High speed video observation of lightning attachment process and the associated leader behaviors

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ABSTRACT: Optical observations of natural lightning with high speed cameras (Phantom M310 and V711) were conducted during the Shandong Artificially Triggering Lightning Experiment (SHATLE) in the summer of 2013. Various features of lightning development were captured at operational speeds ranging from 10,000 fps up to 290,000 fps. A total of 37 flashes observed with relatively large field of vision were suitable for investigating the lightning attachment process and the associated leader behaviors. During the downward propagation, the stepped leader would develop several branches that compete to bridge the gap between cloud and ground. Generally, the branch with lower tip being closest to ground succeeded in the connection. In most cases, the leader branches that failed to reach the ground stopped its downward extension at instant of the attachment, indicating a transient drop of high potential difference between the leader branches and ground. The branch would be re-illuminated and then quickly extinguished (within 1 ms) as the return stroke wave passed the branching point and propagated down through the whole ungrounded branch. This lead to a single discharge channel with high current soon after the inception of the return stroke. In 5 cases, two grounding points were observed with time intervals of less than 0.4 ms. Being low enough of the secondary grounding branch (at the instant of the first attachment), and the sustained propagation of the associated upward connecting leader was found to be the possible reason for this phenomenon. In a few cases, some unconnected downward leader branches continued their extension for a short while after the return stroke, although such behavior was rarely observed, it may also be a potential mechanism of multiple grounding points in a same CG flash.

INTRODUCTION

The study of attachment process in cloud-to-ground (CG) lightning flashes is of critical importance for both the research of lightning physics and the design of lightning protection. Although the observations in early years had implied that the attachment process occurred when the upward connecting leader (from ground objects) was induced by and then connected with the approaching downward leader (Wagner and Hileman, 1958; Berger and Vogelsanger, 1966), the detail characteristics of this process were poorly understood for a long time, due to the relatively lack of direct optical observation with fine temporal and spatial resolution.

Based on photodiodes array imaging systems (ALPS in early years and LAPOS in recent years), Yokoyama et al. (1990) and Wang et al. (1999) conducted reliable observations of upward connecting leaders in tower lightning and triggered lightning, respectively. Wang et al. (1999) firstly documented the bidirectional development of return stroke from the junction point of the downward and upward leaders as they meet. Recently, Wang et al. (2013) further observed the speeds of the initial bidirectional propagation of return stroke in triggered lightning, which were in the magnitude of 10^8 m/s. As facilitated by the development of high speed camera technology, more and more visualized images of lightning channel were obtained and some of them were valuable for revealing the lightning attachment process. Baigi et al. (2009) captured the upward leaders in response to the dart or dart-stepped leaders in triggered lightning. Lu et al. (2013) obtained the speed variation of the downward and upward leaders as they get closing to each other, they found that downward leader may conduct more significant effect on upward leader than upward leader does in contrast. Some other observations found that a few CG flashes involved multiple grounding points as two or more downward leader branches almost simultaneously made connection with ground (Ballarotti et al., 2005; Qie and Kong, 2007). Stolzenburg et al. (2012; 2013) captured the so called "upward illumination" (UI) which occurred as a secondary connecting of downward leader branch to the ground within milliseconds after the main branch realizing the connection, and they considered a cutoff of the UI leader from the main leader.

In this paper, we preliminary analyzed the lightning attachment process and the associated leader behaviors on basis of the high speed camera observation.

OBSERVATION AND DATA

The images for analysis of this paper were captured by at the SHandong Artificially Triggering Lightning Experiment (SHATLE), during the summer of 2013. High-speed cameras of Phantom V711 and Phantom M310 were used, configured with Nikon 14 mm lens and 28 mm lens, respectively. The Phantom V711 was generally operated at the frame rate of 12 kfps with the spatial resolution of 720×720 pixels, while for some particular cases, much faster frame rates were set, such as 180 kfps (480×64 pixels), or even 290 kfps (368×48 pixels). The Phantom M310 was always operated at the frame rate of 10 kfps with the spatial resolution of 640×480 pixels. Besides the optical data, the electric fields detected by the fast and slow antennas with bandwidths of 2 MHz and 5 MHz, respectively, and low-frequency (30-300 kHz) magnetic fields measured by the crossed magnetic induction coils, were also documented. A short-base line very high-frequency (VHF) lightning location system based on time-difference of arrival (TDOA) provided the radiation source location and 2-D channel evolution with high time resolution.

ANALYSIS AND RESULTS

Fig. 1 shows the images of the attachment and resultant return stroke of lightning 20130812135608 with multiple grounding points. The upward connecting leader initiated from ground object was clearly imaged in Fig. 1b, with the expanded view in Fig. 1a. As shown in the figure, the upward connecting leader had connected to the downward leader, indicative of the inception of the return stroke at this instant or soon after this instant. It is clear that the upward leader exhibited considerably weaker luminosity than the downward leader.

During the downward propagation, the stepped leader would develop several branches that compete to bridge the gap between cloud and ground. Generally, the branch with lower tip being closest to ground would succeed in the connection. The lightning 20130812135608 exhibited two main branches as the downward leader was approaching the ground. It is interesting that the left branch which involved longer distance from the lower tip to the ground firstly realized the connection, being different from what we generally observed. As in Fig. 1b, no evident upward leader was captured below the right branch at the instant of 0 ms. This may be partly due to that the left branch showed more intensive luminosity which possibly indicated larger charge density in the channel, and hence, a stronger electric field below the channel tip for inducing the upward connecting leader.

In Fig. 1c, the image was overexposed due to the occurrence of the return stroke, fortunately the lightning channel could still be recognized. As compared to Fig. 1b, the downward leader did not extend any further, which was different from the leader development before it connected to the ground. In Fig. 1d, the image was even more overexposed, and it is somehow unexpectedly that the right branch also realized the connection with the ground, even though it did not exhibit channel extension in the preceding two frames. In the following frames, the left grounded channel exhibited more intensive luminosity and slower luminous decay than the right channel, indicative of a stronger discharge current with longer duration that flowed through the firstly grounded channel.

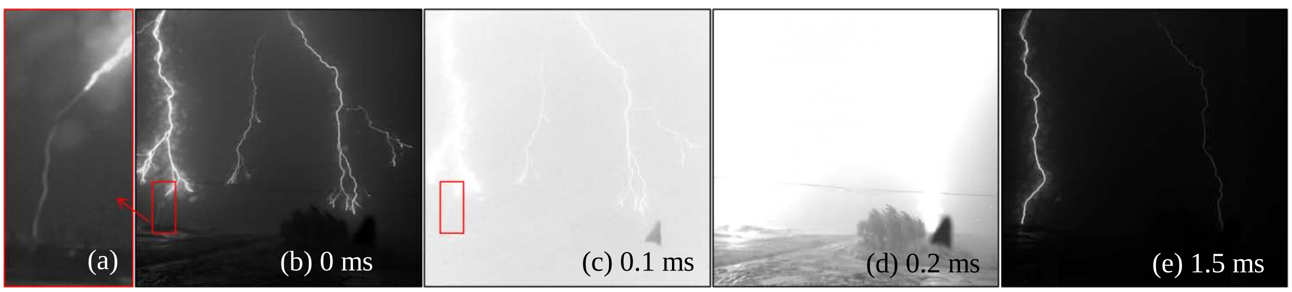

Fig. 1 Images of lightning 20130812135608, captured by V711 with a frame rate of 10 000 fps: (a) expanded view of the upward connecting leader and its connection to the downward leader tip, (b) the frame showing the connection of the upward leader and the downward leader, (c) the frame at 0.1 ms, (d) the at 0.2 ms, (e) the frame at 1.5 ms.

Since the return stroke propagated in very quick speed and resulted in very intensive luminosity of the channel, the images with frame rate of tens kfps could hardly reveal the channel evolution just after the return stroke, due to the long distance propagation of return stroke during a frame interval and the overexposure. In the 2013 summer observation, we fortunately captured a lightning flash 20130812115956 at a very fast frame rate of 180 kfps (5.56 μs resolution). The grounded channel just being outside the field of view of the camera (the right side), so the overexposure was avoided.

As judged by the luminous intensity of the images, the attachment process and the initiation of the return stroke occurred at a instant between frame 1 and frame 2 (with a significant enhancement of the background luminosity). By comparing frame 2 with frame 1, the channel branch inside the field of view of the camera stopped its downward extension due to the occurrence of the return stroke, similar to Fig. 1b and c showing no extension of the leader branch. This indicates a transient drop of the high potential difference between the leader branches and the ground, making the downward leader development unsustainable.

In frame 3, a channel branch was re-illuminated, suggesting that the upward electromagnetic wave of return stroke passed a branching point of the leader channel, and then propagated through this branch. Then the return stroke wave passed a higher branching point and the leader branch shown in frame 1 and 2 was re-illuminated. Frame 4 and 5 evidently indicated that in the leader branch which failed in connecting to the ground, the return stroke wave developed from the branching point and propagated downward, till it passed through the whole branch.

After the ungrounded branch was re-illuminated by the return stroke, it would quickly extinguished, As in Fig. 2, the frame 9, 17 and 31 exhibited significant decay of the channel luminosity. Actually, it was only 0.17 ms after the attachment process at the instant of frame 31. Due to such a branch decay, the CG flash generally exhibited a single main discharge channel soon after the inception of the return stroke.

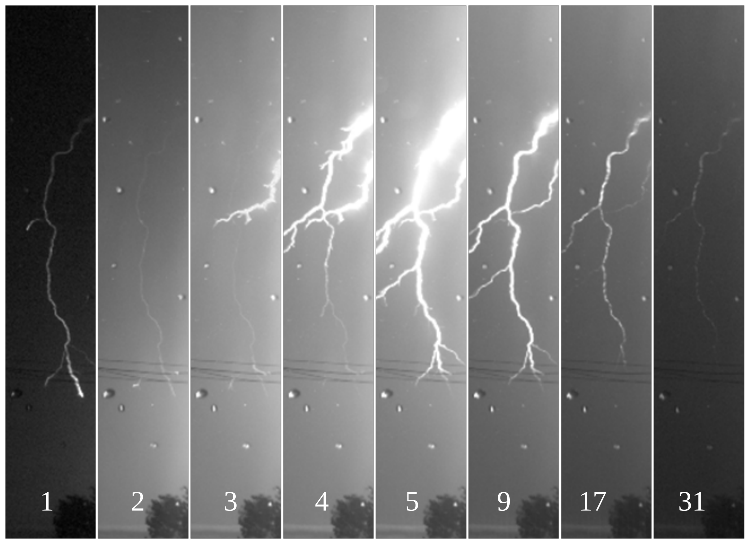

Fig. 2 Images of lightning 20130812115956, captured by V711 with a frame rate of 180 kfps (5.56 μs resolution). Note that the leader branch connecting to the ground was outside the field of view of the camera. The images showed the luminous evolution of the leader branch that failed to connect to ground, as the return stroke occurred.

In most cases of our observation, those ungrounded leader branches stopped their extension at the instant of the attachment process (or the initiation of the return stroke). For a few cases however, the leader branch would further developed for a little while, as illustrated in Fig. 3.

Due to a relatively long distance from the lightning to the camera, the upper channel of the lightning could not be well imaged in Fig. 3a. No upward connecting leader was captured, possibly due to that the upward leader did not yet initiate at the instant of Fig. 3a, or it exhibited too weak luminosity to be imaged. The right channel realized the connection with the ground (between 0 ms and 0.1 ms). It is clear in Fig. 3b, c, d and e that the lowest tip of the left branch continued to get closer to the ground during a period of 4 frames (0.3~0.4 ms) after the inception of the return stroke, although it performed as a luminous segment with a decreasing size in Fig. 3c, d and e. The vertical propagation was estimated to be tens meters. As also shown in Fig. 3 c, d and e, the downward extension of the left branch tip seemed to be cut off from the channel above.

DISCUSSION AND CONCLUSION

The stepped leader breaking down virgin air branched significantly during its downward development, and there is a competition between the leader branches in connecting to the ground. It was generally observed that the branch with lower tip being closest to ground would succeeded in the connection, and the ungrounded branches stopped their downward extension at the instant of the return stroke inception, due to the transient drop of high potential difference between the leader branches and ground. So most of the CG flashes exhibited a single discharge channel, and in this study, it accounted for 86.5 % (32 of 37).

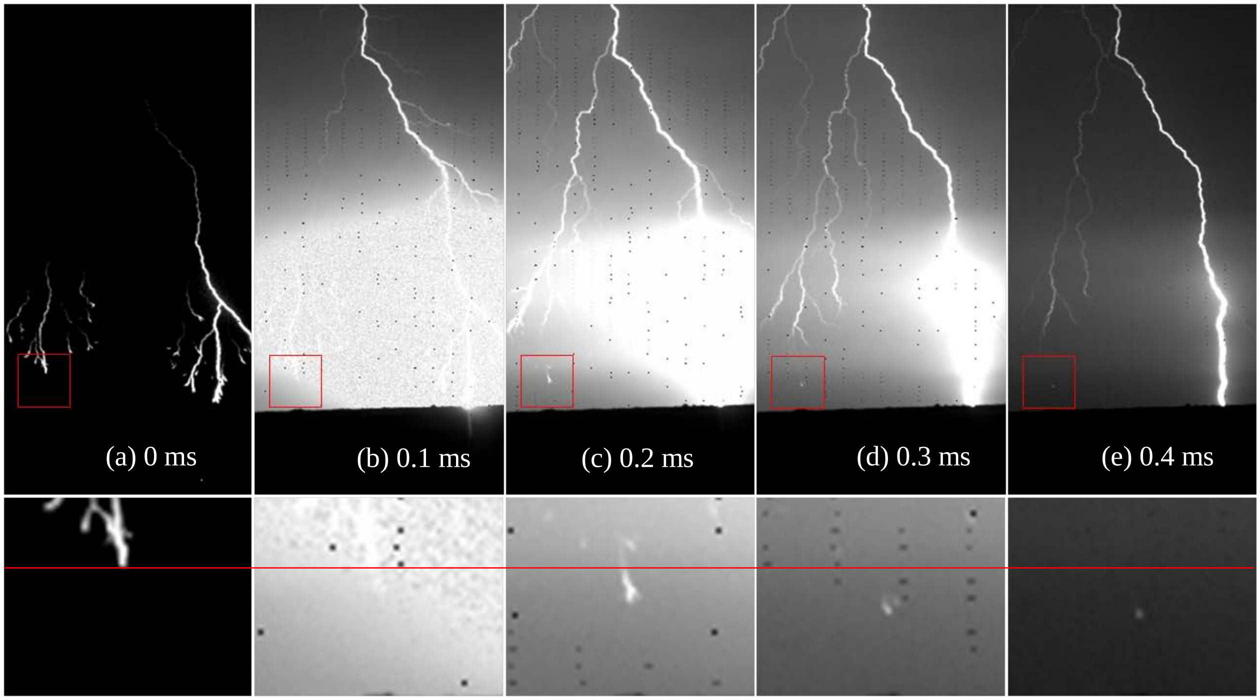

Fig. 3 Images of lightning 20130812130719, captured by V711 with a frame rate of 10 000 fps. Note that the bottom panel shows the expanded view of the area in the red box of the top panel.

Although most of the ungrounded branches stopped developing as the return stroke occurred, we also observed a few cases showing a continuous extension after the return stroke. It seemed that these leader extension were not significantly influenced by the return stroke, owing to a possible current cut off. This is somehow similar to the so called UI-leader as observed by Stolzenburg et al. (2012; 2013), although in their observation, the "cut off" occurred at the branching point from the main channel. Their UI-leader would induced a so called UI-stroke that exhibited as a secondary grounding soon after the occurrence of the main return stroke as the main channel connected to the ground.

Five cases in our observation exhibited two concurrent grounding points. In Fig. 1, the right branch was very close to the ground at the instant of the left branch inducing the return stroke. Since the stop of the right branch development was evident in Fig. 2c, it is reasonable that the sustained propagation of the upward connecting leader at the right side and its connecting to the right branch was the reason for this secondary grounding. As combining the analysis of Fig. 3 and the comparison with the observation by Stolzenburg et al. (2012; 2013), we suggest two possible scenarios leading to the multiple grounding of the CG flashes. The first one is that when the main channel induced the return stroke, the secondary grounding branch should be low enough with a close distance to the ground, and the associated upward connecting leader sustained propagated to realized the connection. The second one is that the secondary grounding branch continued to propagate downward (owing to a possible current cut off) after the return stroke inception, and it finally connected to the ground.

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