Close view of the lightning attachment process unveils the streamer zone fine structure

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Abstract

A very close high-speed video observation of lightning attachment to a building revealed novel details regarding the leader streamer zone dynamics. Upward leaders propagate in a steady and unbranched manner, displaying a uniformly luminous corona brush. The exception being the upward connecting leader (UCL) just before connection, when its streamer zone increases in size and develops a more filamentary pattern. Downward negative leaders have 3-m long multiple streamers emanating from each negative leader tip. In some occasions, plasma formations known as space stems are seen to form in the location previously occupied by negative streamers. Space stems have luminosities comparable to the main leader channel, but are detached from it by 4 m. Some space stems display streamers of their own, including cases where streamers are emanating from both ends. The space stem formation hampered the propagation of the negative leader that was closest to the UCL.

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Key Points

- *Characteristics of upward and downward leaders before attachment*
- *Formation of corona brush, streamers and space stems*

Abstract

A very close high-speed video observation of lightning attachment to a building revealed novel details regarding the leader streamer zone dynamics. Upward leaders propagate in a steady and unbranched manner, displaying a uniformly luminous corona brush. The exception being the upward connecting leader (UCL) just before connection, when its streamer zone increases in size and develops a more filamentary pattern. Downward negative leaders have 3-m long multiple streamers emanating from each negative leader tip. In some occasions, plasma formations known as space stems are seen to form in the location previously occupied by negative streamers. Space stems have luminosities comparable to the main leader channel, but are detached from it by 4 m. Some space stems display streamers of their own, including cases where streamers are emanating from both ends. The space stem formation hampered the propagation of the negative leader that was closest to the UCL.

Plain Language Summary

A serendipitous close observation of a natural lightning flash revealed novel details of the lightning attachment process to residential buildings in highly-populated areas. A staggering total of 33 lightning precursor channels (called leaders) were launched from nearby buildings in an attempt to intercept the down coming negative leaders. The upward positive leaders propagate almost in a straight path manner, do not branch, and display a uniformly-luminous "corona brush" at their tips. This contrasts with the negative leaders coming down from the cloud, which present substantial branching and have numerous filaments (called streamers) emanating from their tips. The high-speed and high-resolution images obtained also revealed that, in some cases, the negative leaders display a luminous formation that is about 2 meters long and is detached from the main channel by about 4 meters. These observations consist one of the rare sightings of these luminous formations known in the peer-reviewed literature as "space stems". It is understood that space stems play a key role in the stepped propagation of negative leaders. In these observations, it seems that they hamper the leader propagation, making the upward connecting leader intercept a different downward branch, which was originally more distant from the striking point.

1 Introduction

The effectiveness of a lightning protection system (LPS) depends on its efficiency to intercept the down coming lightning leader which is usually done by emitting an upward connecting leader (UCL). Detailed characterization of UCLs and of the attachment process is a key step towards quantifying the LPS zone of protection for improving LPS designs. Unconnected upward leaders (UUL), i.e., those events that initiate an upward leader but fail to make contact with the downward leader, are also of great importance in lightning protection. They can cause damage to equipment vulnerable to sparks or induced currents, and enough to injure someone.

Although lightning attachment observations have been reported from tall towers (e.g. Saba et al., 2015, Visacro et al. 2017, towers higher than 60 m over mountains), from buildings (Saba et al., 2017), and from small structures (Schoene et al. 2008, vertical conductor of 7 m height), no close and detailed high-speed video observation of the attachment process of UCL from common buildings is presently available in the literature. This study presents observational data of several positive upward leaders competing to connect with negative leaders of a downward cloud-to-ground flash that struck a residential building. Furthermore, the use of high-resolution and high-speed video images reveals details of the electrical discharge development around the leader tip and the formation of several streamers and space stems ahead of the advancing negative leader.

Leader channels in negative cloud-to-ground flashes propagate in a stepped manner, with the overall dynamics within the leader streamer zone being quite complex. It is understood that plasma formations, known as space stems, detached from the main leader channel, play a key role in the negative leader's stepped propagation (Gorin et al., 1976; Gallimberti et al., 2002). In recent years, space stems have been observed in both natural and rocket-triggered lightning. They have luminosities comparable to the main leader channel, but appear detached from it, typically 1–8 m ahead of the leader tip. Additionally, space stems are typically between 1-10 meters in length and sometimes occur in small groups ahead of the leader tip, generating between 1 and 3 luminous zones (Biagi et al., 2010; 2014; Gamerota et al., 2014; Hill et al., 2011; Jiang et al., 2017; Petersen and Beasley, 2013; Qi et al., 2016; Tran et al., 2014). The fact that space stems only appear in negative leader channels begs the question: *Are space stems the root cause of the polarity asymmetry between positive and negative leaders, or are they merely another symptom?* Other important symptoms of the polarity asymmetry include the large discrepancy in: leader speeds, VHF power emission, and channel branching (Williams, 2006; Mazur and Ruhnke, 2014). In this work we present streamer zone and space stem photographs with unprecedented level of detail and image fidelity. In a particular example, it is possible to see the double-ended structure of a space stem with streamers emanating from both of its ends, creating an embryonic space leader (Montanya et al., 2015). This work is among the few observations of space stem occurence in natural lightning available in the peer-reviewed literature (Hill et al., 2011; Petersen and Beasley, 2013; Qi et al., 2016).

2 Methodology

In order to observe lightning attachment to residential buildings, a high-speed camera Phantom v2012 was installed in São José dos Campos, Brazil. Several building tops were within the field of the view of this monochrome, 12-bit depth, 28-micron pixel size sensor camera. The camera was set to operate at 40,000 frames per second with exposure times of 23.84 μs and time intervals of 25.0 μs. Image spatial resolution used for the flash herein described was 1280 × 448 pixels. Each frame of the video was time stamped by means of a GPS antenna.

On 30 March 2021 a cloud-to-ground lightning flash containing five negative strokes made five different ground contacts. The negative leader of the second stroke started a different path to ground and connected to an UCL that was initiated on a chimney atop of a 27-story building, marked as building number **11** in Figure 1. The distance of the striking point to the camera was only 161 m and according to the lightning detection system, the peak return stroke current was –29.6 kA and occurred at 02:58:47.631051 UTC. Data from a 9-sensor lightning location system (LLS) were used to obtain the polarity, the time, and an estimate of the peak current of the return strokes observed. For the case analyzed in this work the location error of the LLS for the ground contact point of the flash observed was 188 m, which is considered very good. Further information about the LLS is provided by Morales et al. (2018).

Besides the UCL, 32 UULs also emerged from nearby buildings. Figure 2 shows some of the UULs seen by the high-speed camera. They were initiated from buildings number **1**, **2**, **3**, **10**, **11**, **12** and rods **a** and **b** in Figure 1. Remarkably this flash produced a staggering total of 33 upward leaders detected by our video cameras, only some of them appear in Figure 2.

We manually analyzed 20 video frames preceding the lightning return stroke, spanning a 500 μs interval. Filters were applied to enhance the clarity of the images. In order to track leader characteristics as a function of time, each frame of the video was marked and each leader was labelled, as shown in Figure 2. We use a decimal notation (with a ".") to track branching in the negative leaders. Positive leaders do not require this effort as they do not branch. The attachment process happens when downward leader **15.5** connects to upward leader **6**.

In each camera frame, data was collected concerning: leader tip position, streamer zone size/length, streamer zone morphology, and streamer count. Length scales were converted from pixels to meters using the known story height in buildings **1** and **11**. All leaders on the left-hand side of Figure 2 were assumed to be at the distance of building **1**, which was 261 m. Similarly, all leaders on the right-hand side of the image, were assumed to be 161 m away, which is the distance to building **11**. Uncertainties were generated by accounting for the fact that the lightning flash may have occurred within 100 m of the actual striking location. The imagery suggests that all downward leaders hover over buildings **1** and **11.** The 100-m figure corresponds to the horizontal distance between the two buildings. The approach employed here generated upper bounds for the error in length estimates of roughly 19 and 31% for leaders on the left- and right-hand side of Figure 2, respectively. All reported distances and speeds given hereafter were measured in 2D and therefore are underestimated.

Fig. 1. Buildings and structures observed by the camera installed in São José dos Campos, Brazil.

3 Results

Figure 3 shows the distance travelled by some of the leaders displayed in Figure 2. The slope in distance versus time gives the average leader speed within the video record. The UULs shown in Figure 3 have speeds of about $4x10^4$ m/s, while the UCL is roughly 3 times faster, at $1.4x10^5$ m/s. The UCL has a speed comparable to the average speed in the downward leaders, which is $1.2x10^5$ m/s. The fastest downward leader is the downward connecting leader (DCL in Figure 3), which has a speed of $3.7x10^5$ m/s. Statistical properties for the measured leader speeds are reported in Table 1. The values are comparable to what has been measured previously (Saba et al., 2017). The error in the determination of 2D distances was found to be within 20–30%, and the coefficients of determination (R^2) of the linear fits used for speed calculation were higher than 0.96. The speed of negative leaders is tracked only for some dominant branches and from its root all the way down to its lowest point. For example, the position of leader **18.3.1.4** (on the left-hand side in Figure 2) is tracked all the way back to the top, when it emerges in the frame and is labelled as leader **18**.

Upward leaders are seen to pulse a few times before setting their course. After ignition, upward leaders propagate continuously in the same general direction (seldomly straying abruptly from the same path), with its direction determined by the geometry of the downward leaders. For instance, UULs **12** and **13** travel toward downward leader **15**. Upward leaders are not branched. Detailed analysis of the video frames indicates that leaders **6** and **7** most likely initiated in different locations in the building.

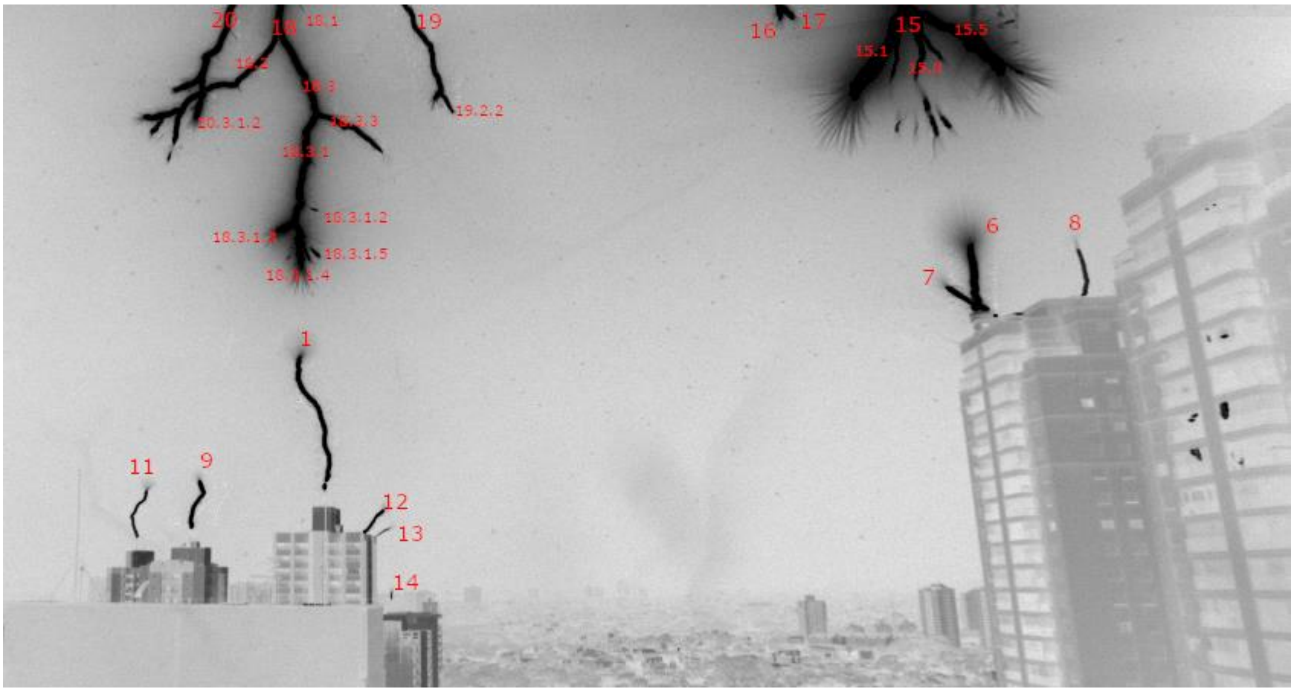

Fig. 2. Lightning attachment to building **11**. This figure shows one frame before the occurrence of the return stroke. Not all 33 upward leaders are shown in this frame. A combination of color inversion and a Reinhard tone map were used to improve clarity of the image. An animated gif of the 20 relevant frames with all leaders properly labelled is available at: https://doi.org/10.5281/zenodo.7117249.

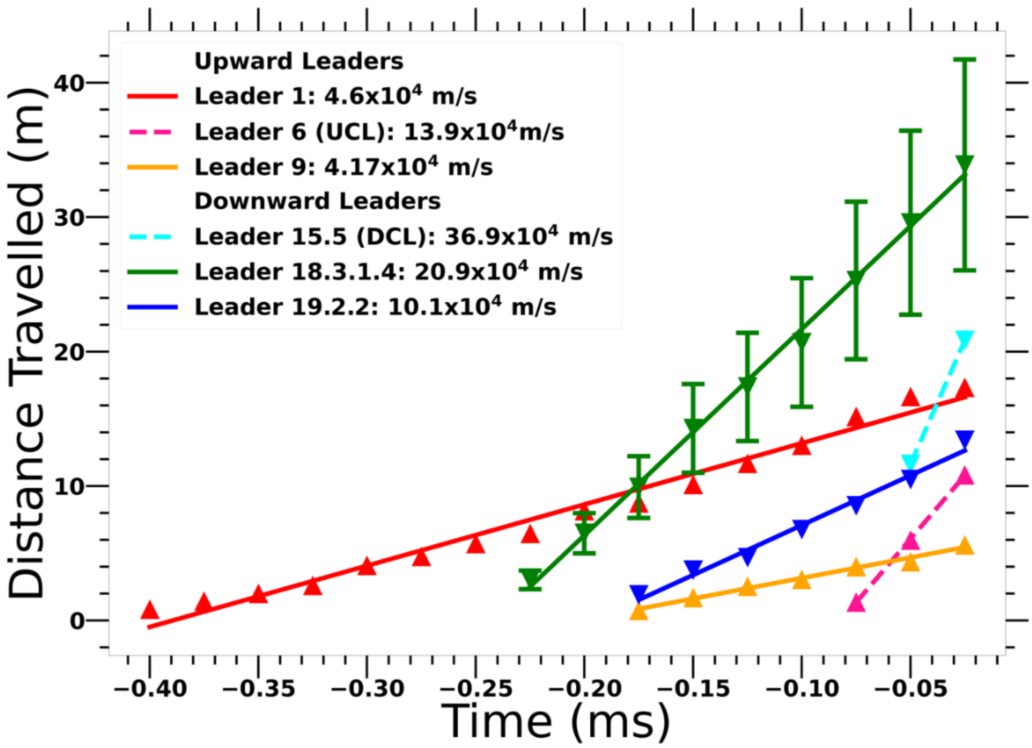

Fig. 3. Distance travelled by some of the lightning leaders analyzed. The curve slope (measured with a linear fit) yields the leader average velocity, as listed in the figure legend. Upward and downward leaders are represented by upward- and downward-pointing triangles, respectively. Error bars are produced by propagating a ±50 m horizontal location uncertainty into vertical position uncertainties. UCL and DCL stand for the upward and downward connecting leaders, respectively.

Table 1. Measured properties for 20 different leaders (16 upward and 4 downward), 14 of which are pictured in Figure 2.

Feature	N	Min	Max	Average	Average Error
Upward Leaders					
Size of corona brush (m)	10	0.7	3.0	1.2	±0.3
Speed (10^4 m/s)	9	3.2	13.9	6.3	±0.2
Downward Leaders					
Number of streamers per leader tip	39	1	14	5	
Length of streamer zone (m)	39	1.1	5.5	2.5	±0.8
Space stem length (m)	4	1.5	2.4	1.9	±0.5
Distance between space stem and leader tip (m)	4	2.5	5.4	4.4	±3.4
Speed (10^4 m/s) (for dominant branches only)	4	10.1	36.9	12.1	±0.4

As the highly branched downward negative leader approaches the ground, it is possible to observe several streamers emerging from each leader branch tip. Figure 4a shows a zoom into leader **15** and its branches. Up to 14 easily-distinguishable streamers are seen emanating from a single leader tip. Figure 4a shows two frames before the return stroke, while Figure 4b shows the subsequent one — the same one as shown in Figure 2. We can see that leaders **15.1** and **15.5** continue its propagation by emitting a fan of streamers from their tips. On the other hand, the dynamics for leader **15.3** is more complex. In the 25 µs time scale between the two frames, we see the emergence of space stems, highlighted in Figure 4c, and traced in magenta color in Figure 4d. These plasma formations appear in regions previously occupied by the leader streamer zone in the preceding frame, as it can be seen by using the reference height line in Figures 4a and 4b. Additionally, the space stems have luminosities comparable to the main leader channel. Existing theoretical work suggests that the 25 µs time span between two frames is more than sufficient for heating of atmospheric air, which promotes streamer-to-leader transition (da Silva and Pasko, 2013; Malagon-Romero and Luque, 2019). In some cases, streamers can be seen emanating from the space stems, as traced in green in Figure 4d. Particularly, they appear to emit streamers from both ends, creating embryonic bidirectional space leaders (Figures 4c–4d). Space stems have lengths of about 2 m, and appear 4 m away from the main leader tip. Other key properties of space stems are listed in Table 1. The numbers reported in Table 1 are comparable, but not identical to what has been previously found. For instance, Hill et al. (2011) found that space stems had longer lengths (of 4 m), but were located closer to the main leader tip (only 2 m away). But we note that Hill et al.'s observation was from a further distance away, of the order of 1 km (not precisely determined). Perhaps the observation geometry that is most similar to this work was attained by Qi et al. (2016). Based on observations from a distance of 350 m, these authors found that space stems have average lengths of 5 m and were located 4 m away from the leader tip.

In Figure 4, the upward leaders emerging from the building structure underneath are not branched, and each one of them presents a fan-shaped and uniformly-luminous corona brush (traced in yellow in Figures 4e–4g). The length of the corona brush gets longer as the distance between the downward leader and the upward leader diminishes. The typical scale size for a corona brush is 1.2 m, as listed in Table 1. It is interesting to note that the UCL corona brush (Figure 4e) transitions into a more filamentary streamer zone just before connection (Figure 4f). The streamer-like structures are highlighted with green traces in Figure 4g.

Looking back into Figure 2, we can see that space stems appear in a number of other negative leaders, but (most importantly) not in all of them. For instance, we can see space stems in leaders **18.3.1.2** and **18.3.1.5**. This finding suggests that space stems are not a requirement for the negative leader propagation, but perhaps simply a byproduct of the intricate dynamics taking place in its streamer zone. Existing theoretical models of space stems hint on a possible physical mechanism that can explain their occurrence, but fail to explain why they only appear in negative streamer zones, and why they only appear in some cases. The most probable physical mechanism involves a plasma instability triggered by electron attachment to oxygen molecules in a decaying streamer channel (Malagon-Romero and Luque, 2019).

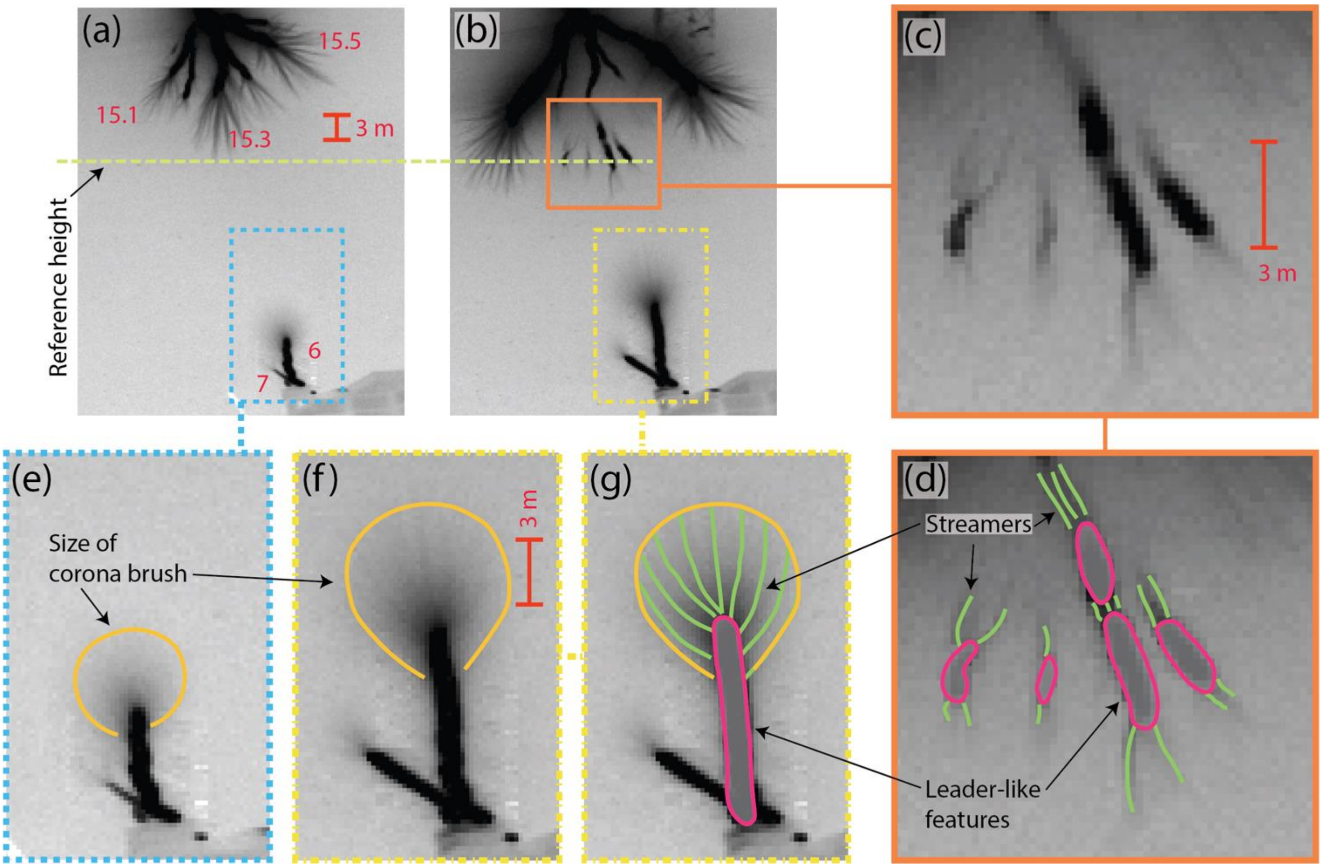

Fig. 4. (a,b) Zoom into leader **15** for two consecutive video frames before attachment. (c,d) Further zoom into streamer zone and space stems of leader **15.3**. (e-g) Further zoom into UCL. Panels (d) through (g) show attempts to trace the leader- and streamer-like structures in magenta and green colors, respectively. Time between frames (a) and (b), and between (e) and (f) is 25 μs. The image was processed in the the same way as Figure 2. A reference 3 m ruler is added to the three sets of panels for reference.

Figure 5 shows that, unexpectedly, it is leader **15.5** that connects to the longest upward leader (# **6**). Figure 5a indicates that the middle branch (**15.3**) may have been initially closer to the UCL, but the emergence of space stems seems to hamper its propagation (Figure 5b). As a consequence, the attachment process happens with both leaders intersecting at an angle of almost 90 degrees. The upward leader that connected to the downward leader had its origin on the oven's chimney for the top-floor apartment (Figure 5d). Upward leader **8** had its origin on the single 3-m vertical rod of the building's lightning protection system, but it failed to connect with any of the downward leaders. The unprotected chimney was severely damaged by the return stroke current and its fragments flew in all directions (Figure 5e).

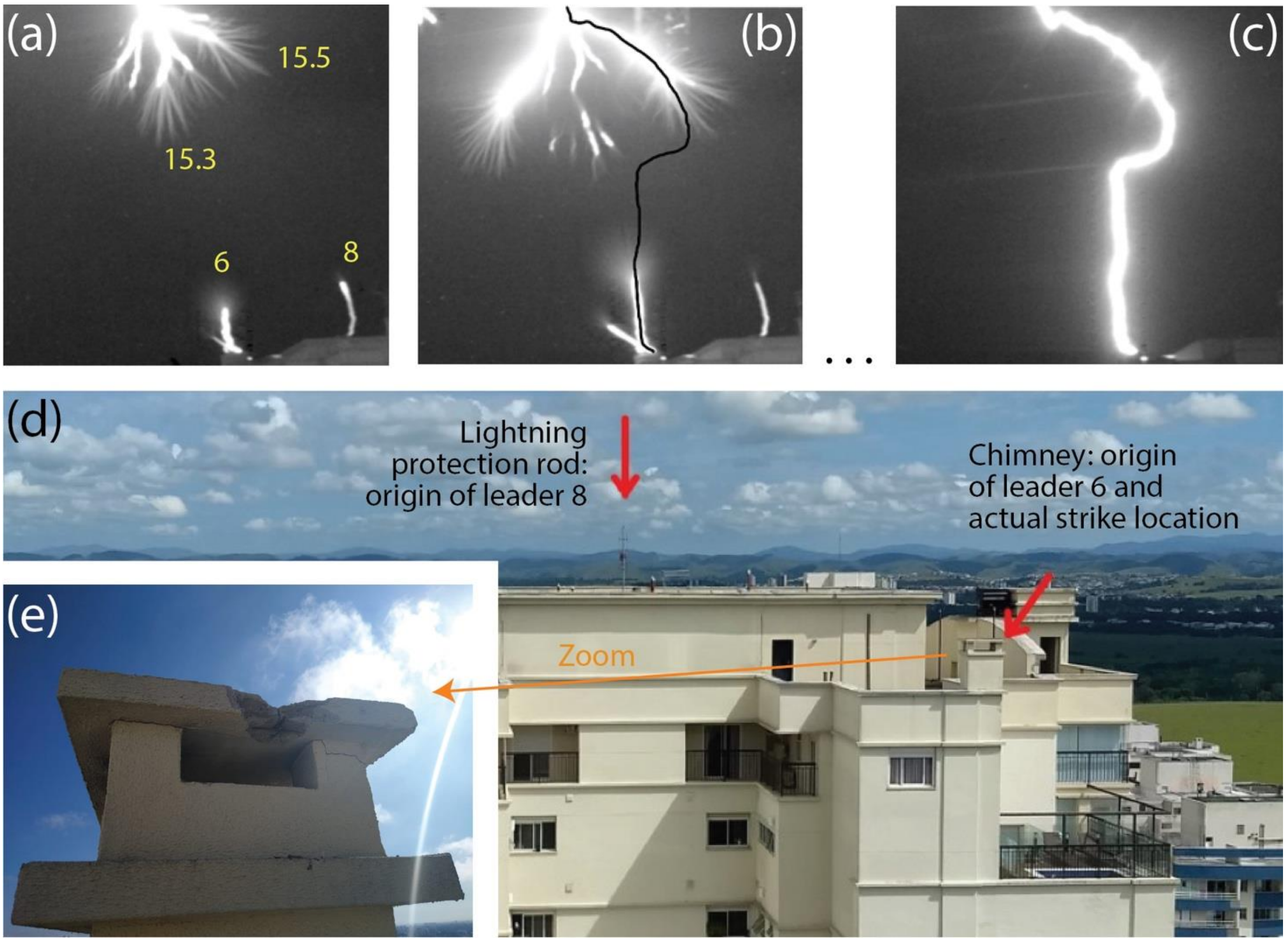

Fig. 5. (a) Branched downward leader (**15** and its branches) displaying multiple streamers. (b) return stroke path traced over the frame (25 µs) just prior to the attachment. (c) Return stroke image 1 ms after attachment. (d) Lightning connected to chimney in the corner of the building despite the presence of a taller lightning protection rod at the top. (e) Destruction caused by the lightning strike.

4 Summary and Conclusions

In this study, a very close high-speed video observation of lightning attachment to an apartment building revealed novel details regarding: leader propagation, the morphology of streamer zones in positive and negative leaders, and the appearance of space stems in negative leaders. A staggering total of 33 upward leaders were seen to originate from several buildings near the striking location. Upward leaders propagate in a steady and unbranched manner, with speeds of the order of 10^4 m/s. The upward connecting leader (UCL) was the fastest of all upward leaders (3 times faster). Upward positive leaders have a "streamer zone" which does not seem to have any streamers at all. It resembles a uniformly-luminous corona brush. The exception being the UCL just before connection, when its streamer zone transitions into a more filamentary pattern. The length of the corona brush gets longer as the distance between the downward and upward leaders is reduced. Downward negative leaders are heavily branched, and up to one order of magnitude faster than positive ones. We can distinguish multiple streamers emanating from each negative leader tip, with lengths of the order of 3 m. In some occasions, plasma formations known as space stems are seem to form in the location previously occupied by negative streamers. Space stems have luminosities comparable to the main leader channel, but are detached from it by 4 m. Some space stems display streamers of their own emanating from both ends, forming an embryonic bidirectional space leader. The space stem formation hampered the propagation of the negative leader that was (apparently) closest to the UCL, as a result the attachment process happened with a different downward leader branch, resulting in a connection at an angle of almost 90 degrees.

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Data Availability Statement

The high-speed videos and data analyzed in this work are available at: https://doi.org/10.5281/zenodo.7117249.

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