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Characteristics of downward leaders in a cloud-to-ground lightning strike on a lightning rod

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ABSTRACT

A natural downward negative cloud-to-ground (CG) lightning was observed at a close distance of 370 m by using electric field change measurements and a high-speed camera at 5400 frames per second (fps). Two subsequent leader-return strokes of the lightning hit a lightning rod installed on the top of a seven-story building in Beijing city, while the grounding point for the stepped leader-first return stroke was 12 m away, on the roof of the building. The 2-D average speed of the downward stepped leader (L1) before the first return stroke (R1) was approximately 5.1×10^4 m/s during its propagation over the 306 m above the building, and those before the subsequent strokes (R2 and R3) ranged from 1.1×10^6 m/s to 2.2×10^6 m/s. An attempted leader (AL) occurred 201 ms after R1 and 10 ms before R2 reached approximately 99 m above the roof and failed to connect to the ground. The 2-D average speed of the AL was approximately 7.4×10^4 m/s. The luminosity at tip of the leader was brighter than the channel behind it. The leader inducing the R2 with an alteration of terminating point was a dart-stepped leader (DSL), which propagated through the channel of AL and continued to develop downward with new branches at about 17 m above the roof. The 2-D speed of the DSL at the bottom 99 m was 6.6×10^5 m/s. The average time interval between the stepped pulses of the DSL was approximately 10 μs, smaller than that of L1 with value of about 17 μs. The average step lengths of the DSL were approximately 6.6 m. The study shows that the stepped leader-first return stroke of lightning will not always hit the tip of a tall metal rod due to the significant branching property of the leader. However, under certain conditions, the subsequent return strokes may alter the grounding point to the tip of a tall metal rod. For the lightning rod, the protection against subsequent return strokes may be better than that against the first return stroke.

1. Introduction

The research concerning the leader propagation and attachment processes of natural lightning plays an important role in the lightning protection designs of common buildings and tall objects and hence, has led to widespread concern from international researchers (Zhang et al., 2015; Saba et al., 2016; Wang et al., 2016). A lightning rod with a good grounding condition is important for the lightning protection and disaster reduction of a building. The leader process and attachment process prior to return strokes are closely related to the physical mechanisms of lightning stroke (Wang et al., 2015; Lu et al., 2015). It is generally believed that the lightning stroke point has been determined at the beginning of the connection process. The damage to the objects hit by lightning directly is considerable. Therefore, it is necessary to understand the features of lightning leaders which occur prior to the attachment process and the possible connection between grounding points and lightning rods. Furthermore, it is also an important cognitive basis for the lightning protection designs of the Power Department, the Communication Department, and various kinds of buildings.

The process of lightning leader attachments to the ground or to grounded objects is one of the least understood and most poorly documented processes of cloud-to-ground (CG) discharge. With the development of optical detection technology in recent years, some progresses have been made (Wang et al., 2015; Lu et al., 2015; Jiang et al., 2015; Saba et al., 2016). The attachment process occurs for both the first and subsequent lightning strokes. For the first return stroke, the

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leader occurs in virgin air, while for the subsequent return stroke, the leader usually traces in the remnants of a previous channel. It is generally thought that a more pronounced attachment process occurs in the first return stroke than in the subsequent return strokes, likely because more potential energy has been accumulated during the period of the stepped-leader propagation (Rakov and Uman, 2003). Furthermore, due to the much faster propagation of the subsequent leaders along the pre-conditioned channel, the upward connecting leaders in the subsequent return stroke are not easy to be observed, and had hardly been imaged. Some subsequent strokes are initiated by dart-stepped leaders (DSLs) that exhibit pronounced stepping in the bottom portion of their channels. Only 14% of the subsequent strokes create new terminations, and approximately 20% of the new terminations were established by the second stroke (Rakov and Uman, 2003). The average speed of the DSL, which is related to the intervals between return strokes, varies between 0.5×10^6 m/s and 8×10^6 m/s (Schonland, 1956; Wang et al., 1999). In terms of the speeds of DSLs, many results have shown that the speed of DSLs gradually decrease when the DSLs get closer to the ground, but there is also a small set of results showing the opposite (Orville and Idone, 1982; Davis, 1999). The step lengths of DSLs are typically 10 m, and the time intervals between steps are approximately 10 μs (Schonland, 1956). The average time intervals between pulses prior to subsequent return strokes are shorter than that of the first return stroke (Krider et al., 1977). The downward dart leaders or DSLs may have significant impacts on the grounding behaviors of lightning, especially when these leaders break down virgin air and generate abundant branches during their downward propagation (Lu et al., 2012). The upward connecting leaders for the first return stroke were from tens of meters to hundreds of meters before the lightning grounding (Krider and Wetmore, 1987; Yokoyama et al., 1990; Lu et al., 2013; Qie et al., 2015). Most of the upward connecting leaders in the subsequent return strokes had lengths with small ranges of 10–30 m (Orville and Idone, 1982; Idone et al., 1984; Idone, 1990) based on the observations of the triggered lightning and tower-initiated lightning. Wang et al. (1999) found shorter junction heights of 4–11 m for subsequent return strokes based on their observations with their Automatic Lightning Progressing Feature Observation System. Recently, Wang et al. (2013) observed 14 return strokes induced by dart leaders or DSLs and found that the junction heights ranged from 7.2 m to 21.0 m. Several upward connecting leaders could be initiated from different high buildings when the downward negative step leader gets closer to the ground (Saba et al., 2016), but usually, only one upward connecting leader would win the competition.

In this paper, the propagation characteristics of the downward negative stepped leader (L1) before the first return stroke (R1), an attempted leader (AL) and DSL prior to the first subsequent return stroke (R2) are investigated based on high-speed video camera observations and the electric field change measurements of a lightning occurring at a close distance of 370 m. For this CG lightning flash, the subsequent strokes involved a grounding point at the lightning rod, differing from that of first return stroke on the roof of the building. The possible effects of the lightning rod and DSL on the lightning channel propagation and on the alteration of termination point are discussed. The observations and conclusions may provide some useful information for the study of the leader propagation and attachment processes of lightning striking common buildings and high objects, which is crucial for the improvement of lightning protection.

2. Instruments and data

The data were acquired using comprehensive observations of natural lightning in Beijing city, China, in 2010, and the special case presented here occurred at the local time of 20:13:48. The termination point of the lightning was at the top of a seven-story common building located a horizontal distance of 370 m from a high-speed video camera (Photron FASTCAM SA1), which was installed on the 9th floor of the 40# building of the Institute of Atmospheric Physics, Chinese Academy of Science. The optical images were obtained at a frame rate of 5400 frames per second (fps) and the exposure time is 185 μs. The 2D spatial resolution was 0.55 m per pixel. The fisheye lens focal length was 16 mm. The electric field changes were detected concurrently by fast and slow antennas. The bandwidths of the fast and slow antenna instruments were 5 MHz and 2 MHz, respectively, and their time constants were 0.1 ms and 6 s, respectively. The rise time of the slow antenna was about 0.2 μs, and was less than 0.1 μs for the fast antenna. The sampling rates were 5 MS/s (0.2 μs time resolution) and the record length was 1 s. The E-filed measurements by fast and slow antennas were stamped with GPS time, while the optical instrument was not synchronized with GPS. The sign convention of atmospheric electricity is used in the manuscript, with positive polarity being assigned to the field change due to the lowering of negative charge to ground or raising of positive charge upward from ground.

3. Analysis and results

3.1. General characteristics of the lightning

The electric field changes detected by the fast and slow antennas are shown in Fig. 1. The solid and dash-dot curves correspond to the electric field changes detected by the fast and slow antennas, respectively. The data of the electric field change was normalized (The maximum value of the measured electric field is defined as "1") and the values shown in figure are the relative values. The observed lightning was of negative polarity, with three return strokes occurring at about 194 ms, 406 ms and 479 ms (marked R1, R2 and R3), respectively. There is an obvious large pulse at 396 ms in Fig. 1, only 10 ms prior to R2. Combined with the high-speed camera observations, this pulse is recognized to be due to a downward attempted leader (marked as AL in Fig. 1) along the original discharge channel of R1, which almost reached the ground, but stopped at 99 m above the roof of the building. The leader inducing the R2 was a dart-stepped leader (marked as DSL in Fig. 1).

The main discharging channels of the three return strokes, as captured by the high-speed camera, are shown in Fig. 2. The channels of these three strokes are found to be the same in their higher parts. However, there were significant differences between the channel of R1 and those of the two subsequent strokes in their lower portions, i.e., approximately 17 m above the termination point of the roof of the building, as shown in the box in Fig. 2. The grounding points of the

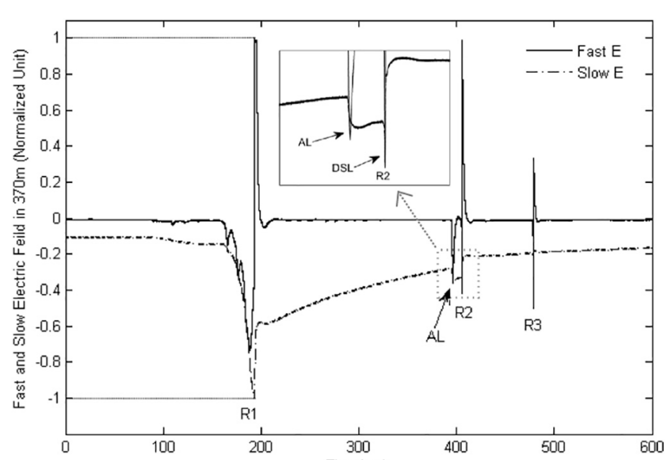

Fig. 1. The electric field changes detected by the fast and slow antennas with time. (The AL and DSL expanded view is shown in the box above the curve. The maximum value 9.835 V and 6.978 V corresponding to the strongest return stroke measured by the fast antenna and slow antenna of electric field change is the unit respectively, as shown in the midpoint line of the figure.)