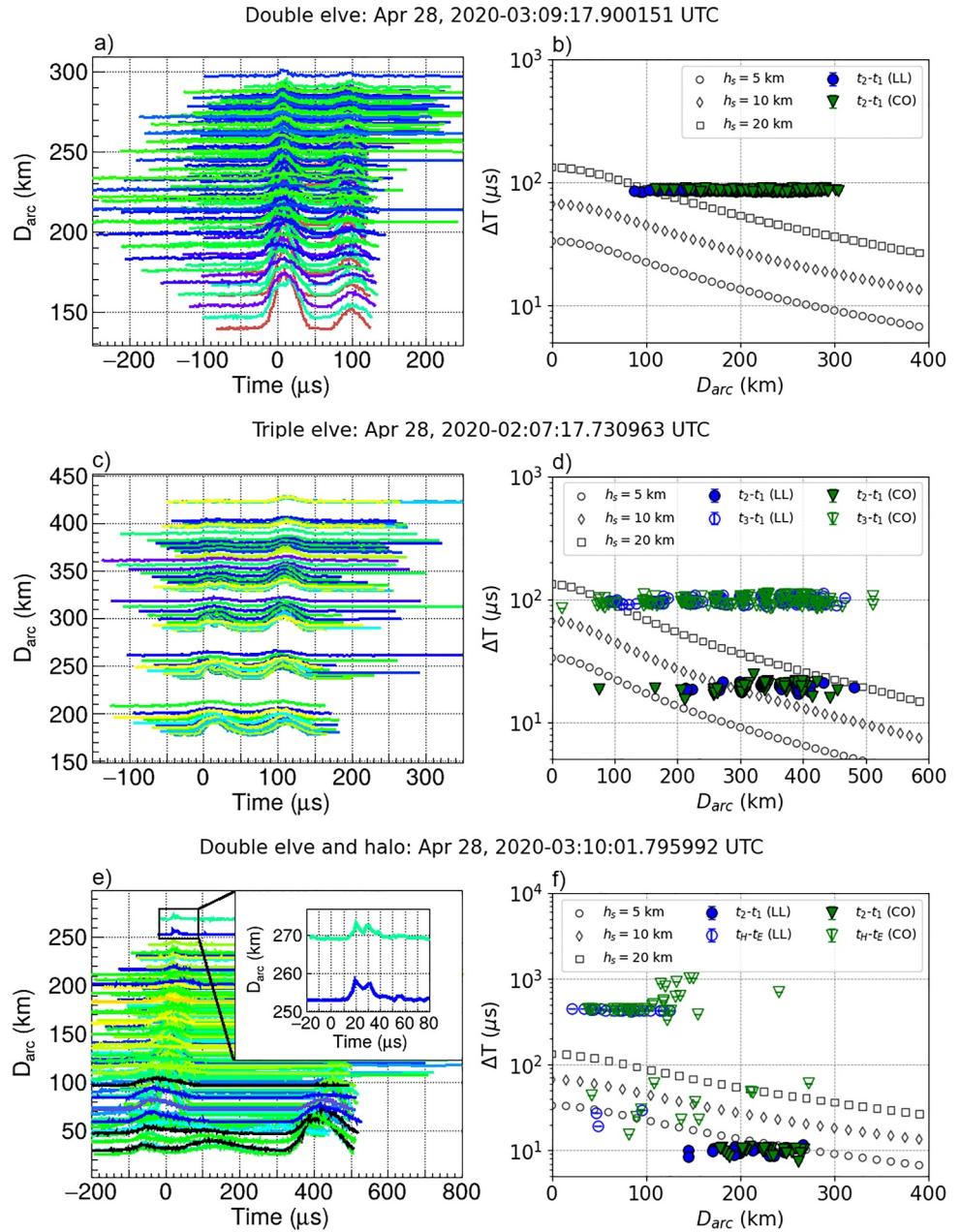


Figure 4. (a) All traces of the double elve event from Figure 2 in Coihueco (CO), with the first peak aligned to the lightning source time ($t = 0$). (b) Time difference of the event at CO and Los Leones (LL), with a mean value of $(87 \pm 1) \mu s$. The bouncing mechanism model curves for 5, 10, and 20 km lightning heights are also displayed. (c) Traces of the triple elve event from Figure 2 in CO, with the first peak aligned to the lightning source time ($t = 0$). (d) The result of $(t_2 - t_1)$ and $(t_3 - t_1)$ from LL and CO, with mean values of $(19 \pm 2) \mu s$ and $(98 \pm 8) \mu s$ respectively. (e) Traces from an event showing multiple pulses that are significantly wider (halo) compared to typical elve pulses, occurring between 20 and 150 km of D_{arc} . $t = 0$ is the time of the lightning bolt occurring on 28 April 2020, at 03:10:01.795992 UTC. Beyond 150 km, traces of a double elve are observed (see zoomed-in plot). (f) Time difference $(t_2 - t_1)$ for the double elve, with a mean value of $(10 \pm 1) \mu s$. Other values represent the time difference between the double elve and halo traces ($t_H - t_E$). This event was detected at two FD buildings, CO and LL.

corresponding to the event detected at Coihueco (CO), yielding a mean value of $\overline{\Delta T_d} = (87 \pm 1) \mu s$. This time difference is consistent across two detection buildings, as evidenced by the fact that $t_2 - t_1$ remains similar for traces of the same event detected at Los Leones (LL). These findings contradict the predictions of the ground

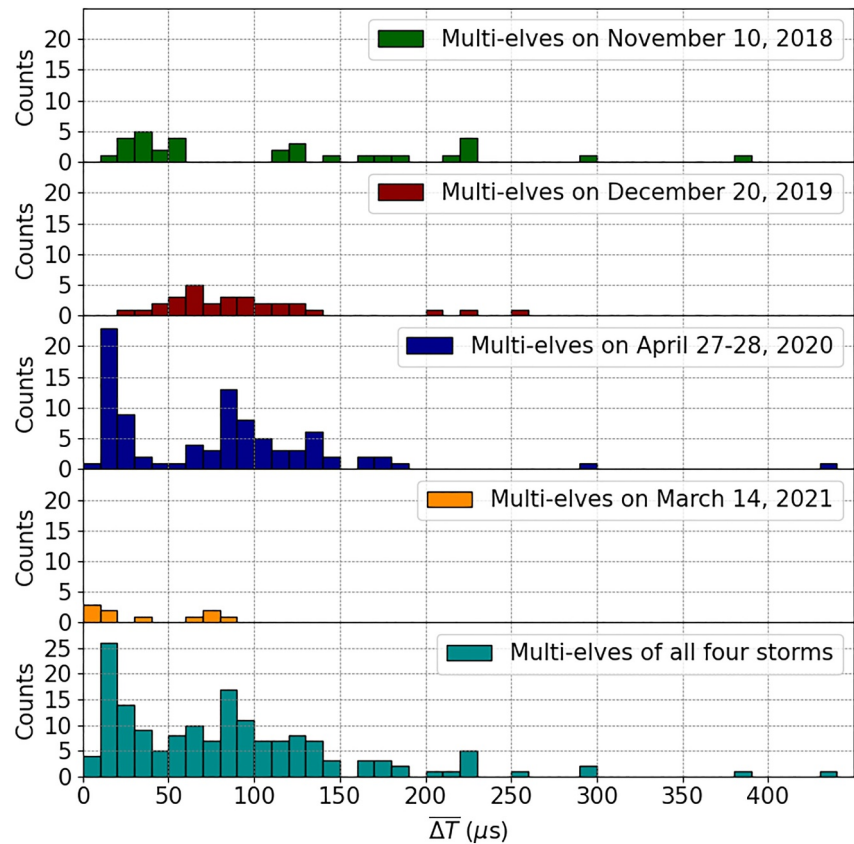


Figure 5. Distribution of the average time difference of the multi-elves of four storms detected by the FD. Each storm has a different distribution, with the April storm having the most events. The FD high temporal resolution allows reporting events with $\overline{\Delta T} < 10 \mu\text{s}$. The fifth histogram shows that most events fall within the 10 to 40 μs range and between 60 and 100 μs . Additionally, some events exhibit $\overline{\Delta T}$ values exceeding 200 μs , and in rare cases, around 450 μs , associated with combined elves and halo events.

reflection model proposed by R. A. Marshall et al. (2015), which is represented by curves decreasing with D_{arc} for three different lightning heights (5, 10, and 20 km) in the same plot.

A similar behavior is observed in triple elve events, where $\Delta T_d = t_2 - t_1$ and $\Delta T_t = t_3 - t_1$ tend to remain constant. Panel c of Figure 4 displays the traces of the triple event discussed in Figure 2. Notably, the time differences between peaks remain constant, as shown in the plot of ΔT versus D_{arc} (panel d). In this case, we obtained average values of $\overline{\Delta T_d} = (19 \pm 2) \mu\text{s}$ and $\overline{\Delta T_t} = (98 \pm 8) \mu\text{s}$ at two FD buildings, Coihueco and Los Leones.

Upon analyzing the traces of events from the four storms listed in Table 1, we identified instances where $\overline{\Delta T_t} > 350 \mu\text{s}$, which drew our attention. Upon further examination of the traces from these events, we observed that they involved a combination of two TLEs: elves and halos. Panel e of Figure 4 shows the traces of an event from the 28 April 2020 storm. In this example, traces between 20 and 150 km exhibit multiple pulses significantly wider than the typical elve pulses. Furthermore, beyond 150 km, we observe the traces of a double elve event (see zoomed-in plot) with an average $\overline{\Delta T_d} = (10 \pm 1) \mu\text{s}$. In the ΔT versus D_{arc} plot (panel f), we distinguish the $t_2 - t_1$ corresponding to the double elve event, while the other values represent the time difference between the elve and halo traces ($t_H - t_E$). This result was observed independently at Coihueco and Los Leones. The number of halos occurring with multi-elves events is listed in the Table 1 with the tag “Halo.”

In Figure 5, we show the resulting histogram of the mean time delay of the events analyzed. Each storm exhibits a distinct distribution of $\overline{\Delta T}$, and it is evident that the storm of April 27-28, 2020, presents the highest occurrence of

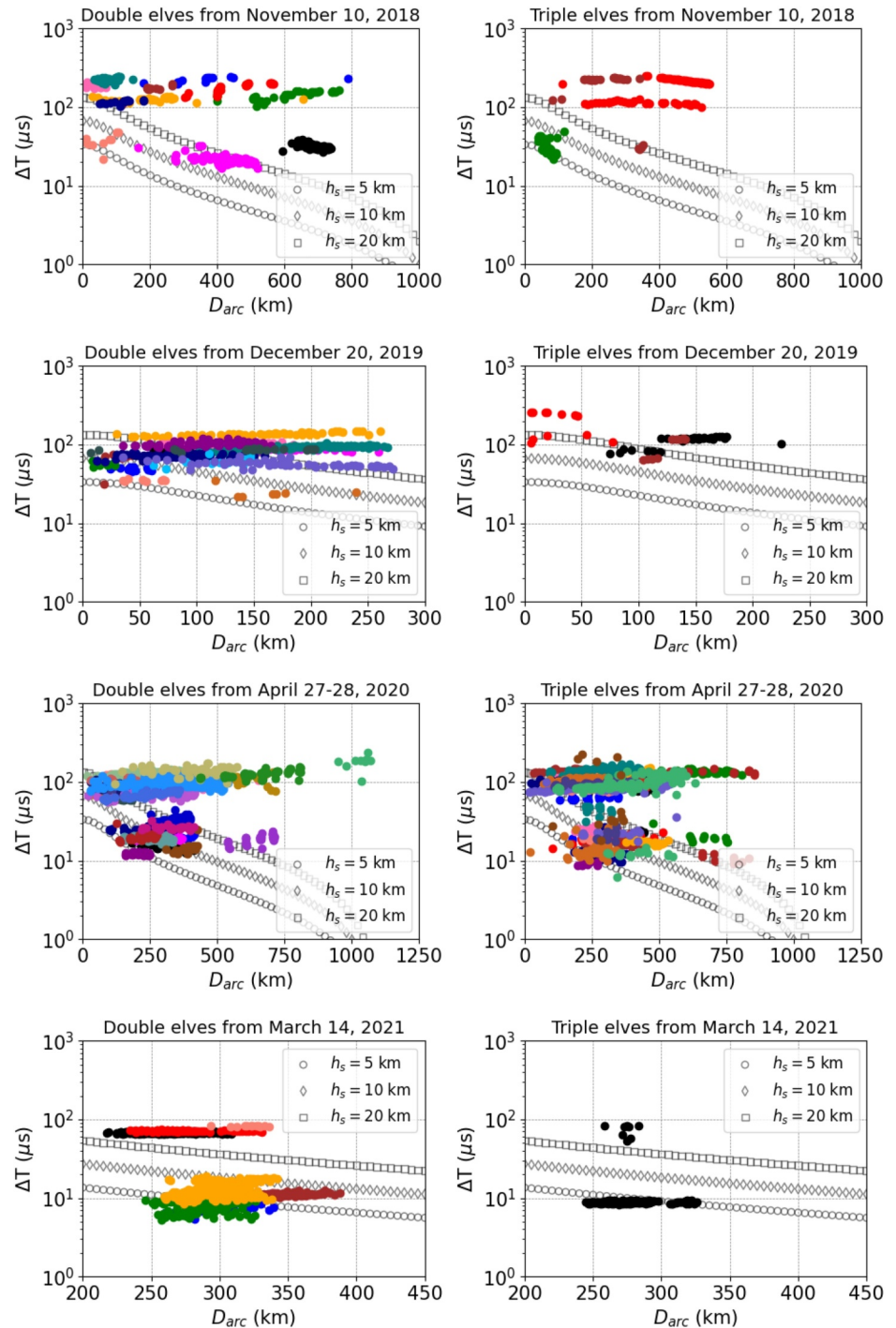


Figure 6. Temporal differences (ΔT) for double (left) and triple (right) elves across the four selected storms. Each color represents ΔT for a specific event. The empty markers illustrate various curves predicted by the model of R. A. Marshall et al. (2015), assuming intracloud lightning at height h_s . The Auger FD data frequently show multi-elves with nearly constant ΔT values. This consistent ΔT trend is evident even in the March storm detected by HEAT at distances ranging from 200 to 400 km.

multi-elves. The high temporal resolution of the FD allows us to report events with $\overline{\Delta T}$ as short as 7 μ s. However, most events fall within 10 μ s to 40 μ s and 60 μ s to 100 μ s, as shown in the fifth histogram in the same figure. Furthermore, we have observed events with time delay exceeding 200 μ s and, in some cases, around 450 μ s.

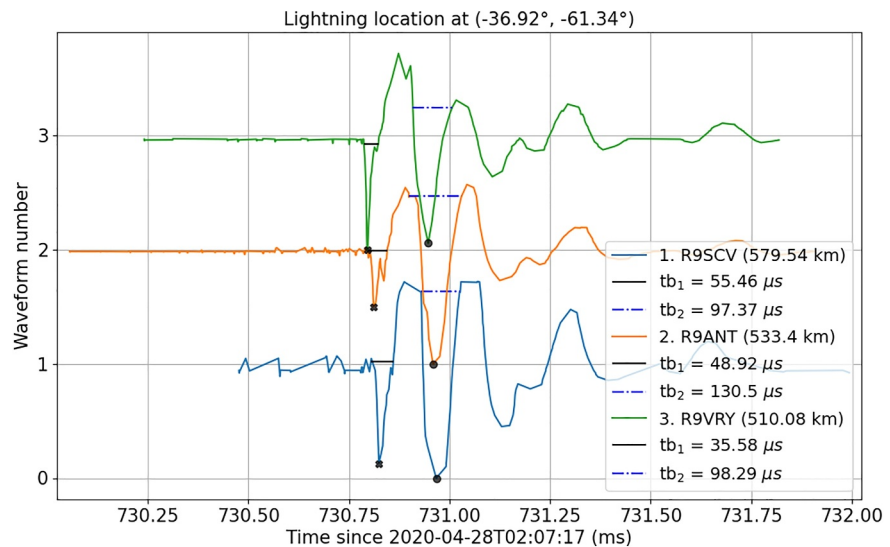


Figure 7. Waveforms from ENTLN sensors located within 500 and 600 km from the lightning correlated with the triple elve event shown in Figures 2 and 4. The most prominent peaks in each signal are identified using the *find_peaks* function from SciPy. The peak corresponding to the first component of the waveform is marked with a cross, while the peak corresponding to the second component is marked with a dot. The horizontal lines indicate the width of each peak at 95% of the pulse amplitude, t_{b1} and t_{b2} respectively. The legend shows the sensor label and its distance from the source, with the corresponding t_{b1} and t_{b2} values.

While these longer ΔT events may involve elves in conjunction with other TLEs such as halos, our current study does not delve into this aspect. Our primary focus remains on reporting the observed time delay of events exploiting the FD high temporal resolution.

Finally, Figure 6 illustrates the temporal differences for double and triple elves across the four different storms, demonstrating that this result is independent of the specific characteristics of each storm. In these plots, each color represents the ΔT of a particular event. On the left, we show the double elves, and on the right, the triple elves. Additionally, the curves with empty markers represent the reflection model, which does not fit any of the events.

5. Discussion

The temporal resolution of the FD cameras allowed us to capture a broad range of temporal difference values between the rings of the multi-elves. These events predominantly cluster into time delay values between 7 and 40 μs , and between 60 and 100 μs . This bimodal distribution may indicate distinct physical mechanisms underlying the generation of multi-elves.

To explore an alternative explanation for these observations, we adopted the time-domain model of the lightning electromagnetic pulse interaction with the lower ionosphere proposed by R. A. Marshall (2012), which suggests that double elves are a consequence of the rise time, τ_r , and fall time, τ_f , of the lightning pulse waveform.

We studied the waveforms from ENTLN sensors located in the region of northern Argentina within the field of view of the Auger observatory. The ENTLN (Zhu et al., 2022) is a globally distributed ground-based network with 1,800 broadband electric sensors capable of detecting intracloud and cloud-to-ground flashes. On average, the ENTLN reports approximately 50 lightning events per second worldwide. These sensors record raw electric field waveforms within a frequency bandwidth of 1 Hz–12 MHz, which are then processed using the time-of-arrival technique to determine real-time lightning geolocation.

Figure 7 shows the waveforms recorded by ENTLN sensors located 500–600 km from the lightning correlated with the triple elve presented in Figures 2 and 4. The most prominent peaks in each waveform are identified using SciPy's *find_peaks* function. The peak corresponding to the first waveform component is marked with a cross, and the second (skywave) is marked with a dot. Horizontal lines denote the width of each peak at 95% of the pulse amplitude, defining the base times t_{b1} and t_{b2} , respectively. In waveform analysis, the base time of pulses is

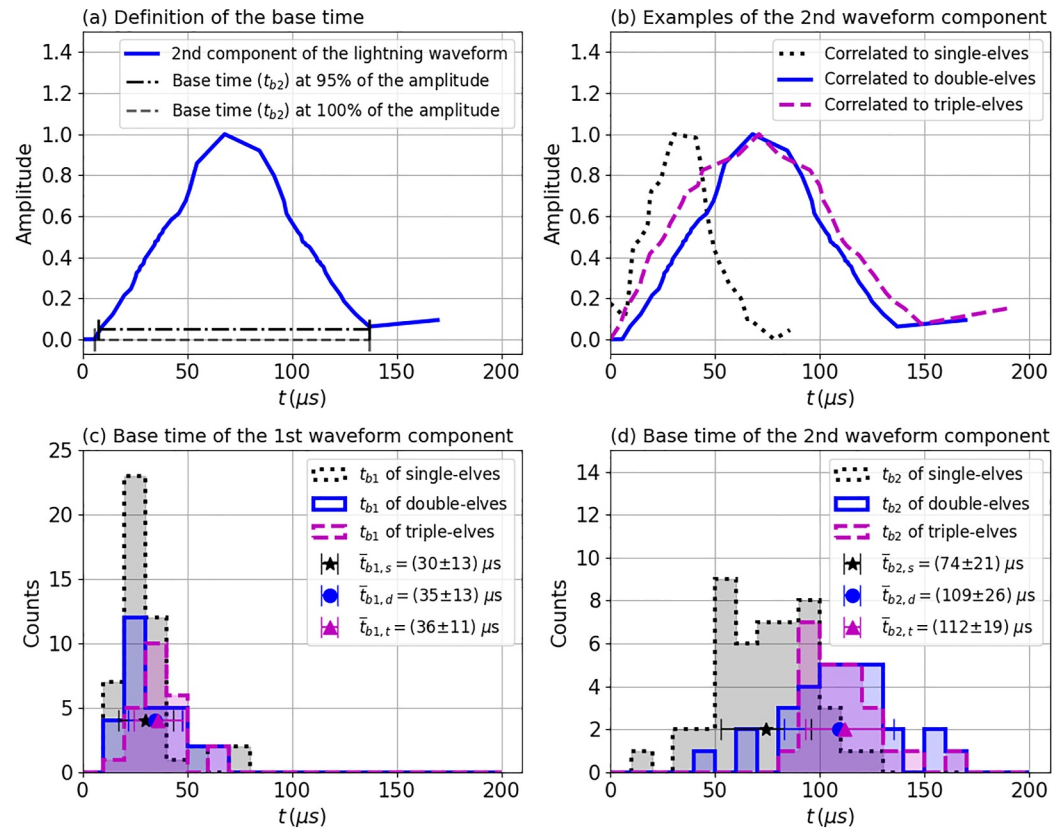


Figure 8. (a) Definition of the base time of the lightning waveform pulse given by Earth Networks. (b) Examples of the second component of lightning waveforms correlated with single (dotted line), double (solid line), and triple elves (dashed line). Distribution of the base time for the (c) first component and (d) second component of the waveform pulses correlated with elves detected on April 27–28, 2020. The mean value $\bar{t}_{b1}$ is comparable across events associated with single, double, and triple elves. In contrast, the mean value $\bar{t}_{b2}$ for single elves is $(74 \pm 21) \mu$ s, which is significantly shorter than the mean values observed for double and triple elves, $(109 \pm 26) \mu$ s and $(112 \pm 19) \mu$ s, respectively.

typically measured at a percentage of their amplitude to mitigate overestimation. In this study, optimal values for the base time were determined at 95% of the amplitude for 101 out of the 131 events correlated with the ENTLN.

In these waveforms, we selected the skywave that reflects once in the ionosphere, as it is the most likely to generate the observed elves in the FD, exciting the molecules within it. Many of the signals correlated with elves exhibited saturation, despite the distance between the lightning strike and the antenna being between 500 and 600 km. Consequently, we conducted the study using the pulse base time (t_{b2}) rather than the individual rise and fall times, as it is challenging to determine τ_r and τ_f . Furthermore, according to the model, τ_r and τ_f must be sufficiently large to separate the peaks of the multi-elves, implying that a longer t_{b2} would result in a greater temporal difference (ΔT) between these peaks.

We observed that t_{b2} associated with single elves tends to be narrower than those linked to multi-elves and that the pulse base time is correlated with the temporal difference between the rings of each event. An example of the pulse corresponding to the second component of a lightning waveform is shown in panel (a) of Figure 8. The dashed line indicates the base time of the pulse (t_{b2}) at 100% of its amplitude, and the dashed-dotted line corresponds to 95%. Panel (b) illustrates examples of a pulse correlated with a single elve event (dotted line), a double elve (solid line), and a triple elve (dashed line), with t_{b2} values of 56, 130, and 148 μ s, respectively.

In panels (c and d) of the same figure, the distribution of the base time of the first (t_{b1}) and second component of events correlated with single, double and triple elves is presented. It is noteworthy that, unlike the first component (which mean values are $\bar{t}_{b1} = (30 \pm 13) \mu$ s, $(35 \pm 13) \mu$ s and $(36 \pm 11) \mu$ s for singles, doubles and triples, respectively), the base time of the second component is distinguishable between events correlated with single elves and multi-elves. The single elves distribution has a mean value of $\bar{t}_{b2} = (74 \pm 21) \mu$ s, which is shorter than

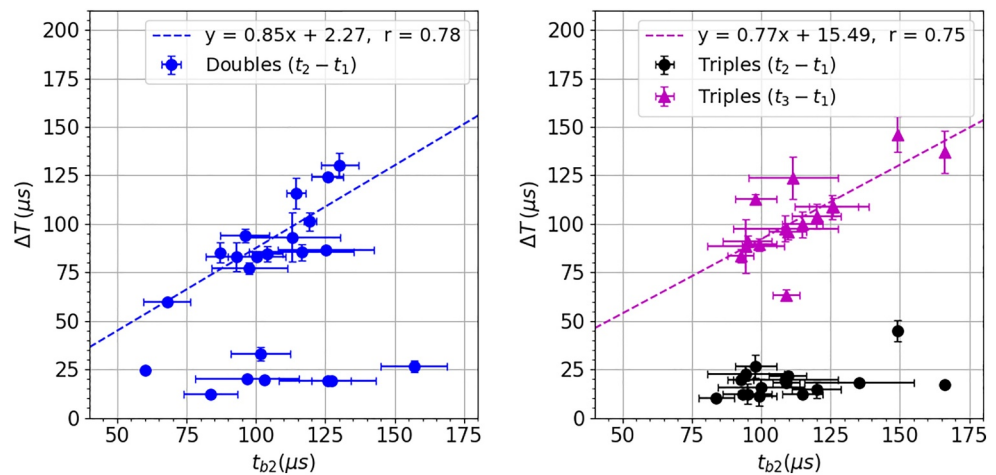


Figure 9. Base time of the second component of waveforms (t_{b2}) correlated with double elves (left) and triple elves (right) detected on April 27–28, 2020. In both cases, it can be observed that, beyond 50 μs of peak separation time for multi-elves (ΔT), there is a high correlation with t_{b2} : $r = 0.78$ in the fitting of doubles and $r = 0.75$ in the triple events. As the base time increases, the temporal gap between the peaks of multi-elves also widens.

mean values from double and triple elves distributions, $(109 \pm 26) \mu\text{s}$ and $(112 \pm 19) \mu\text{s}$ respectively. These events correspond to the night of April 27–28, 2020, where we observed the highest proportion of multi-elves.

From the waveform of the same lightning event across multiple sensors, we calculated the average value and standard deviation of t_{b2} for each event. Figure 9 illustrates the relationship between t_{b2} and the time gap between the rings of multi-elves. In this plot, it is evident that for values above 50 μs , ΔT increases with the base time of the pulse for both double and triple elve events. A strong correlation with t_{b2} is observed, with a correlation coefficient of $r = 0.78$ for double elves and $r = 0.75$ for triple elves.

These results indicate that the origin of multiple rings of elves with $\Delta T \geq 50 \mu\text{s}$ depends on the duration of the current density pulse of the lightning that produces them. As shown by Liu et al. (2017), short EIPs of 20 μs tend to produce double elves, whereas longer EIPs of 30–40 μs are more effective in separating the rings, resulting in the visualization of quadruplet elve events. It is important to note that these durations refer to the first component of the waveforms (known as the surface wave), while our analysis focuses on the second component, which is typically much longer.

Results below 50 μs do not demonstrate a clear relationship. Note that varying combinations of rise time and fall time can yield different ΔT values. In this context, using the base time, which is a combination of both, can result in the formation of these two subgroups in the graphs. However, these results align more closely with the predictions of R. A. Marshall (2012) than with the bouncing mechanism (R. A. Marshall et al., 2015), because the time gap between the peaks of double and triple elves remains typically constant regardless of the arc distance to the lightning that generates them. We expected that events with $\Delta T < 100 \mu\text{s}$ could be associated with intracloud lightning occurring at heights not exceeding 14 km. However, we observe that the decreasing curves predicted by the model do not align with the observations from the Auger FD even in the events with ΔT between 7 and 40 μs . These multi-elves with $\Delta T < 50 \mu\text{s}$ may originate from alternative mechanisms.

6. Conclusions

We have found that the time gap between rings in both double and triple elves remains relatively constant with the arc distance to the lightning source. We frequently observed this behavior in the Auger FD data and reported the time difference of multi-elves from four different storms occurring at various times and distances of the FD. Our study benefits from the high temporal resolution of the FD, which enables us to report double and triple ring events with temporal differences ranging from 7 μs to 260 μs and very rare events around 300 and 450 μs that are related to halos occurring with elves.

These results suggest that the reflection of the EMP produced by intra-cloud lightning does not cause the multiple rings in the elves observed at the Pierre Auger Observatory. Contrary to the expected behavior from the model, the temporal difference between the rings is nearly constant with the arc distance to the lightning source.

On the other hand, multi-elves with a time gap exceeding 50 μ s display a linear relationship with the base time of the second component of the lightning waveform, indicating that the generation of multiple rings is primarily governed by the duration of the lightning current density pulse rather than the bolt height. Although we report an unprecedented number of events with time delays shorter than 50 μ s, we did not find a direct relationship with the pulse base time that could explain their origin. Moreover, within the temporal and spatial resolution of our measurements, none of the events matched the dependence of ΔT on D_{arc} predicted by the ground reflection model, which may suggest that the ground and atmospheric conditions in the field of view of the FD are not optimal for this mechanism or point to the involvement of a different underlying process. These results contribute to understanding the origin of multi-elves and provide a basis for further, more in-depth investigation into this phenomenon.

Appendix A: The Pierre Auger Collaboration

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Data Availability Statement

The analysis presented in this manuscript utilized the elves data set available in (Vásquez-Ramírez, 2024). These data files, in `.root` format, containing the traces of elves for each pixel triggered by the event in the Auger Observatory's fluorescence detector telescopes. The `multi-elves.ipynb` notebook includes the developed code used to analyze these traces. In addition, we used `enipy-3` (Stock & Lapierre, 2018) to analyze the data of the lightning waveform. `enipy-3` is an open-source Python toolkit developed by Earth Networks under the MIT license and available at <https://bitbucket.org/earthnetworksrd/workspace/repositories/>. For further details on reproducing the figures in this manuscript, refer to the README file in (Vásquez-Ramírez, 2024).

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