2015 International Symposium on Lightning Protection (XIII SIPDA), Balneário Camboriú, Brazil, 28th Sept. - 2nd Oct. 2015.

Upward connecting leaders from buildings

Marcelo M. F. Saba, Amanda R. de Paiva, José Claudio de Oliveira e Silva, Lucas D. Noveline, Carina Schumann, Kleber P. Naccarato, Christopher P. Sato
Electricity Atmospheric Group
INPE – National Institute for Space Research
São José dos Campos, Brazil

Marco A. S. Ferro
Atmospheric Science Division
IAE - Institute of Aeronautics and Space
São José dos Campos, Brazil

Abstract— **Although there are some data on lightning attachment to tall towers (height over 60 m), there are no observational data of lightning attachment to common structures or buildings (under 60 m) that are present in almost every city. In this paper we analyze upward leaders induced by a downward negative lightning flash that struck a building located in São Paulo, Brazil. The attachment process was analyzed by a high-speed camera running at 10,000 images per second and an electric field sensor. The striking distance observed was different from the ones given by some common models. The ratio of speeds of the downward leader and the upward connecting leader was between 5 and 6. The final jump discharge initiated from the positive upward connecting leader. An upward connecting leader was also observed during the propagation of the dart leader of a subsequent stroke.**

Keywords— ***Upward connecting leader, cloud-to-ground flash, lightning rod, lightning protection systems***

I. 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 LPS installed on the structure or building to be protected. This interception prevents a lightning strike to a critical part of the structure being protected.

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 a LPS and in the improvement of LPS designs.

However, a good observation of a lightning attachment to a structure may require a very long observation time. Tall structures are more likely to be struck by lightning, however if their height is over 100 m they will almost always initiate upward lightning flashes. Therefore the common attachment process that affects the majority of structures and buildings is not observed.

Although there are some data on lightning attachment to tall towers (height over 60 m), there are no observational data of lightning attachment to common structures or buildings that are present in almost every city (under 60 m). Research on lightning attachment to these common structures is therefore mostly theoretical and based on laboratory observations of electrical discharges. This research is often done assuming that some parameters observed in laboratory can be used in models.

This work provides some preliminary results obtained from high-speed video observations of lightning attachment to buildings. These observations can provide some parameters that are crucial in lightning protection studies like: (a) striking distance, (b) the length and speed of the downward leader, (c) the length and speed of the UCL. We will also analyze some unconnected upward leaders (UUL), i.e. those events that fail to make contact with the downward leader.

II. INSTRUMENTATION

A. Video cameras

In order to observe lightning attachment to common buildings some cameras were positioned at a distance of 200 m from two identical 14-story apartment buildings (Figure 1) in São Paulo city (southeastern Brazil). The tip of their lightning rods is at a height of 52 m. Their steel reinforced concrete structures are used as natural LPS. The flash density Ng for the region is about 11 flashes/km^2·year [1].

Fig. 1. Identical buildings (P1 on the left, P2 on the right) with the same LPS installed.

A high-speed digital video camera (Vision Research's Phantom v711) with time-resolution and exposure times of 50 and 100 microseconds (20,000 and 10,000 images per second) was used to record the images of the lightning attachments. For more details about the measuring systems and about the use of high-speed camera for lightning observations, see the works by Saba et al. [2].

Figures 2a and 2b shows the locations of the two buildings and cameras, and the topography of the terrain within 500 m of the buildings. It can be seen that the buildings are on relatively flat terrain in terms of lightning attraction.

All distances and speeds reported in this work were measure in 2D and therefore will be underestimated.

B. Electric Field Measurement System

Electric field measurements were used to support the observations. The electric field measuring system consisted of a flat plate antenna with an integrator/amplifier, a GPS receiver, and a PC with two PCI-cards operating at a sampling rate of 5 MS/s on each channel and with the resolution of the A/D converter of 12 bits. The lower frequency and the upper frequency bandwidth of the system is 306 Hz and 1.5 MHz respectively.

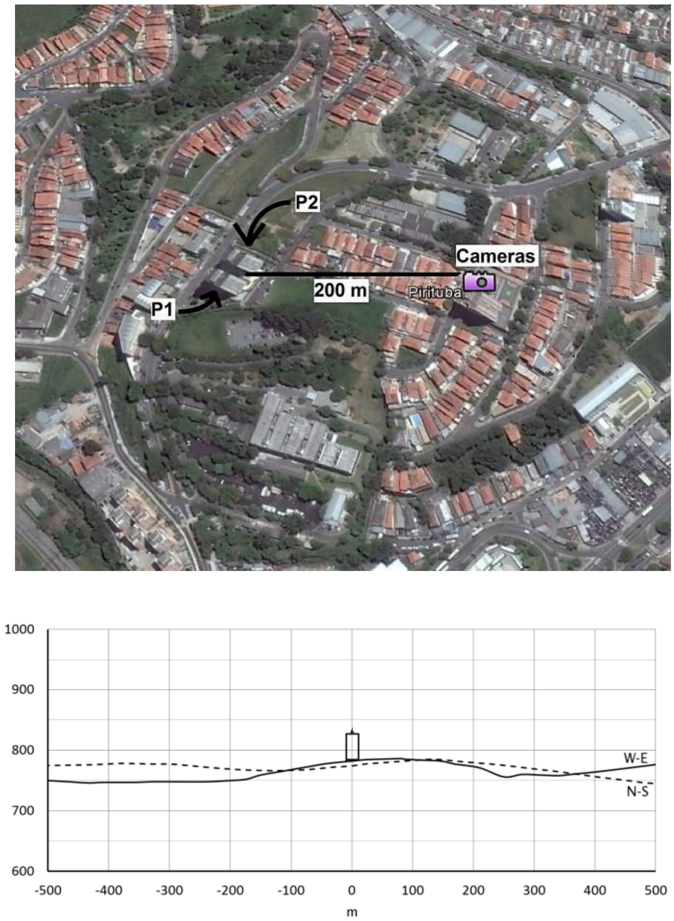

Fig. 2. a) Location of the twin buildings and cameras; b) approximate elevations (m) of the terrain along two directions: West to East (solid line) and North to South (dashed line), taken from Google Earth. The building is drawn on W-E elevation curve in scale.

III - DATA

Since January 2012, a total of 15 (UCL) from buildings and other tall structures (mobile phone and water towers) were observed with high-speed cameras. In the same period, 12 UUL were observed. The twin buildings (P1 and P2) produced 6 UCL and 6 UUL. Figure 3 shows some examples of UCL and UUL.

Fig. 3. Examples of UCL and UUL from mobile phone towers and the twin buildings. Each image corresponds to a frame extracted from a high-speed video recording.

IV – RESULTS

In this paper we will only discuss one lightning attachment case observed on a lightning rod of the twin buildings P1 and P2. In particular, attention will be given to a 5-stroke negative cloud-to-ground flash. The three first strokes had different ground contacts that were not seen by the cameras. The 2 last strokes of this flash struck the vertical rod of building P2. In this attachment process to P2, one UCL occurred during the approach of the stepped leader that preceded the fourth stroke and another UCL occurred in response to the dart leader of the fifth (and last) stroke. Two UUL were initiated from P1. Some features of this lightning attachment are described in detail in the following sections.

A. UUC and UCL during first strokes

In Figure 4, a sequence of video images shows the lightning attachment process of a negative cloud-to-ground flash (22:37:38 UT, March 01, 2014) to the LPS of building P2. It is possible to observe the initiation and development of an UCL from building P2 and two UUL from building P1. In Figure 4a we can see the inception of the UCL from the vertical air-termination rod of building P2. Figure 4c shows the branching of the downward propagating negative leader and the inception of an UUL from the vertical rod of P1. In Figure 4c we see also the inception of an UUL from one of the corners of P1. Figure 4d shows the imminent connection between the downward leader and the UCL and Figure 4e shows the lightning channel

1.8 ms after the return stroke. The return stroke occurred at 22:37:38,962 552 according to the lightning location system data.

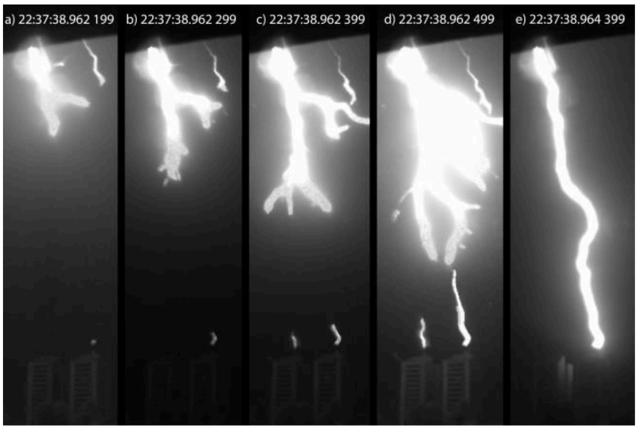

Fig. 4. - Sequence of video images showing the initiation and development of an UCL and two UUL. The UT time of each video frame (stamped at the end of the frame integration) is given as hh:mm:ss.xxx yyy (xxx digits are milliseconds and yyy are microseconds).

The analysis of displacement and speed of the downward leader and the corresponding UCL, UUL are presented in Figures 5 and 6. Time 0 is set at the beginning of the return stroke.

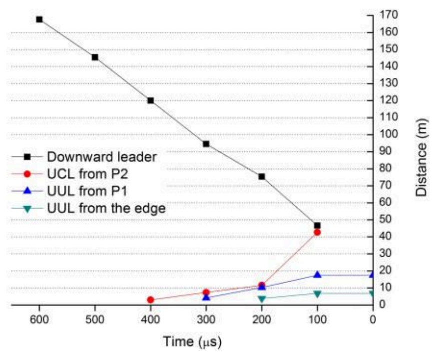

Fig. 5. – Distance travelled by each leader as a function of time in 100-µs intervals.

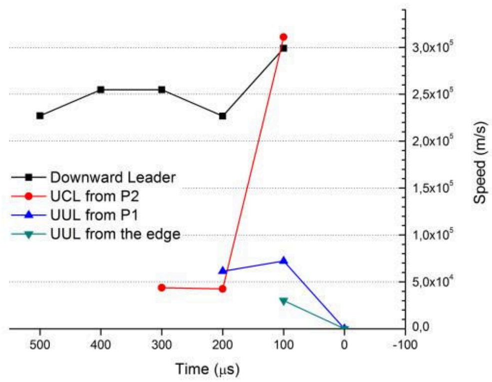

Fig. 6 – Average speed for each leader in 100-µs intervals.

The downward stepped leader has an almost constant propagation speed. The UUL from P1, after some gain in speed (Fig. 4b-d), stops its propagation when the electric field collapses following the completion of the attachment on P2. The speed of the UUL from the corner of P1 also goes to zero. The UCL from P2 moves at a constant average speed of 4.3×10^4 $m \cdot s^{-1}$ (Fig. 4a-c) and accelerates drastically to an average speed of 31×10^4 $m \cdot s^{-1}$ (7.3 times higher) during the frame interval just prior to the attachment (Fig. 4d). The ratios between the speed of the downward leader and the UCL varies from 5.8 (Fig. 4a-b) and 5.3 (Fig. 4b-c) to 0.96 (Fig. 4c-d). We believe that the significant increase in the average speed of the ULC is mainly due to a much higher speed of the final jump discharge that takes place during the frame interval. An evidence of this is also given by the presence of a thinner portion of the upward leader channel in Figure 4d. In this frame the tip of the downward leader was just 4 meters away from the tip of the UCL. This means that the ending of the image integration occurred only a few microseconds before the connection. Therefore, the thin part of the channel could have been traced by the final jump discharge during a very small percentage of the total 100 µs frame interval. Either way, note that the final jump discharge had its origin in the positive UCL and not in the negative downward leader.

The striking distance, a concept that has been widely used in lightning protection studies, was defined by Golde [3] as the separation between the tip of the stepped leader and the tip of a grounded structure when a stable upward connecting leader is initiated from the tip of the structure. Another definition of striking distance is the distance of the tip of the stepped leader to the grounded structure when the attachment of the stepped leader occurs. This attachment can be established between tip of the leader and the grounded structure (as considered by the Electro-Geometrical-Model, EGM) or between the tip of the leader and the tip of the UCL initiated on the grounded structure. According to the first definition, the striking distance for this case would be 120 m (Figure 7a). According to the second, it would be 46 m (Figure 7b).

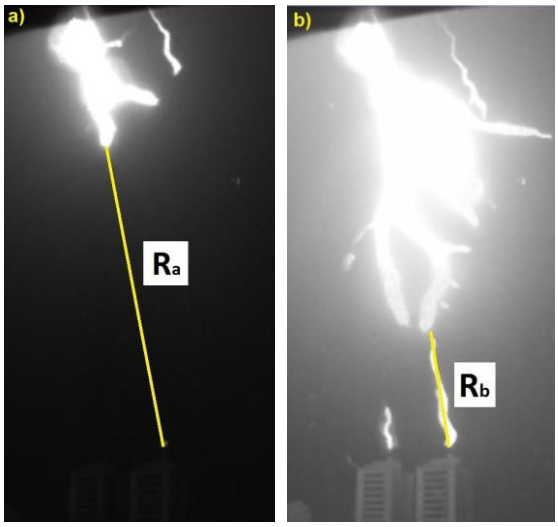

Fig. 7 – Striking distances according to different definitions (R_a = 120 m and R_b = 46 m).

As the striking distance depends on the critical breakdown electric field needed across the final gap, and it is assumed that the return-stroke peak current is proportional do the charge on the leader, several analytical expressions for the striking distances are found in the literature and used by the EGM. They are represented by the general equation:

$$R = aI^b$$

Where R is the striking distance in meters, I is the peak current in kA, and a and b are constants. Table 1 shows the parameters used in different models.

Table 1 – Parameters a and b for different models and the resulting striking distance for I = 21 kA.

Models	a	b	R (I = 21 kA)
Amstrong and Whitehead [4]	6.0	0.80	69
Brown and Whitehead [5]	6.4	0.75	63
Love [6]	10.0	0.65	72
IEEE Standard 1243 [7]	8.0	0.65	58
IEC standard 62305 [8]	10.0	0.65	72

Note that the given striking distance values for different models using an estimated peak current of 21 kA are all different from the values R_a and R_b obtained from video measurements (Figure 7a and 7b). Note also that the estimated peak current value was obtained from local lightning location system. Considering an error of 10 kA in the peak current value (I varying from 11 to 31 kA), the striking distances given by the different models would vary from a minimum of 38 m to a maximum of 94 m for this event.

B. UCL during a subsequent stroke

Orville and Idone [9] reported that UCL were not observed in any of the 21 dart leader events in natural lightning observed with streak photography. They suggest that connecting leaders do not occur or they are on the order of only a few meters or less in length. Contrary to what was observed then, we observed a UCL during the propagation of a dart leader (Figure 8).

As mentioned, the fifth stroke of the negative flash also struck the vertical rod of P2. It occurred 53 milliseconds after the previous return stroke. The estimated peak current by the LLS of this return stroke (8 kA) was not as high as the previous one. The amplitude of electric field change produced by this return stroke was 67 % of the amplitude produced by the previous one.

During the approach of the dart leader preceding the fifth stroke it is possible to observe another UCL from P2 (Figure 8). Interestingly, the length of the UCL responding to this dart leader has the same length (46 m) of the UCL that responded to the stepped leader in the previous stroke to P2. This means that the peak-current dependent equation to calculate the striking distance R is probably not applicable to subsequent strokes.

The length of this UCL is much higher (2 or 3 times) than what was observed in triggered lightning (20 and 30 meters by Idone et al. [10] and 7-11 meters by Wang et al.[11].

It is also worthwhile to note that although the dart leader speed (estimated from frame a to b in Figure 8) was at least 1.2×10^6 m·s^{-1} it comes to a halt during the final jump discharge (Figures 8b and 8c).

It shall be noted that the point of connection between UCLs and downward leaders seems the same for both the fourth stroke (return stroke) and the fifth stroke (subsequent stroke). It suggests that the lightning channel holds certain characteristics between two (or more) consecutive strokes that favor the connections to occur at the same point. Otherwise, the observed equal length UCLs shall be deemed to be pure coincidence.

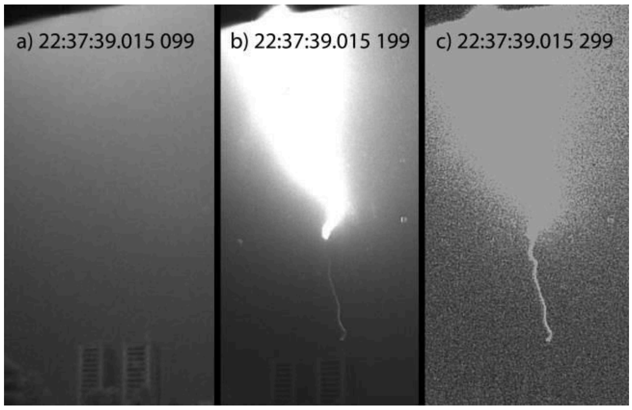

Fig. 8. Sequence of video images showing the initiation and development of the UCL for fifth subsequent return stroke.

V - Discussions

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 [12]. Recent studies on the subject have analyzed this mechanism for negative CG flashes on tall structures [e.g. 13, 14] and for triggered lightning [15].

The case studied here (contrary to past observational studies on lightning attachment) occurred on a type of building that is extremely common in cities. The proximity of the camera and the high frame rate used allowed us to see some interesting details that may improve the understanding of the attachment process and, consequently, the lightning protection studies.

This case study allows us to conclude that:

a) the final jump discharge has its origin in the positive UCL;

b) the downward stepped and the dart leader stop propagating when they attach to the final jump discharge;

c) the ratio of speeds of the downward leader and the UCL is between 5 and 6;

d) the striking distances according to both definitions are 120 and 46 m;

e) an UCL was observed during the propagation of a dart leader; and

f) the length of UCL to return and to subsequent strokes may be the same.

ACKNOWLEDGEMENTS

The authors would like to thank Raphael B. Guedes da Silva and Lie Liong Bie (Benny) for all support in data acquisition, Robson Jaques for software development, Dr Vernon Cooray for some fruitful discussions and Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) for supporting the research through the Project 2012/15375-7. The authors would also like to thank Luiz Fernando Gonçalves, Domênico Benenati and Eduardo Bochicchio for all the information regarding the twin buildings P1 and P2 (named Violeta and Azaléia respectively).

REFERENCES

[1] ELAT/INPE, http://www.inpe.br/webelat/ABNT_NBR5419_Ng/, (May 2015); official webpage providing Ng data for the new Brazilian Standard on Lightning Protection: ABNT NBR 5419 Series, May 2015.

[2] Saba, M. M. F., C. Schumann, T. A. Warner, J. H. Helsdon Jr., W. Schulz, and R. E. Orville (2013), Bipolar cloud-to-ground lightning flash observations, J. Geophys. Res. Atmos., 118, doi:10.1002/jgrd.50804.

[3] Golde, R. H., Ligthning Protection, Edward Arnold, London, 1973.

[4] CIGRÉ WG 33-01 (convener A. Erickson), Guideto Proceduresfor Estimatingthe Lightning Performance of Transmission Lines, Cigré Brochure 63, October 1991.

[5] Brown G.W. and E. R. Whitehead, Field and analytical studiesof transmission lineshielding, *IEEE Trans. on PAS*, **88**, pp. 617-626, 1969

[6] Love E.R., Improvements on lightning stroke modelling and applications to the design of EHV and UHV transmission lines, M.Sc. Thesis, University of Colorado, 1973.

[7] IEEE Std. 1243, IEEE guide for improving the lightning perfomance of transmission lines, June 26, 1997.

[8] IEC 62305, International standard on protection against lightning. 2006.

[9] Idone, V and Orville, R. Lightning leader characteristics in the Thunderstorn research international program (TRIP). *J Geophysical Research*, **87**. pp177-192, 1982

[10] Idone, V. P., and Orville, R. E. Three unusual stroke in a triggered lightning flash. J. Geophys. Res., 89, pp. 7311-7316, 1984.

[11] Wang, D., V. A. Rakov, M. A. Uman, N. Takagi, T. Watanabe, D. E. Crawford, et. Al., Attachment process in rocket-triggered lightning strokes, *J. Geophys. Res*., **104**, pp. 2143-2150, 1999

[12] J. R. Dwyer and M. A. Uman, The physics of lightning, Physics Reports, 534, (2014), 147-241, http://dx.doi.org/10.1016/j.physrep.2013.09.004.

[13] W. Lu, L. Chen, Y. Ma, V. A. Rakov, Y. Gao, Y. Zhang, Q. Yin, and Y. Zhang, Lightning attachment process involving connection of the downward negative leader to the lateral surface of the upward connecting leader, Geophys. Res. Lett., 40, (2013), 5531–5535, doi:10.1002/2013GL058060.

[14] Saba, M. M. F., Schumann. C., Warner. A. A., Helsdon J. H. High-speed video and electric field observation of a negative upward leader connecting a downward positive leader in a positive cloud-to-ground flash. Electric Power System Research, 118, pp 89-92, 2015.

[15] D. Wang, W. R. Gamerota, M. A. Uman, N. Takagi, J. D. Hill, J. Pilkey, T. Ngin, D. M. Jordan, S. Mallick, and V. A. Rakov, Lightning attachment processes of an“anomalous”triggered lightning discharge, J. Geophys. Res. Atmos., 119, (2014) doi:10.1002/2013JD020787.