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Key Points:
- First observation of lightning attachment process to a common building
- Observation of the lightning interception process with high-speed camera videos
- Determination of parameters largely used in lightning attachment models and protection standards

Supporting Information:
- Supporting Information S1
- Movie S1
- Movie S2
- Movie S3

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Lightning attachment process to common buildings

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Abstract The physical mechanism of lightning attachment to grounded structures is one of the most important issues in lightning physics research, and it is the basis for the design of the lightning protection systems. Most of what is known about the attachment process comes from leader propagation models that are mostly based on laboratory observations of long electrical discharges or from observations of lightning attachment to tall structures. In this paper we use high-speed videos to analyze the attachment process of downward lightning flashes to an ordinary residential building. For the first time, we present characteristics of the attachment process to common structures that are present in almost every city (in this case, two buildings under 60 m in São Paulo City, Brazil). Parameters like striking distance and connecting leaders speed, largely used in lightning attachment models and in lightning protection standards, are revealed in this work.

Plain Language Summary Since the time of Benjamin Franklin, no one has ever recorded high-speed video images of a lightning connection to a common building. It is very difficult to do it. Cameras need to be very close to the structure chosen to be observed, and long observation time is required to register one lightning strike to that particular structure. Models and theories used to determine the zone of protection of a lightning rod have been developed, but they all suffer from the lack of field data. The submitted manuscript provides results from high-speed video observations of lightning attachment to low buildings that are commonly found in almost every populated area around the world. The proximity of the camera and the high frame rate allowed us to see interesting details that will improve the understanding of the attachment process and, consequently, the models and theories used by lightning protection standards. This paper also presents spectacular images and videos of lightning flashes connecting lightning rods that will be of interest not only to the lightning physics scientific community and to engineers that struggle with lightning protection but also to all those who want to understand how a lightning rod works.

1. Introduction

The effectiveness of a lightning protection system (LPS) depends on its efficiency to intercept the down coming lightning leader. The interception is usually done by an upward connecting leader (UCL) launched from the air termination system installed on the structure or building to be protected. This interception prevents a lightning strike to a critical part of the structure. Therefore, the understanding of the characteristics of an UCL and of the attachment process with the downward leader plays an important role in the determination of the volume or zone of protection of the air termination system of a LPS and in the improvement of LPS designs.

Most of what is known today comes from leader propagation models that are mostly based on laboratory observations of long electrical discharges or from observations of lightning attachment to tall structures [*Rizk*, 2009; *Cooray and Becerra*, 2012]. However, values taken from laboratory experiments cannot be just extrapolated and used to describe what happens in nature and a statistically representative observation of lightning attachment to structures of different characteristics and heights may require a very long observation time.

Tall structures are more likely to be struck by lightning. In fact, there are a few reports on the behavior of upward connecting leaders in response to downward propagating leaders from tall towers [*Yokoyama et al.*, 1990; *Warner*, 2010; *Lu et al.*, 2013; *Saba et al.*, 2015]. However, depending on their height, there will be a strong tendency of producing upward lightning [*Saba et al.*, 2016] or very long UCL [*Lu et al.*, 2013] which are not expected in common structures or buildings of low to moderate heights.

There are no available observational data of the stages of lightning attachment to low structures or buildings (under 60 m) that are commonly found in almost every populated area around the world. This work provides some results from high-speed video observations of lightning attachment that will help to validate or improve the lightning attachment models that have been adopted by lightning protection standards. The main and original contributions in this paper concern the observation of downward and upward leader speed, the final jump before attachment, and the striking distance. These parameters address the core issue of lightning protection.

For three well-documented lightning strikes to common buildings, we present the ratio between the speed of propagation of the downward leader and the upward leader, a critical parameter that will define where the condition for a final jump will take place. We show evidences that suggest that, during the final jump, it is the positive upward leader that bridges the final gap and report values of striking distances, a parameter used to estimate the effectiveness of air terminals in the protection of ground structures.

2. Methods

In order to observe lightning attachment to common buildings, a high-speed video and a still camera and two standard video cameras were positioned at distances of 210 m and 411 m from a pair of identical 14-story apartment buildings, named P1 and P2 (see Figure 1), located in São Paulo City (23.483°S, 46.728°W, Brazil). Their steel reinforced concrete structures are used as natural LPS. Each building has a vertical lightning rod, and their tips are at a height of 52 m respective to ground floor. The buildings are located on a relatively flat terrain, and the average flash density Ng for the region is about 11 flashes/km^2 yr [*ELAT/INPE*, 2015].

A high-speed camera (Vision Research's Phantom v711) with time resolution and exposure times of 50 and 100 μs (20,000 and 10,000 images per second) was used to record the images of the lightning attachments. The standard cameras were used to reconstruct the 3-D trajectory of the lightning flash. For more details about the use of high-speed camera for lightning observations, see the works by *Saba et al*. [2013]. In this work, all reported distances and speeds were measured in 2-D and therefore will be underestimated. Each frame of the video is time stamped by means of a GPS antenna.

In order to check the stroke order and polarity of the stroke that connected the buildings, an electric field measuring system was used. It consisted of a flat plate antenna with an integrator/amplifier and a GPS receiver, located 9 km away from the buildings. The waveform recording system was configured to make continuous recordings at a sampling rate of 5 MS/s. More information about the electric field measuring system is described by *Schumann et al*. [2013].

All flashes were detected by lightning location systems (LLS). Further information about these systems and their performance are given by *Naccarato et al*. [2012]. Data from the LLS were used to obtain the polarity, the exact time of the return stroke, and an estimate of the peak current (Table 1). A study on the accuracy of peak current estimation given by the LLS has not been performed yet. However, for one recent event of a cloud-to-ground flash that struck building P1, the error was within 20%. During this event, four strokes were detected by the LLS and they were directly measured by a current sensor installed in the vertical lightning rod to where the attachment occurred.

3. Data Presentation

3.1. Overview

This study presents results from measurements of three cloud-to-ground lightning flashes that struck a pair of identical 14-story apartment buildings. In all cases we observed that the UCL was always accompanied by an unconnected upward leader (UUL) from the vertical air termination rod of the other building, as shown in Figure 2. In some cases, an UUL was also initiated on the air termination conductor situated along the edge of the buildings (see Figure 2d).

All flashes had multiple terminations on the ground. The strokes that connected to the buildings were the first strokes to those structures, although they were not the first strokes of the flash.

Due to the proximity and the limited field of view of the camera, some strokes that have not connected to the buildings were not captured by the camera. Information about the flashes (number of strokes, stroke order of

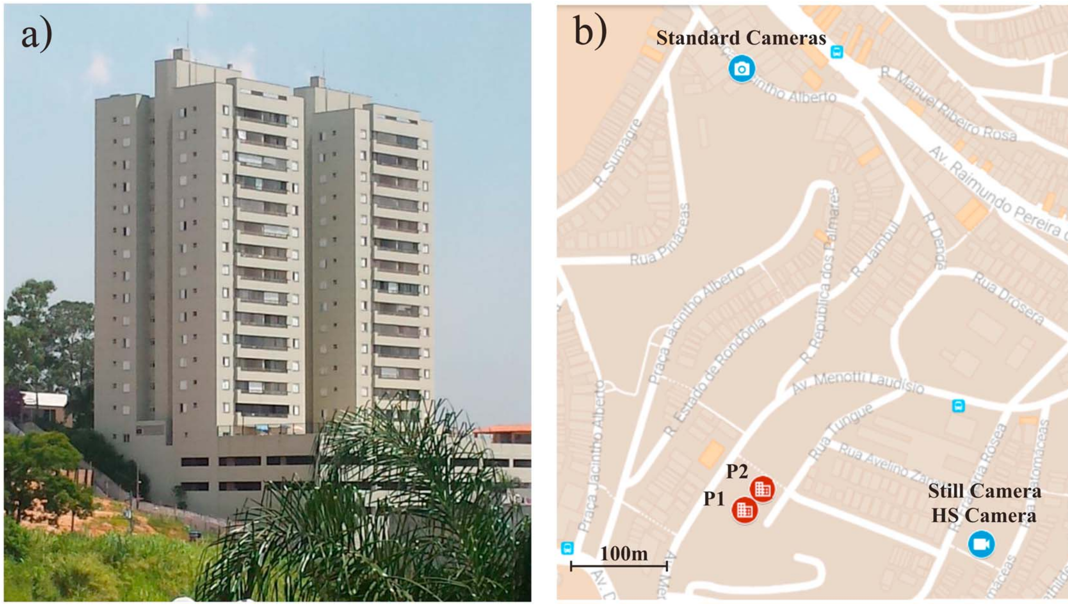

Figure 1. (a) Identical 14-story apartment buildings (P2 on the left and P1 on the right). (b) A plan view of buildings P1 and P2 and the locations of the standard and high-speed video cameras and the still camera.

the attachment to the buildings, and estimated peak current), number of upward leaders, and the frame rate of the video recordings are given in Table 1. The criterion used to group the strokes into flashes was the value of the time intervals between consecutive strokes (maximum observed time interval of 142 ms). For the original videos refer to the supporting information.

3.2. Average Leader Speed

Distances travelled by downward leaders (that connected the buildings) and by UCL and UUL (that appeared in two consecutive video images) are presented in Figure 3. Time 0 is set at the beginning of the return stroke. Note that in all cases the initiation of the upward leaders (UCL and UUL) occurs only a few hundreds of microseconds before the return stroke. The initiation of a stable upward leader occurs when the downward leader tip is a few tens of meters away from the tip of the lightning rod (see Table 2).

In this work the average leader speed values (shown in Figure 3 and in Table 2) were calculated based on the 2-D distances travelled by the leaders from frame to frame. The error in the determination of 2-D distances was found to be within 10%, and the coefficients of determination (R^2) of the linear fits used for speed calculation were higher than 0.95. The downward stepped leaders have an almost constant propagation speed, ranging from 13.4 to 27.5 × 10^4 m/s. The UCLs from lightning rods move also at a constant speed, ranging between 4.3 and 6.2 × 10^4 m/s. In case B (Figure 3, middle) the last observable position of the UCL (shown by an arrow) is not used to compute the upward speed because we believe that it is strongly influenced by the final jump condition (as discussed in the following section). The ratios between the speed of the downward leader and the speed of the UCL for each event are shown in Table 2.

Table 1. Cases of Attachments

	Case A	Case B	Case C
Date and time of the stroke	9 February 2014 21:28:37.711490	1 March 2014 22:37:38.962550	25 February 2015 20:05:00.769540
Attachment point	Vertical rod of P2	Vertical rod of P2	Vertical rod of P1
Upward leaders from buildings	P1: one UULP2: one UCL	P1: two UULP2: one UCL	P1: one UCL, one UULP2: two UUL
Attachment: stroke order and number of strokes in the flash	Fourth stroke of a four-stroke flash	Fourth stroke of a five-stroke flash	Second stroke of an eight-stroke flash
Estimated peak current of attachment stroke from LLS	−17 kA	−21 kA	−14 kA
Video frame rate (images per second)	10,000	10,000	20,000

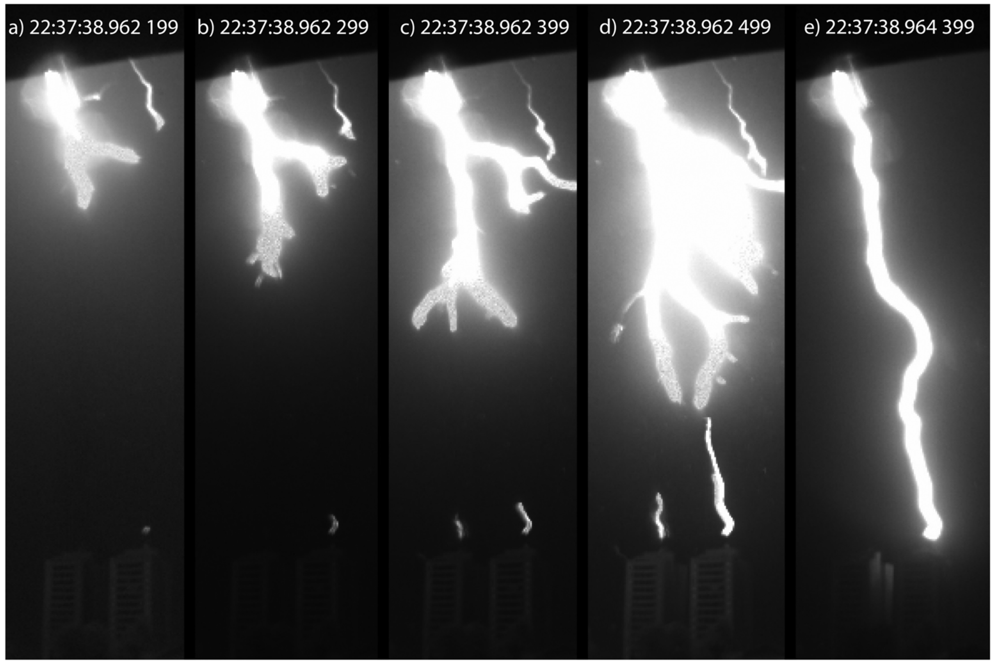

Figure 2. Sequence of video images showing the initiation and development of an UCL on P2 (right-hand side) and two UUL on P1 (left-hand side), one of them being launched from the building corner. This flash (case B) occurred on 1 March 2014. The UT time of each video frame (stamped at the end of the frame integration) is given as hh:mm:ss.xxx yyy (xxx digits are milliseconds and yyy are microseconds).

From the image analysis of another case of negative lightning flash (Figure S1) to building P1 (not included in this paper due to the absence of a high-speed video), we could estimate the 3-D trajectory of the leaders. The 3-D trajectory of the lightning channel was reconstructed from images recorded by a still camera placed at the same location of the high-speed video and a standard video camera placed at a viewing angle of approximately 90 degrees from each other (see Figure 1b). Considering that the upward leaders analyzed in this paper start only when the downward leaders are less than 200 m away from the lightning rods, the 3-D/2-D ratio for this lower part of the lightning channel was computed and an approximate ratio of 1.4 was found. Note that the 3-D/2-D ratio varies from case to case and for lightning channels with relatively long horizontal portions (as it is likely in case C) this ratio may vary largely. Therefore, the 1.4 ratio should be considered as approximate 3-D speed estimation from 2-D images.

3.3. Final Jump

When the upward leader approaches the downward leader, the average potential gradient between their tips increases and reaches a value high enough for the final attachment. This situation is referred to as the final jump condition [*Cooray and Becerra*, 2012].

Although the video frame rates used in this work are not high enough to resolve the propagation of the leaders during the final jump condition, we found evidences that suggest that it is the positive upward leader that bridges the final gap.

It is known that when the downward and the upward leaders connect, a bidirectional return stroke wave is launched from the junction point [*Hill et al*., 2016; *Jerauld et al*., 2007; *Wang et al*., 1999, 2013, 2014]. In case A and case B, if the luminosity of the images is properly adjusted, one can observe that a partial saturation of the image (indicating the location of the connection) starts very close to the position of the tip of the downward negative leader in the previous frame (Figures 4a and 4b and Figures 4d and 4e) and not close to the position of the positive upward leader in the previous frame. This could be an indication that in cases A and B, it is the positive upward leader that bridges the gap between leaders during the final jump condition.

According to a recent study by *Hill and Mata* [2016], the bright light due to the return stroke may produce parasitic light leakage onto the previous frame when the camera sensor is highly saturated by return

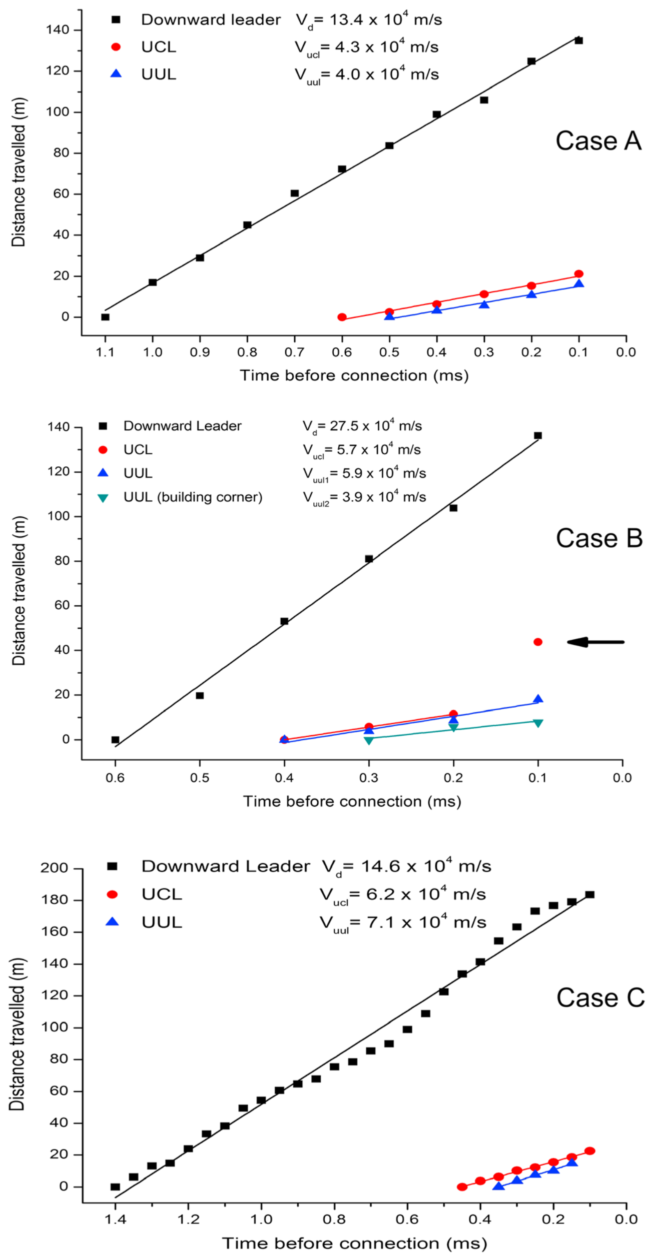

Figure 3. Distance versus time plots and linear regression fits for each case. Each plot starts when the leader first appears in the video image. The average speed for the linear fits are also shown. The connection instant has an uncertainty of frame duration (50 to 100 μs).

stroke. Having this into consideration, the luminous path between the tip of the downward propagating leader and the tip of the upward leader, which could indicate bridging discharges in cases A and C (Figures 4b and 4h, respectively), are not considered in the analysis because they occur in the frame prior to the highly saturated ones.

However, in case B, the fast elongation of the UCL (Figure 4d) occurs two frames prior to the highly saturated frame and most of its portion is situated in a region where the next frame is not saturated also. Therefore, allowing for the fact that it is a real lightning optical phenomenon, if the last position of the upward leader tip (about 4 m from the tip of the downward leader, see Figure 4d) is considered for the speed calculation, we conclude that while the downward leader maintains a steady propagation (constant speed), the upward leader accelerates drastically to an average speed of 31×10^4 m/s (7 times higher than the speed evaluated in the previous frame). This significant increase in the average speed of the upward leader would suggest a final jump condition occurrence during that frame. On the other hand, it is difficult to explain why the intense luminosity corresponding to the initiation of the return stroke in Figure 4e occurs only in the subsequent frame after the imminent connection illustrated in Figure 4d. Therefore, with the present data it is not conclusive that the thinner portion of the upward leader in Figure 2d corresponds to the final jump. Videos with higher sampling rates and, ideally, from a camera less susceptible to parasitic light leakage would be required to reach a final conclusion.

From case C, although it is not possible to see a clear final jump condition, the sequence of high-speed video images in Figures 4g–4j and the still photograph of the flash (Figure 4k) suggest that the downward leader and its branching remain unaltered by the presence of the buildings as assumed by some models (see discussion in *Cooray and Becerra* [2012]).

3.4. Striking Distance

The striking distance is a concept that has been widely used in lightning protection studies. It can be defined by *Golde* [1973] as the separation between the tip of the downward stepped leader and the tip of a grounded

Table 2. Characteristics of the Leaders and Striking Distances

	Unit	Case A	Case B	Case C
Downward leader average speed (V_d)	m/s	13.4×10^4	27.5×10^4	14.6×10^4
UCL average speed (V_{ucl})	m/s	4.3×10^4	5.7×10^4	6.2×10^4
Speed ratio (V_d/V_{ucl})		3.1	4.8	2.3
UUL average speed (V_{uul})	m/s	4.0×10^4	5.9×10^4 3.9×10^4	7.1×10^4
Time interval between leader inception and return stroke (attachment)	ms	0.54	0.40	0.47
Distance between the down-coming negative leader tip and the tip of the vertical rod at the inception of a stable upward positive leader	m	82	120	62
Distance between the tip of the vertical rod and the negative leader tip at the moment of attachment	m	44	46	40–50

structure when a stable upward connecting leader is initiated from that tip of the structure. Another definition of striking distance is the distance of the tip of the downward stepped leader to the point of a grounded structure from which the UCL was initiated, when the attachment of the stepped leader occurs [*Cooray et al*., 2014]. Values of striking distances according to both definitions are presented in Table 2 for cases A, B, and C.

4. Discussion

The physical mechanism of leader attachment to ground together with the characteristics of upward connecting leaders is one of the most important issues in lightning physics research according to *Dwyer and Uman* [2014]. Such subject has been analyzed in recent studies for cloud to ground flashes on tall structures [*Yokoyama et al*., 1990; *Lu et al*., 2013; *Saba et al*., 2015; *Visacro et al*., 2016] and for triggered lightning [*Wang et al*., 1999].

The cases studied here, in contrast to past observational studies on lightning attachment, occurred on a type of building that is extremely common in populated areas. The proximity of the camera and the high frame

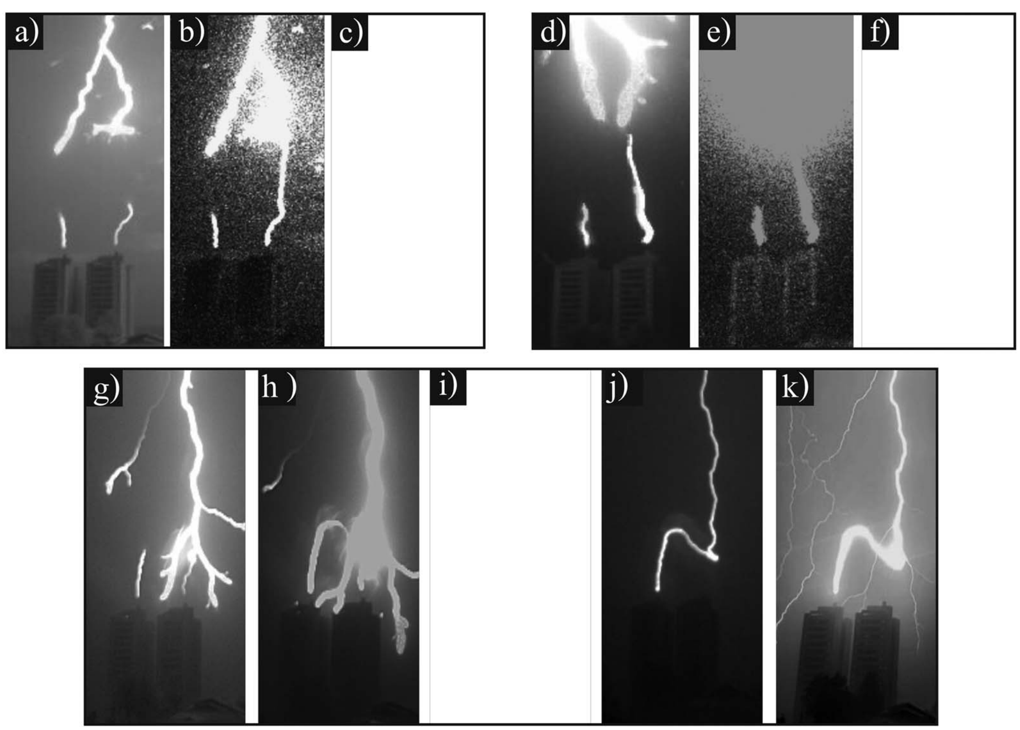

Figure 4. High-speed video images of the final jump at the moment of attachment (a–c) in case A, (d–f) in case B, and (g–j) in case C. (k) Still photograph image of the flash in case C.

rate allowed us to see some interesting details that may improve the understanding of the attachment process and, consequently, the lightning protection studies.

The attachment point between the downward leader and the UCL strongly depends on their speed. Due to the lack of data, the ratio between their speeds is assumed by *Eriksson* [1987a, 1987b] and *Rizk* [1990, 1994] to be equal to 1. *Dellera and Garbagnati* [1990a, 1990b] assumed this ratio to change from 4 to 1 during the attachment process, and *Ait-amar and Berger* [2005] uses a range of ratios from 0.5 to 4.

Speeds and speed ratios found for very tall structures seem not to be valid for common structures (height lower than 60 m). In very tall structures, as described by *Lu et al*. [2013] the leader length is comparable to the structure height (hundreds of meters) and in these extreme situations, these very long UCL can accelerate to the point of having speed values that significantly exceed the speed of downward leaders.

Contrary to what is assumed in some leader propagation models or observed in tall structures, we found that (a) the speed of the downward and upward leaders are approximately constant and (b) the speed of the upward leaders is lower than the speed of the downward leader with speed ratio values between 2.3 and 4.8 (before final jump condition).

It was not possible to resolve the propagation of the bridging discharge during the final jump condition with the frame rate used by the high-speed cameras. However, some evidences suggest that the discharge that bridges the final gap is the positive UCL and not the negative downward leader.

There are several models and expressions available in the literature that express the striking distance as a function of return stroke peak current and structure geometry [*Cooray and Becerra*, 2012; *Cooray et al*., 2014]. The striking distances presented in this work are the first observed values for common buildings, i.e., for relatively low structures. As the values of striking distances vary according to the definition used, both values are presented in Table 2. In agreement with several past models described in the literature, longer striking distances are expected from return strokes with higher prospective peak current values.

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