Characteristics of lightning leader propagation and ground attachment

Rubin Jiang1,2, Xiushu Qie1,2, Zhichao Wang1, Hongbo Zhang1, Gaopeng Lu1,2, Zhuling Sun1, Mingyuan Liu1, and Xun Li3

1Key Laboratory of Middle Atmosphere and Global Environment Observation, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China, 2Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Nanjing University of Information Science and Technology, Nanjing, China, 3College of Meteorological Observation, Chengdu University of Information Technology, Chengdu, China

Abstract The grounding process and the associated leader behavior were analyzed by using high-speed video record and time-correlated electric field change for 37 natural negative cloud-to-ground flashes. Weak luminous grounded channel was recognized below the downward leader tip in the frame preceding the return stroke, which is inferred as upward connecting leader considering the physical process of lightning attachment, though not directly confirmed by sequential frames. For stepped leader-first return strokes, the upward connecting leaders tend to be induced by those downward leader branches with brighter luminosity and lower channel tip above ground, and they may accomplish the attachment with great possibility. The upward connecting leaders for 2 out of 61 leader-subsequent stroke sequences were captured in the frame prior to the return stroke, exhibiting relatively long channel lengths of 340 m and 105 m, respectively. The inducing downward subsequent leaders were of the chaotic type characterized by irregular electric field pulse train with duration of 0.2–0.3 ms. The transient drop of the high potential difference between stepped leader system and ground when the attachment occurred would macroscopically terminate the propagation of those ungrounded branches while would not effectively prevent the development of the existing space stem systems in the low-conductivity streamer zone apart from the leader tip. When the ungrounded branches are of poor connection with the main stroke channel, their further propagation toward ground would be feasible. These two factors may contribute to the occurrence of multiple grounding within the same leader-return stroke sequence.

1. Introduction

The attachment process of cloud-to-ground (CG) lightning flashes is an important issue both in the study of lightning physics and lightning protection design because it determines the ground striking point through which the severe damaging current flows. It is generally considered that the attachment process starts with the downward leader (as it gets close enough to the ground or the grounded objects) inducing the upward connecting leader with opposite polarity from ground. Both the stepped leader breaking down virgin air and the subsequent leader tracing through the preconditioned channel can trigger upward connecting leader. The first return stroke is generally considered to involve more pronounced attachment process than the subsequent return stroke, probably due to a larger electric potential of the stepped leader [Rakov and Uman, 2003]. The upward connecting leaders before first return stroke were reported to have propagated tens of meters (sometimes up to hundreds of meters) before getting contact with the downward leader [Krider and Wetmore, 1987; Yokoyama et al., 1990; Lu et al., 2013; Tran et al., 2014; Qie et al., 2015]. While based on the observation of triggered lightning and tower-initiated lightning, most of the observed upward connecting leaders in subsequent return strokes were found within a small length range of 10–30 m [Orville and Idone, 1982; Idone et al., 1984; Idone, 1990] and sometimes even shorter [Wang et al., 1999, 2013].

The characteristics of the downward leader propagation may have a significant impact on the grounding behavior of lightning, especially considering that those leaders breaking down virgin air would generate abundant branches during their downward development. Lu et al. [2012] found that as the downward negative stepped leader gets close to the ground, several upward connecting leaders could be initiated from different high buildings, most of which were aborted without connecting to the downward leader branches. They further analyzed the speed variations of those downward and upward leaders involved
in the attachment process and found that the downward leader may exert a more significant effect on upward leader than the upward leader does in contrast [Lu et al., 2013]. Before the first return stroke, the branches of the downward leader can be regarded as competing branches for first accomplishing the attachment [Stolzenburg et al., 2013], which eventually determines the grounding point of flash. Meanwhile, this may also be influenced by the competing upward leaders from grounded objects. Those objects with different heights upon the surrounding terrain would be subject to varying electric field threshold to initiate upward connecting leaders.

Due to the branching of downward leader and the possible multiple upward connecting leaders from various ground objects, some cloud-to-ground lightning flashes were found to involve multiple grounding points when two or more downward leader branches achieved connection with their corresponding upward leaders [Thottappillil et al., 1992; Ballarotti et al., 2005; Qie and Kong, 2007; Kong et al., 2009]. These CG flashes exhibited multiple luminous grounding channels in the optical record and sequential peaks with very short time interval (several tens of microseconds in general) in the electric field measurement [Kong et al., 2009]. More recently, Stolzenburg et al. [2012, 2013] defined a kind of “upward illumination” (UI) stroke on the basis of high-speed video observations. Such UI stroke exhibited as a secondary grounding by a downward leader branch which was cut off from the main leader channel with normal return stroke propagating though, after the main leader channel first realized the attachment with ground. Since the UI leader develops as one of the branches of the main leader channel through which the main return stroke propagates, it is reasonable to consider the flashes with UI strokes as multigrounding flashes. Stolzenburg et al. [2013] found an average time interval of 1.25 ms between the UI stroke and the main return stroke. A pronounced feature of the UI strokes is that they could hardly propagate sufficiently high to connect into the main stroke channel.

In this paper, the characteristics of leader propagation and the associated grounding behavior were analyzed, mainly on the basis of high-speed video camera observation and the electric field change measurements. Weak luminous grounded channel below the downward leader tip (whether it involved dark gap from or had been connected with the downward leader) was imaged for both the first and subsequent leader-return strokes. It is inferred as upward connecting leader by rationally considering the physical process of lightning attachment. Characteristics of the upward connecting leaders and their dependence on the downward leaders were analyzed in detail. The multiple grounding due to an identical stepped leader system with successive attachments was also studied, with the physical mechanism carefully investigated.

2. Observation and Data

The high-speed video images analyzed in this study were captured at the Shandong Artificially Triggering Lightning Experiment during summer of 2013. Two digital high-speed cameras were used to capture the luminous evolution of both triggered lightning and natural lightning. The first was a Phantom V711 equipped with a Nikon 14 mm lens at f/2.8. The second was a Phantom M310 with a Nikon 28 mm lens at f/1.8. During different thunderstorms, the V711 camera was operated at frame rates ranging between 10 and 220 kfps (kilo frames per second), and images captured at frame rates of 10 kfps, 12 kfps, and 180 kfps, with spatial resolutions of 800 × 800 pixels, 720 × 720 pixels, and 64 × 480 pixels, respectively, were used for the analysis of this paper. The Phantom M310 was always operated at the frame rates of 10 kfps with spatial resolution of 640 × 480 pixels. The video images captured by both cameras were stamped with GPS time for a comparison with other complementary measurements. In addition to the optical data, electric field changes (measured by fast and slow antennas with bandwidths of 1 MHz and 2 MHz and time constants of 0.1 ms and 0.2 s, respectively), low-frequency (30–300 kHz) magnetic fields, were also obtained.

A total of 37 natural CG flashes, observed with relatively large field of view in which the grounding point (or points) and main branches of the leader were imaged, were used for the analysis. Twenty eight of them were located by the lightning location network that was set up and operated by the State Grid Corporation of China. The lightning location data were used to estimate the horizontal distance of these flashes from the observation site. Much more flashes were captured at 180 kfps with small field of view. They were just used for supporting the analysis and not included in the sample number of 37. All flashes analyzed in this paper were of negative polarity.
3. Analysis and Results

3.1. Upward Connecting Leader

Figure 1 shows the images of the first return stroke of flash A (20130812135608): (a–d) sequential frames with the upward connecting leader imaged in frame b, (b*) expanded view on the upward connecting leader in response to the left main branch of the downward stepped leader, and (e) the frame at 1.5 ms. The images were captured by the V711 camera operated at frame rate of 10 kfps with exposure time of 40 μs.

Figure 1. Images of the stepped leader-first return stroke of flash A (20130812135608): (a–d) sequential frames with the upward connecting leader imaged in frame b, (b*) expanded view on the upward connecting leader in response to the left main branch of the downward stepped leader, and (e) the frame at 1.5 ms. The images were captured by the V711 camera operated at frame rate of 10 kfps with exposure time of 40 μs.

3.1. Upward Connecting Leader

Figure 1 shows the images of the first return stroke of flash A (20130812135608). Here the marked number in the brackets means that the flash occurred at 13:56:08 (UTC), 12 August 2013. The lightning location network failed to locate this flash, so the distance is not exactly known. As shown in the figure, the negative stepped leader of the flash exhibited three main channel branches with many subbranches at their lower portion before the attachment process. The left and the right main branches were closer to ground than the middle one. In Figure 1b, a luminous grounded channel below the left branch was captured, as shown in Figure 1b* with an expanded view. We infer the weak luminous grounded channel herein, and also in Figures 2–4, to be representative of upward positive connecting leader by considering the characteristics of the channel and the physical process of lightning attachment as reviewed in the Introduction. Although most of the imaged channels below the downward leader were found in only one frame with the direction not clearly determined, it is found that all the imaged weak channels were connected with the ground or the ground objects, whether they involved dark gap from the downward leader or not. And in our data set, we do find a case exhibiting "upward" direction, as shown in Figure 2. In a recent publication by Tran and Rakov [2015], similar channels termed as faintly luminous formations (FLFs) were studied, all of which were also grounded and

Figure 2. Sequential frames of the downward stepped leader before the first return stroke of flash-B (20130812141337). The images were captured by the M310 camera operated at frame rate of 10 kfps with exposure time of 90 μs. Those marked with asterisk are the expanded view of the red box area.
some exhibited decreasing luminosity with height. By additionally excluding the possibility of being the downward extending negative corona streamer of stepped leaders which showed shorter length scale and different optical characteristics, these FLFs were confirmed with high certainty to develop upward. Nevertheless, for these upward channels with weak luminosity, Tran and Rakov [2015] inferred them as mostly consisted of relatively low-conductivity streamers, and in this paper, we simply consider them as upward connecting leaders. Actually, upward positive leaders (UPLs) were studied based on the rocket-triggered lightning. Although the UPLs during the initial stage of triggered lightning and the upward connecting leader during the lightning attachment are not the same, with different inducing factors and different consequential process, they should still share some similarity, for both are of positive polarity and both propagate upward. It is found that the UPLs of triggered lightning are very weak in the initial stage, and the imaged channels are quite faint until adequate length (generally tens of meters), in spite of which Biagi et al. [2011] and Jiang et al. [2013] still termed them as leaders, taking into account the channel extension (determined with sequential images) and the measured current in the channel base as related to the leader formation. In addition, since the grounded channel in this paper was imaged in only one frame, it possibly had not yet been initiated in the previous frame. Then, being less exposed may also lead to the weak luminosity of the channel. Based on the above consideration, we treat the weak luminous grounded channels as upward connecting leaders, and by admitting the validity of this, the following analysis are conducted.

Figure 3. The images of flash-C (20130812131307): (a–c) three sequential frames of stepped leader-first return stroke, (d–f) three sequential frames of subsequent leader-fourth return stroke, and (g–i) three sequential frames of subsequent leader-fifth return stroke. The red lines indicate the ground level, the yellow lines indicate the leader tips, and the blue line indicates the altitude that the stepped leader had propagated to when it was first imaged with sufficient luminosity at 2.1 ms before return stroke. The images were captured by the M310 camera operated at frame rate of 10 kfps with exposure time of 90 μs.

As shown in Figure 1b*, the downward leader branch at the left had been connected with the corresponding upward leader. Apparently, there was a conspicuous difference between the luminosities of the downward leader branch and the corresponding upward connecting leader that the upward leader was considerably weaker.
This may be due to the different luminous properties of positive and negative leaders in different development stages. Since the upward positive connecting leader was just initiated, the line charge density and the current flowing in the channel should be considerably smaller than that of the downward negative leader. Meanwhile, as discussed above, the initiation of the connecting leader was between Figures 1a and 1b; it had been exposed for less time as compared to the downward stepped leader. By comparing the left and right downward branches in Figure 1b, it is found that the lower tip of the left branch with visible induced upward connecting leader was actually higher than the right branch, while at this instant, no evident upward connecting leader can be recognized below the right branch or it is possible that the upward connecting leader due to the right branch was too dim to be imaged. This is not the same with the typical observation for the CG flashes striking the flat terrain that the downward leader branch with lowest tip would generally succeed in the attachment process by connecting with the corresponding upward leader. Here an elaborated comparison confirms that the left branch involved more intense luminosity than the right branch, indicative of a more vigorous development of the left branch with larger line charge density in the channel, which reasonably leads to a stronger electric field below the channel tip, being more conducive to induce the upward connecting leader. Based on the current and the associated optical measurements on the tower lightning, Diendorfer et al. (2003) found a positive correlation between the discharge current and the channel brightness. For leader-return stroke sequences, it was also found that the return strokes with stronger optical emission would involve larger electromagnetic field magnitude and current peak (Jordan and Uman, 1983; Idone and Orville, 1985). Nevertheless, it should be noted that the inference above was based on the assumption of similar distance of the imaged channels to the camera. There is an uncertainty on the 3-D structure of the discharge channels, and it is not sure which channel was nearer to the camera. Meanwhile, being shorter or longer exposed in the frame may also lead to different brightness of the channel branches.

Figure 2 shows images of the first return stroke of flash-B (20130812141337). Within the field of view of the camera, this flash developed into two main channel branches before the attachment process, and both branches contained several subbranches. It is clear that the left branch of the downward stepped leader exhibited more powerful luminosity than the right one. However, the first recognizable upward connecting leader was initiated in response to the approaching of the right branch, from a 45 m telecommunication tower that is about 1130 m from the observation site. The higher grounded metal objects or buildings may involve more pronounced electric field distortion under high electric potential of the downward leader (Zhang et al., 2014), which lead to an earlier initiation of the upward connecting leader. Figures 2a–2c show...
the expanded view on this tower-initiated upward connecting leader with detectable luminosity in three sequential images. In Figure 2a*, the upward leader channel was not clearly recognized, except for a luminous segment at about 20 m above the tower tip. In the following images (Figures 2b* and 2c*), the luminous channel of the upward leader had reached altitudes of more than 40 m and 50 m, respectively, with the channel luminosity being less intensive than the corresponding downward leader branch. By comparing these three images, it is inferred that at the moment of 0 ms, the upward leader had already been induced. The luminous segment in Figure 2a* indicates a relatively bright luminosity in the upper advancing tip of the upward leader. However, the luminosity of the channel between the upper segment and the tower tip was below the lower limit of detectable luminosity of the camera, probably because the upward leader was in the initial stage with weak discharge intensity.

Although this upward leader from the tower first exhibited detectable luminosity, and it had propagated into more than 50 m length in Figure 2c*, the attachment of the flash was not accomplished by this upward leader and its corresponding downward leader branch. As shown in Figure 2c, another upward leader in response to the left branch of the downward leader was imaged and they had been connected with each other. If roughly ignored the 3-D uncertainty and assume that this grounding point and the telecommunication tower involve similar distance to the camera, then the junction height for the attachment process is estimated to be about 40 m. This upward connecting leader from the ground terrain exhibited much weaker luminosity than the tower-initiated upward leader, due to a shorter exposure time of the channel or probably because of the weaker discharge intensity as well. The reasons for the upward leader from the tower being an aborted one may be attributed to that the right main leader branch involved a relatively large horizontal distance from the tower, while the subbranch (marked by the blue triangle in Figures 2a and 2b) that the upward leader actually responded to was weakened and eventually extinguished as the connecting leader propagated upward. In Figure 2c, the lower tip of the right main channel had even been below the tower top. On the other hand, regardless of the 3-D uncertainty, the left main leader branch was much stronger than the right one, as indicated by the channel luminosity. In the following frames after Figure 2c, the return stroke occurred, traversing through the left downward leader branch that had connected with the corresponding upward leader.

Figure 3 shows images of the stepped leader prior to the first return stroke and the subsequent leaders prior to the fourth and fifth return strokes, for flash-C (20130812131307). This flash was located by the lightning location network, and the grounding point was 11.3 km away from the observation site. At this distance, a single pixel of the captured image represents a 2-D space length of about 8.1 m. As in Figures 3a and 3b, the downward stepped leader developed into several branches as approaching the ground and no evident upward connecting leader from ground was imaged. The return stroke occurred in the following frame and led to serious overexposure, making the discharge channel unrecognizable. It is possible that the upward connecting leader had not yet been induced in response to the downward stepped leader at the instant of Figure 3b, or considering a relatively long distance from the flash to the camera, the upward leader channel was too faint to be imaged because of the attenuation of light. Nevertheless, since the lower tip of the downward leader was about 90 m above ground in Figure 3b, the full height of the upward leader when the attachment occurred should definitely be lower than this value.

In general, the attachment process of the subsequent leader-return stroke is less pronounced than that of the stepped leader-first return stroke [Rakov and Uman, 2003]. Furthermore, owing to a much faster propagation of the subsequent leader developing through the channel remnants of the prior return stroke, the upward connecting leader in the subsequent return stroke could hardly be imaged by our cameras with the current operation setting. It is a little surprised that for flash-C, the upward connecting leader in response to the subsequent leader which induced the fifth return stroke was imaged (as shown in Figure 3h), although no evident upward leader was captured in the images of the first return stroke. At the instant of Figure 3h, the lower tip of the downward dart leader was about 490 m above ground, and correspondingly, the upward connecting leader had propagated to 340 m height. For the other three subsequent return strokes of this flash, as the downward leader got close to the ground, no upward leader was captured, similar to most of the cases we documented. As an example, Figures 3d–3f give the images of the fourth leader-subsequent return stroke of flash-C. The interstroke interval between the fourth and fifth strokes was 124.7 ms, and the grounded luminous channel of the fourth return stroke lasted for 4.5 ms as determined by the sequential frames. By comparing Figures 3h and 3b, the junction height for the attachment process of the fifth subsequent return stroke was much higher than that of the first return stroke. Among the documented attachment
process of subsequent return strokes by different authors, the length of the induced upward connecting leader was generally on the order of 10 m or even less \cite{Rakov_and_Uman_2003}. Based on the streak-photographic observation on rocket-triggered lightning with dart (or dart-stepped) leader-return strokes, \cite{Idone1984} inferred two upward connecting leader lengths of 20 and 30 m. \cite{Wang1999} reported the junction heights of within 4–11 m, captured by their Automatic Lightning Progressing Feature Observation System. Recently, by using an improved observation system Lightning Attachment Process Observation System, \cite{Wang2013} observed 14 return strokes induced by dart or dart-stepped leaders in four triggered lightning flashes, and the junction heights ranged from 7.2 ± 1.4 to 21.0 ± 4.6 m. As compare to these results, the imaged upward leader of subsequent return stroke in flash-C is extremely long.

By carefully inspecting all the high-speed video images, only two upward connecting leaders for a total of 61 subsequent leader-return stroke sequences were captured. The other case was the eighth stroke of the flash-B, of which the second return stroke was induced by a newly developed stepped leader, with grounding point different from that of the first return stroke as shown in Figure 2. The frame of the stepped leader just prior to the second return stroke is shown in Figure 4a. The lightning location network provided a 960 m distance from this grounding point to the camera (0.68 m/pixel at such distance). The third to eighth return strokes of this flash traced through the grounded channel of the second return stroke. As shown in Figures 4b and 4c, the subsequent leader had propagated down to 154 m height in the frame prior to the return stroke, while the upward connecting leader reached an altitude of about 105 m. The junction height for his subsequent return stroke was also higher than that for the stepped leader-return stroke. Although the upward connecting leader was not evidently captured in Figure 4a, the stepped leader breaking down virgin air had propagated down to about 52 m above ground, indicating that the corresponding junction height should be lower than this value.

Figure 5 shows the electric field change waveforms of the stepped leader-first return stroke, fourth and fifth subsequent leader-return strokes for the flash-C, as detected by the fast antenna. It is clear that the electric field peak of the fifth subsequent return stroke was larger (about 1.5 times) than the first return stroke. Actually, the fifth return stroke involved the largest electric field peak among all the return strokes of this flash. This may be the reason for capturing upward leader with relatively long development length in response to subsequent leader rather than stepped leader. As shown in Figure 5a, the electric field exhibited

![Figure 5: The electric field changes for flash-C, corresponding to the frames in Figure 3: (a) the stepped leader-first return stroke, (b) the subsequent leader-fourth return stroke, and (c) subsequent leader-fifth return stroke. The field was detected by the fast antenna with time constant of 0.1 ms, at a distance of 11.3 km from the flash. The rectangles indicate three sequential frames, with the black representative of the frame in Figure 3g, the yellow representative of the frame in Figure 3h, and the white representative of the frame in Figure 3i.](image-url)
regular pulsed waveform before the return stroke, which is typical for the stepped development of negative downward leader breaking down virgin air. The duration of the pulsed electric field waveform are not well recognized, for the pulses occurring several milliseconds before the return stroke (or earlier) could hardly be identified from the background noise. In Figure 5c, irregular pulses were found preceding the return stroke, with a duration of 0.25 ms for the pulse train. Such irregular pulsed waveform was not the same as the electric field observation for the common subsequent leaders termed as dart leaders, as an example in Figure 5b; no distinct pulse was recognized prior to the return stroke. Due to the chaotic behavior of the pulses with varying amplitudes, widths, and separations, this kind of subsequent leader was generally termed as chaotic leader [Weidman, 1982; Willett et al., 1990; Gomes et al., 2004] or chaotic dart leader [Hill et al., 2012]. We found that for the other cases of subsequent leader with imaged upward connecting leader, the electric field waveform was also chaotically pulsed, with the pulses train duration of 0.30 ms. It seems that being chaotic leader rather than ordinary dart leader may be conducive to induce more pronounced upward connecting leader for the attachment process of subsequent return strokes. Hill et al. [2012] observed that in triggered lightning, when an upward connecting leader with length of 11.5 m was imaged immediately prior to the return stroke by their high-speed camera operated at 300 kfps, the downward leader was also of the chaotic type, with a 25 m streamer zone below the chaotic leader tip. Rakov and Uman [1990] found that the chaotic leaders characterized by irregular pulses were usually associated with those larger subsequent return strokes, which were comparable to the return strokes induced by stepped or dart-stepped leaders. Mäkelä et al. [2007] and Lan et al. [2011] reported that the high-frequency radiation emitted from the chaotic leaders were much more intensive than that from the normal subsequent leaders. Further investigation indicated that the pulse train duration of the chaotic leader corresponded to its dart phase propagation [Lan et al., 2011; Hill et al., 2012], with developing speed on the order of $10^7$ m/s. Nevertheless, we should also note that in our data set, some cases were of the type with chaotic leader preceding the subsequent return stroke, while no upward connecting leader was captured. For the eighth return stroke of flash-B and the fifth return stroke of flash-C in this paper, only one frame with the luminous chaotic leader channel was imaged. By comparing Figure 3h with Figure 3g, and considering the frame resolution, a quick propagation speed of the downward leader was confirmed, with lower estimation of $2 \times 10^7$ m/s. As indicated in Figure 5c, three sequential frames are time aligned to the electric field waveform (note that we had conducted coordination by comparing optical and field data of different return strokes, and the time instants of the frames are within the period indicated by the rectangles). In the frame before the upward connecting leader as indicated by the black rectangle, no luminous channel was imaged within the field of view of the camera, while the irregular pulses had emerged; it seems that the upward leader did not contribute in the chaotic behavior of E-field waveform preceding the return stroke.

### 3.2. Multiple Grounding

For flash-A (20130812135608), only one upward leader was imaged, in response to the left main branch of the downward stepped leader as shown in Figure 1b. The following image was significantly overexposed as shown in Figure 1c, indicating that the flash had been in the return stroke phase. It is somehow unexpected that the right downward leader branch also made connection with ground in the next frame, leading to the occurrence of a multiple grounding flash.

Figure 6 shows the electric field changes for this stepped leader-multiple grounding return stroke, as detected by the slow antenna. Due to a close distance from the flash to the observation site, the electric field changes exhibited asymmetry V-shaped waveform, with the slow negative-going change representing the downward propagation of the stepped leader from cloud to ground and the abrupt positive-going change representing the return stroke which quickly neutralized the negative charge deposited in the leader channel. By comparing the sequential frames in Figure 1, it can be determined that the first grounding at the left branch (indicating a transform from the leader stage to return stroke stage) occurred before the ending instant of the frame exposure of Figure 1c, while the second grounding at the right branch occurred thereafter. In the expanded view of the electric field changes for the return stroke, two inflection points were recognized, which should be associated with the instants of the grounding for the above two leader branches, as indicated in Figure 6b. So the time interval between these successive two groundings within a return stroke process was 10 μs, much shorter than the time resolution of 100 μs for the sequential images. Based on the above analysis, the image frames and the E-field measurements are further synchronized and
the frame-taken instants (ending instant of the frame exposure) were determined to be within the period indicated by the rectangles in Figure 6b. As shown in the figure, it is a very short time from the instant of the first grounding to the ending instant of the frame exposure of Figure 1c. This means that the first grounding in the left branch exposed for quite a short time in Figure 1c.

For flash-A, no luminous upward leader channel was imaged in response to the right branch of the downward stepped leader through which the second grounding occurred. Meanwhile, this downward leader branch did not exhibit recognizable change in shape after the occurrence of the first grounding. It is wondered why such a second grounding occurred. Actually, the multiple grounding within a stepped leader-return stroke process had been reported by different authors [Thottappillil et al., 1992; Rakov and Uman, 1994; Parker and Krider, 2003; Qie and Kong, 2007; Kong et al., 2009; Stolzenburg et al., 2012, 2013]. Thottappillil et al. [1992] analyzed seven cases of multiple terminations associated with the same stroke and found the geometric mean value of 1.7 km between the different terminations. Ballarotti et al. [2005] found six stroke presenting two ground terminations, and the shortest time interval was 31 μs. Kong et al. [2009] found nine strokes terminated at two points with 0.2 to 1.9 km apart, and the corresponding time interval was 4 to 486 μs. Qie and Kong [2007] even found a stroke with four ground terminations. Here in order to investigate the possible reason for the successive groundings of different branches within a same stepped leader development, we checked the other cases for more information.

Figure 6 shows the images of flash-D (20130812115956) with a frame rate of 180 kfps. The grounding point was outside the field of view of the camera; hence, the attachment process was not observed, unfortunately. However, this situation protected the image from overexposure due to the occurrence of return stroke, making the analysis on the behavior of those ungrounded channel branches feasible. As judged by an abrupt enhancement of the background luminosity, it is rational to think that the return stroke has been initiated in frame 2, and the attachment process occurred at an instant between frame 1 and frame 2. In frame 3, a channel branch was reilluminated. This branch should be a subbranch of the main channel that realized the grounding, and the reillumination was due to the development of the return stroke wave as it propagated up (from the ground) to the branching point of the leader channel and then propagated down through the subbranch. Note that the main return stroke wave would still propagate upward through the main channel. As the return stroke wave propagated higher and passed through more branching points, more subbranches would be reilluminated or mightily illuminated as compared to the existing luminous intensity of the channel branch. Frames 4 and 5 evidently show that in those leader branches which had not propagated down enough to the ground at the instant of the attachment process, the return stroke wave would develop from the branching point (when the return stroke wave had got up to that point through the main grounding channel from ground) and propagate downward through the whole branch.
The ungrounded branches would rapidly extinguish after a transient illumination by the return stroke wave, because the high electric potential would not remain, and no current would further flow in the branch after the charge neutralization. As in Figure 7, the frames 9, 17, and 31, with lagging time (behind the frame 2) of only 27.8 $\mu$s, 83.3 $\mu$s, and 161.1 $\mu$s, respectively, exhibited significant decay of channel luminosity. Because those ungrounded leader branches involve transient illuminating by the return stroke wave and then rapid extinguishment for lacking of energy supply, the CG flashes generally exhibit a single main discharge channel soon after the inception of return stroke as a downward leader branch made contact with the ground.

The analysis above has shown that as the attachment occurred, the transient drop of the former high potential difference between the stepped leader system and the ground would make the downward leader propagation unsustainable. Generally speaking, if those ungrounded branches were well connected with the main branch when the attachment process occurred, they could hardly develop any further, in macroscopically. Nevertheless, when considering the detailed step formation process of the leader, it is also found that the stepping in some branches continued until the return stroke wave reached the tips, as shown in the bottom plot of Figure 7. Similar phenomenon (though not exactly the same) was also observed by Stolzenburg et al. (2013), who stated "not uncommon to see apparently disconnected leaders stepping soon after the RS." The stepping of the leader is not a continuous process, with typical paused interval of 10–20 $\mu$s [Hill et al., 2011], which is not a short time considering the arrival of the return stroke wave with fast propagation speed in the order of $10^8$ m/s. So more detailed information should be taken into account regarding the further extension of the ungrounded leader channel after the return stroke.

As revealed in the literature, a newly formed step starts as a space stem (or bidirectional streamer) development which is ahead of the existing channel tip, in the low-conductivity streamer zone [Gorin et al., 1976; Petersen et al., 2008]. The space stem eventually develops into space leader accompanied by the heating of the channel segment due to the streamer current inside. Then the connection between the space leader and the existing channel tip accomplishes the stepped process [Biagi et al., 2010; Hill et al., 2011]. It seems that the space stem (or space leader in the later phase) with electrical separation from the existing channel would not be substantially affected by the initiation of the return stroke, as compared to the impact of return stroke on the existing channel. The blue circles and triangles in the bottom plot of Figure 7 mark out the newly formed channel segments as compared to their prior frames, which indicate the accomplishment of the sequential processes from the transform of space stems into space leaders and then their connection with the existing channel tips. Note that the middle branch in the bottom plot did not show any further stepping after the return stroke. This branch was different from the left and right branches. In frame 1, the middle branch just accomplished a new step with enhanced luminosity, while the left and right branches had already been in the paused stage of the stepping with dim luminosity. It is rational to believe that when the return stroke occurred, the left and right branches involved existing space stem systems ahead of their tips while the middle branch did not (or the space stem was quite weak because the step connection just occurred). The above analyses indicate that the inception of return stroke could not effectively influence the development of the existing space stem system.
Now we get back to the possible reason for the multiple grounding behavior of the flash-A. Since the initiation of the upward connecting leader is a necessary condition for the attachment process, so, although no upward connecting leader was imaged in response to the right downward leader branch of flash-A, it must have been induced, and quite possibly had propagated to a certain height, at the frame of Figure 1b. The reason for not imaging it may be that the upward channel luminosity was too weak and under the detectable luminous intensity of the camera. Meanwhile, it can also be concluded that the upward leader had not yet developed to the height of the downward leader tip, at which height it might emit detectable luminosity by sufficient development. On the other hand, the right leader branch macroscopically stopped its downward propagation as the return stroke occurred. Then an important factor contributing the connection of such downward leader branch with the corresponding upward leader should be the streamer zone development ahead of the downward leader tip, which is able to sustain after the return stroke, as confirmed by the above analysis. For the downward leader branch which had propagated close enough to the ground, the spatial range of streamer zone would reasonably be larger than that for a regular step as shown in Figure 7. Correspondingly, if its self-sustained bidirectional development eventually propagated to meet both the downward leader and the upward leader, making contact, the second grounding would be achieved.

Next we show another kind of leader behavior after the grounding of the main channel branch. Figure 8 shows images of the stepped leader-first return stroke of flash-E (20130812130719). The stepped leader exhibited two main channel branches during its downward propagation. As shown in Figure 8a, the right branch appeared brighter luminosity and was nearer to the ground. In Figure 8b, the right branch realized the grounding and the return stroke had led to the intensive luminosity of the channel, making the image overexposed. After the inception of the return stroke, the lower tip of the left ungrounded branch continued to develop downward in four more frames, as shown in the bottom plot with expanded view of the red box area. Based on our data, this is the longest duration of the further development for those ungrounded branches after the occurrence of grounding in the main leader channel. This behavior obviously has something to do with the multiple grounding under suitable condition. Stolzenburg et al. [2012, 2013] proposed an important and necessary condition for the occurrence of their UI strokes that the UI leader should be cut off from the main leader channel which realized the first grounding. Under such condition, the UI leader would be hardly affected by the main return stroke, giving the opportunity for a second grounding. In Figure 8, the left branch did not exhibit evident dark gap from the main channel after it was reilluminated as the return stroke occurred. This may be because the exposure time of the images in Figure 8 was considerably longer than the images analyzed by Stolzenburg et al. [2013]. Their exposure time was 19.6 μs, by which the dark and effective cutoff over a short time can be better revealed. Nevertheless, a poor conductivity condition can be inferred from a relatively weak luminosity in the branch as shown in Figure 8 of this paper. Meanwhile, the further development at the lower tip of the ungrounded leader branch seems to be electrically separated from the branch itself.

Figure 8. Images of flash-E (20130812130719), captured by the M310 camera operated at frame rate of 10 kfps with exposure time of 90 μs. The bottom plot shows the expanded view of the red box area in the top plot.
In our data set of 37 cloud-to-ground flashes with the grounding point (or points) and most of the stepped leader branches being captured inside the field of view of the cameras, five were found to involve two grounding points within a stepped leader-return stroke process. Figure 9 shows the images of four cases (another one is shown in Figure 1 and has been analyzed in detail). Except for a special case of flash-I, the multiple grounding CG flashes share some common features: (1) the second grounded leader branch had got very close to the ground when the main return stroke occurred, or both the first and second grounded leader branches involved similar distances from their lower tips to the ground; (2) the luminosity of the second grounding channel was much weaker than the first grounding channel, which supports the idea that the first grounding leads to the main return stroke; and (3) the luminous duration of the second grounding channel was considerably shorter than the first grounding channel (the values are listed in the Table 1). The negative charge transfer from cloud to ground should be mainly accomplished through the first grounding channel with longer discharge duration and larger grounding current. As compared to the images shown by Stolzenburg et al. [2012, 2013], the second termination of the channel branch herein shared some similar features with their UI strokes, such as being considerably weaker than the main stroke and involving relatively short luminous duration.

For flash-I (20130804171802), the second grounding lagged behind the first grounding for about 0.4 ms as inferred by a four-frame interval at 10 kfps rate (the electric field changes were not well recorded, unfortunately), which was considerably longer than the other cases. Since the upper portion of the leader channels were obscured by the cloud, it cannot be determined whether the left and the right leader channels involved electrical connection inside the cloud. However, the captured images showed that the first grounding with short luminous duration of 2.3 ms had hardly affected the leader channel of the second grounding. Meanwhile, the second grounding channel lasted a very long luminous duration, indicative of a sustained continuing current flowing through. These indicate that the two channels were cut off from each other inside the cloud. Generally speaking, a sustained transferring of negative charge from cloud to ground with the grounded channel exhibiting continuous luminosity may demand a leader channel network in the cloud level [Lapierre et al., 2014], which is rational for the second grounding channel in flash-I. This is unlike those so-called UI leaders, the channel of which was isolated without any related in-cloud activities.

### Table 1. Characteristics of the First and Second Grounding Channels for the Multiple Grounded Flashes

<table>
<thead>
<tr>
<th>Flash</th>
<th>Luminous duration of first channel (ms)</th>
<th>Luminous duration of second channel (ms)</th>
<th>Distance between first and second channels (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flash-I</td>
<td>2.3</td>
<td>112.8</td>
<td>1.3</td>
</tr>
<tr>
<td>Flash-A</td>
<td>12.7</td>
<td>8.9</td>
<td>-</td>
</tr>
<tr>
<td>Flash-F</td>
<td>0.8</td>
<td>0.5</td>
<td>0.25</td>
</tr>
<tr>
<td>Flash-G</td>
<td>4.8</td>
<td>1.3</td>
<td>0.1</td>
</tr>
<tr>
<td>Flash-H</td>
<td>4.0</td>
<td>0.4</td>
<td>-</td>
</tr>
</tbody>
</table>
4. Discussion

The lightning attachment depends on the connection between the downward leader and the upward leader. For both leaders, the channel tips generally possess the largest charge density, and the associated radial electric fields will promote them to propagate toward each other. It will make sense to investigate the mechanism of their interaction and evaluate the respective contribution of downward and upward leaders to the attachment process. The facts that the initiation of upward connecting leader relies on the approach of the downward stepped leader and that the upward connecting leader has much shorter development period with weaker intensity seem to indicate that the downward leader may be the more dominant factor affecting the lightning attachment. As in Figure 2 of this paper, although the upward leader from the tower was initiated earlier and exhibited stronger luminosity (than the upward leader in the left branch), it eventually failed to accomplish the attachment. The tower-initiated upward leader seems to have not conducted much influence on the downward stepped leader. The actualization of the grounding at the left branch rather than the right branch depended more on the behavior of the stepped leader itself, of which the left branch was stronger and had propagated closer to the ground. Based on the comparison of speed variations for the downward and upward leaders as they got closer and eventually connected with each other, Lu et al. [2013] stated that the effect of the downward leader on the upward connecting leader is significant, while in contrast, the effect of the upward leader on the downward leader branches is somehow negligible.

It is generally considered that the attachment process is accomplished by the so-called breakthrough phase or final jump, which begins at the common streamer zone (with low conductivity) of the downward and upward leaders when they get close enough to each other. The connection of the downward and upward leaders acts as switching on the operation that serves to launch the initial bidirectional return stroke wave from the junction point [Rakov and Uman, 2003]. It is worth noting that for flash-A, Figures 1b and 1b* show that the upward leader had been connected with the downward leader branch at 0 ms, while in Figure 1c, at 0.1 ms later, although the image exhibited significant overexposure, the connected upward leader did not show considerable variation in the radius of luminous channel if we ignore the background luminosity, meaning that the channel in the frame had exposed for quite a short time after getting into the return stroke stage; that is, the initiation of return stroke occurred much closer to the instant of Figure 1c than Figure 1b, consistent with the data synchronization as shown in Figure 6b. After the upward and downward leaders made contact, there was relatively long delay (almost 100 μs) till the return stroke occurred. It seems that the transform from the attachment phase to the return stroke phase may be much more complicated than expected, and observation with higher temporal resolution should be conducted to reveal what happened during the time interval between Figures 1b and 1c.

To date, the observations on the connecting leaders in subsequent negative return strokes were mostly conducted on basis of the triggered lightning experiment [Orville and Idone, 1982; Idone et al., 1984; Idone, 1990; Wang et al., 1999, 2013, 2014]. The lengths of these upward leaders were determined to range from several meters to tens of meters, mostly (if not all) shorter than 30 m. The reason for hardly observing them in natural lightning may be due to their relatively weak development [Rakov and Uman, 2003] and a possible short duration. The subsequent leader propagating through the preconditioned channel involves faster speed than the stepped leader breaking down virgin air. The two cases of upward connecting leaders herein, with lengths of 340 m and 105 m, respectively, are very long as compared to the previous results. This indicates that the upward connecting leader developing through the channel remnant of the prior return stroke can propagate in a relatively fast speed. Both upward leaders were induced by the chaotic leaders, with irregular electric field pulses preceding the return stroke which involved larger-than-usual electric field peak. Since in our data set, we also found some cases with chaotic pulsed electric field waveform while no distinct upward connecting leader was imaged, it is not able to claim a clear correlation between the chaotic leader and the more pronounced upward leader. Nevertheless, both of them seem to have something to do with the more intense return stroke. The chaotic leader deserves more attention when considering the attachment process for subsequent strokes, and further observations with better resolution are needed.

5. Summary

The leader propagation and ground attachment of negative cloud-to-ground lightning flashes were analyzed by using the high-speed video images and the electric field change data, profited from the relatively large
field of view of the high-speed video observations. The junction height for the first return stroke, as induced by the downward stepped leader and the upward connecting leader breaking down virgin air, was tens of meters. The downward leader branches with more intense luminosity and lower channel tip to the ground were more feasible to accomplish the grounding, although some other branches may induce upward connecting leader earlier as approaching the high grounded objects. The junction heights for two subsequent return strokes (developing through the preconditioned channel) were higher than 340 m and 105 m, respectively. These subsequent return strokes exhibited relatively large amplitudes in electric field change waveforms, and the downward leaders were of the chaotic type characterized by irregular pulse trains with duration of 0.2–0.3 ms.

As the attachment occurred, the high potential difference between the stepped leader system and the ground transiently dropped down, terminating the downward propagation of those ungrounded branches. They were then traversed by the return stroke wave with fast propagating speed, showing a transient channel illumination and a rapid extinguishment. This makes most of the CG flashes being of the type with single grounding channel. Five flashes in our data set of 37 samples exhibited multiple ground terminations, referable to the sustained development of the existing space stem systems in the low-conductivity streamer zone apart from the leader tip or the further propagation of the leader branch with poor connection to the main return stroke channel. Both situations helped to make a secondary connection of the leader branch with the corresponding upward leader.

Acknowledgments
The research was supported by National Key Basic Research Program of China (grant 2014CB441405) and National Natural Science Foundation of China (grants 41405008 and 41175002). This work complies with the AGU data policy; contact the authors (jiangrubin@mail.ial.ac.cn and qix@mail.iap.ac.cn) for data availability.

References
Diendorfer, G., M. Viehbeiger, M. Mair, and W. Schulz (2003), An attempt to determine currents in lightning channels branches from optical data of a high speed video system, paper presented at International Conference on Lightning and Static Electricity, R. Aeronaut. Soc., Blackpool, U. K.


