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Current measurements of upward leaders from buildings

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***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 current measurements of upward leaders induced by a downward negative lightning flash that struck a building located in São Paulo, Brazil. The attachment process was recorded by two high-speed cameras running at 37,800 and 70,000 images per second, two current sensors and an electric field sensor.**

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

I. INTRODUCTION

Previously, we have reported high-speed video images of attachment process of three negative downward cloud-to-ground flashes to an ordinary residential building [1]. As mentioned in the cited paper, the effectiveness of a lightning protection system (LPS) depends on its efficiency to intercept the down coming lightning leader which is usually done by an upward connecting leader (UCL).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. 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 be large enough to cause damage to electronic devices, and enough to injure a person.

A few current measurements of upward leaders have been reported from tall towers (e.g. Visacro et al. [2], height of 60 m over a hill), and from small structures (Schoene et al. [3], grounded vertical conductor of 7 m height). This study presents observational current and video data of both UCL and UUL during lightning attachment to a residential building, commonly found in almost every city. The use of high-speed video images and electric field measurements reveal the nature of the physical process that is generating the currents measured on the vertical lightning rods on top of the buildings.

II. METHODS

In order to observe lightning attachment to common buildings, two high-speed video cameras, a still camera and two standard video cameras were positioned at a distance of 210 m from a pair of identical 14-story apartment buildings, named P1 and P2 (see Fig. 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.

Fig. 1.a) Identical 14-story apartment buildings (P1 on the left and P2 on the right); b) Location of the cameras (210 m from P1 and P2).

Two high-speed digital video cameras (Vision Research Phantom v12 and v711) with exposure times of 13.55 and 25.85 microseconds and time resolution of 14.29 and 26.46 microseconds (70,000 and 37,800 images per second), respectively, were 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. [4]. In this work, all reported distances and speeds were measured in 2D and therefore will be underestimated. Each frame of the video is time stamped by means of a GPS antenna.

In order to check the electric field changes caused by the attachment process, two electric field measuring systems were used. They consisted of a flat plate antenna with an integrator/amplifier and a GPS receiver. One was located on top of building P2 and the other 9 km away from the buildings. The antenna located on top of building P2 was 22.5 m away from the vertical lightning rod on P1 and 4.0 m away from the mast of the lightning rod on P2. The waveform recording system was configured to make continuous recordings at a sampling rate of 5 MS/s.

One Pearson current sensor model 301-X was installed on the lightning rod of each building (see Figure 2). This current sensor is capable of recoding current up to 50,000 A with an useable rise time of 200 nanoseconds, a low frequency 3 dB cut-off of 5 Hz (approximate) and a high frequency 3 dB cut-off of 2 MHz (approximate). The output of the sensor is split in two channels (20 dB and 50 dB attenuation over 50 Ω), and sent to a data acquisition system through a pair of fiber optic links. Before installation, both sensors were tested and calibrated in the high voltage facility at IEE/USP.

The flash studied in this paper consisted of a single stroke that was detected by lightning location systems (LLS). Further information about these systems and their performance are given by [5]. 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%. In that event, four strokes were detected by the LLS and they were directly measured by the current sensor installed in the vertical lightning rod to where the attachment occurred.

More information about the cameras, the locations of the two buildings and the topography of the terrain can be found in the previous work [1].

III - DATA PRESENTATION

A. Overview

This study presents results from measurements of one cloud-to-ground lightning flash that struck the pair of identical 14-story apartment buildings on 1 September 2017. The flash was a single-stroke negative cloud-to-ground lightning discharge that struck the tip of the lightning rod on building P2. According to the LLS, its peak return stroke current was 73 kA and occurred at 19:01:10.689305 (UT). During the approach of the stepped leader, an UCL was launched from the tip of the lightning rod on building P2 together with UULs from the vertical air-termination rod of the other building (P1) and other nearby structures, as shown in Fig. 3. The leaders (numbered 1 to 6 in Fig. 3) have their origin at different distances from the electric field sensor. The distances and leader types are shown in Table 1.

Fig. 2.Current sensors installed on the lightning rods of buildings P1 and P2 (upper picture) and detail of the installation (lower picture).

Fig. 3 – UCL from P2 (number 2), and UULs (numbers 1, 3, 4, 5 and 6) from the mast of P1, the side of P2, and from other buildings nearby (see Fig. 1).

Table 1 – Leader type, origin and distance from the electric field sensor.

Origin of the leader	*Leader number in Fig. 3*	*Leader type*	*Distance from the electric field sensor*
P1 vertical mast	1	UUL	22.5 m
P2 vertical mast	2	UCL	4.0 m
P2 right corner	3	UUL	14 m
New building (corner)	4	UUL	141 m
New building (construction elevator 1)	5	UUL	105 m
New building (construction elevator 2)	6	UUL	63 m

B. Current and electric-field measurements

Fig. 4 presents the electric field measured during approximately 9 ms before the occurrence of the return stroke by the sensor that is located between the vertical masts of buildings P1 and P2. It is possible to note that the electric field is intensified with the approach of the negative downward leader and then reversed with the initiation of the upward positive leaders and the occurrence of the return stroke.

Fig. 5 shows the electric current measurements of upward connecting leaders (number 1 and 2 in Fig. 3) and the electric field (the polarity is reversed for illustrative purposes) during 550 microseconds before the return stroke. Unipolar current pulses of some tens of amps (10's A) from both vertical masts are observed during this interval. The positive polarity of the pulses indicates an upward-directed transfer of positive charge. The peak of the highest current pulse exceeds 250 A and is superimposed to a continuous current that becomes evident from around 200 microseconds prior to the return-stroke current.

Fig. 6 shows the complete recording of the current for the UUL from building P1. Note that when the returns stroke happens there is a reversal of the current. The electric field that was driving the propagation of the UUL from several nearby structures collapses with the occurrence of the return stroke. Therefore the charges contained in these leaders flow back to their origin in a very short time, creating a current in the opposite direction. Although the amplitude of the pulses are quite different, the pattern observed in this case is very similar to current measurements of UUL reported from tall towers (e.g. Fig. 8 in Visacro et al. [2], height of 60 m over a hill), and from small structures (Fig. 6 in Schoene et al. [3], grounded vertical conductor of 7-m height). Excepting the pulses, it is also similar to what is predicted by a current-generation type return-stroke model developed by [6].

V - SUMMARY AND CONCLUSION

The approach of the negative downward leader induced 6 upward leaders prior to the return stroke. Two of them initiated from instrumented lighting rods and had the current measured.

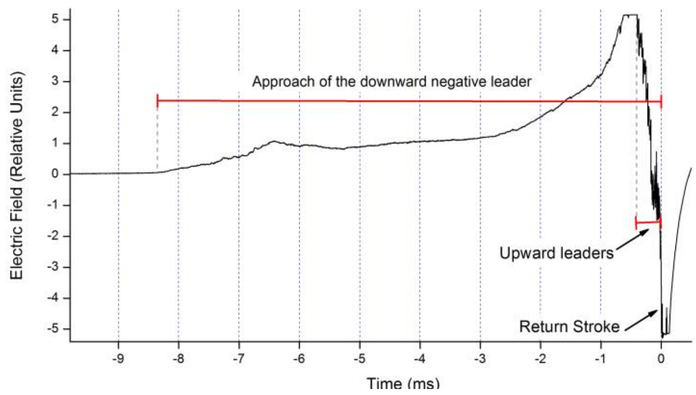

Fig. 4 – Electric field change with the approach of the negative downward leader and the initiation of the positive upward leaders.

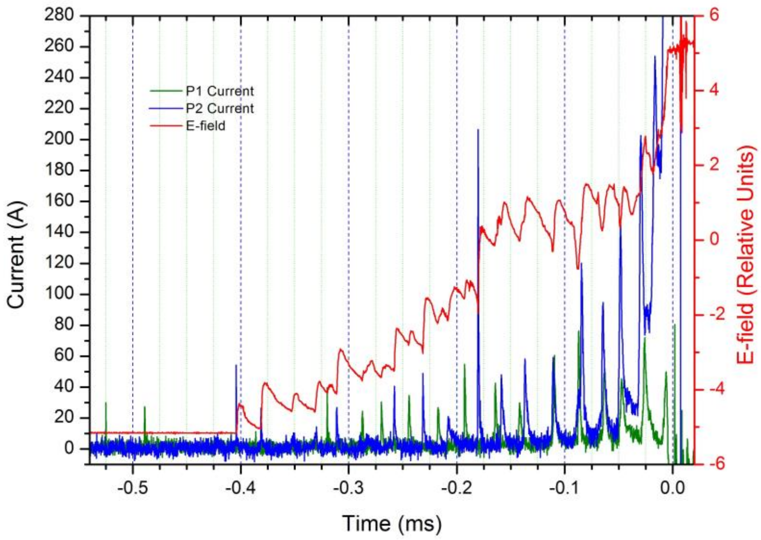

Fig. 5 – Measured current profile of a UCL from P1 and P2 (numbers 1 and 2) and from a UUL (numbers 3 to 6) from the side of P2 and from other buildings (see Fig. 1).The electric field was saturated before time t = -0.4 ms.

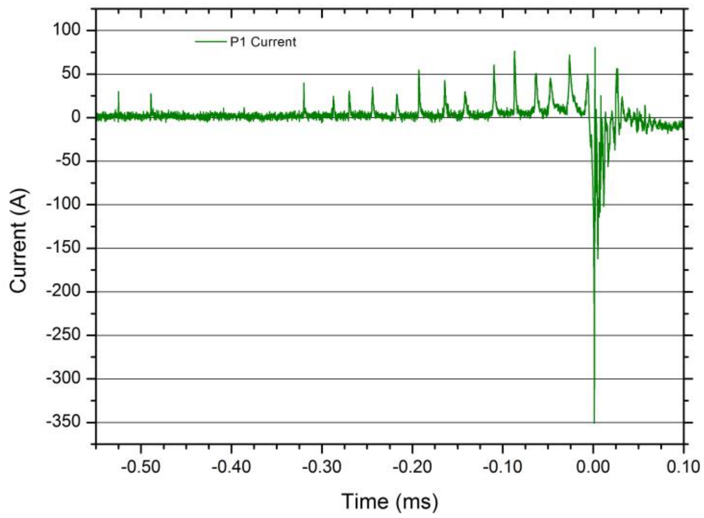

Fig. 6 – Current measurement of the UUL from P1 (leader number 1).

One of them (from building P2) connected to the downward leader. The identification and characterization of the UCL and UUL reported here can help not only the understanding of the attachment process but also the impact of these upward leaders in vulnerable equipment, in the ignition of flammable vapors and in injures caused to humans [3, 6]. The simultaneous measurements of current and electric-field with high-speed video images reveal that: a) multiple current pulses occur from the lightning rods during the approach of the negative downward leader; b) the current peaks of those leader pulses range from 10 A to 250 A; c) the amplitude of the current pulses increases with time; d) there is also a DC component of the leader current that increases with the approach of the descending leader; e) the electric field change at close distance reverses polarity when the upward leader pulses start; f) it changes abruptly with every pulse of current; g) the higher is the current pulse the higher is the electric field change; h) the electric field change is more influenced by the current pulses from the closer mast (at building P2); i) the electric field that was driving the propagation of the UULs collapses with the occurrence of the return stroke, and the current of the UUL reverses with the back flow of the positive charge being transported by the UUL.

The measurements show that the abrupt changes in the electric field are synchronized with the current pulses in upward leaders. The average values of time interval between current pulses from P1 and from P2 were identical, 24 microseconds, which is very close to the average interstep time interval found by [7] for negative cloud-to-ground stepped leaders (25 microseconds) in Arizona. This strongly suggests that the upward leaders are induced by the electric field change produced by the steps in the propagation of the negative downward leader.

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