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Development characteristics of cloud-to-ground lightning with multiple grounding points

Bin FAN[1], Ping YUAN[1*], Xuejuan WANG[1,2], Yang ZHAO[2], Jianyong CEN[3] & Yanling SU[1]

[1] *Key Laboratory of Atomic and Molecular Physics and Functional Materials of Gansu Province, College of Physics and Electronic Engineering, Northwest Normal University, Lanzhou 730070, China;*
[2] *School of Atmospheric Physics, Nanjing University of Information Science and Technology, Nanjing 210044, China;*
[3] *College of Physics and Information Engineering, Shanxi Normal University, Linfen 041004, China*

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Abstract Using the optical images of a cloud-to-ground lightning flash with multiple grounding points obtained by a high-speed video system in the Qinghai Province of China along with synchronous radiated electric field information, the propagation characteristic and the electric field change features of the leaders and the grounding behavior of discharge channels are analyzed. In addition, the two-dimensional velocity of the leader was estimated and its correlation with the time interval of the corresponding subsequent return stroke, and that with the peak current of return stroke are investigated. The results show that the average distance between the three obvious grounded points of the first return stroke channel is about 512.7 m, and the average time interval between the pulses of the corresponding electric field fast changes is 3.8 μs. Further, the average time interval between electric field pulses from the stepped leader is smaller than that of normal single grounding lightning. The observed lightning in our study has two main channels, namely the left and right channels. Based on our observations, it is clear that the dart leader comes close to the ground in case of the left channel after the first return stroke, but it fails to form a return stroke. However, the right channel exhibits a relatively rare phenomenon in that the subsequent return stroke R2 occurred about 2.1 ms after the dart leader arrived at the ground, which was unusually long; this phenomenon might be attributed to the strong discharge of the first return stroke and insufficient charge accumulation near the grounded point in a timely manner. The two-dimensional velocities for the stepped leader of the two main channels are about 1.23×10^5 and 1.16×10^5 m s^{-1}, respectively. A sub-branch of stepped leader for the left channel fails to reach the ground and develops into an attempt leader eventually; this might be attributed to the fact that the main branch connects considerably many sub-branches, which leads to the instantaneous decline of the potential difference between the sub-branch and ground. Furthermore, it might also be because the propagation direction of this sub-branch is almost perpendicular to the atmospheric electric field direction, which is not conducive to charge transfer. The two-dimensional velocities for the dart leaders of five subsequent return strokes are all in the normal range, and they positively correlate with the peak current of the subsequent return stroke.

Keywords Multiple grounding lightning, High-speed camera, Electric field changes, Leader

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1. Introduction

In general, the first return stroke of negative cloud-to-ground lightning has several downward branches. If a branch can reach the ground before the charge in the main channel is completely neutralized in the return stroke, it will form a return stroke with multiple grounding points (Kong et al., 2005). A return stroke with multiple grounding points

* Corresponding author (email: yuanp@nwnu.edu.cn)

usually poses a more severe hazard than one with a single grounding point. Therefore, to explore the characteristics of the return stroke during its formation and transmission process has been an important subject of concern in the field of lightning protection and research. At present, there are few reports on multiple grounding lightning. However, using a high-speed camera system capable of recording 1000 fps and fast and slow antenna lightning electric field change measuring instrument with a time resolution of 1 μs, Kong et al. (2003) investigated the optical and electrical properties of a leader following multiple grounding return stroke channels. Furthermore, based on the data obtained from the photoelectric observation system with a time resolution of 1 μs, Guo and Krider (1982) inferred that the first return stroke with two grounding points is caused by two grounding branches of the same stepped leader. Valine and Krider (2002) analyzed the factors that induce multiple grounding lightning based on video images and electric field change data. Wang D et al. (2000) analyzed the propagation characteristics of return stroke waves for a two-grounding-points lightning. Recently, using a combination of a two-dimensional optical camera and very high frequency (VHF) lightning location system, Wu et al. (2013) investigated the channel development process for a two-grounding-points lightning and observed that the current in the main channel is stronger than those in the branch channels. Furthermore, based on the short baseline VHF lightning location system, Sun et al. (2016) reversed the development process of a multiple-grounding-points lightning and explained the reason for formation of a multiple-grounding-points lightning.

In this study, based on the optical images captured using a high speed video system combined with the corresponding electric field change information obtained using a synchronous fast and slow antenna electric field change measuring instrument, the propagation characteristics, grounding behavior of the leader channels, and relevant electric field change features are analyzed. In addition, the relation between the two-dimensional velocity of the dart leader and peak current of the corresponding return stroke is discussed. Furthermore, reference data are provided for further exploration of the development mechanism of multiple-grounding-points lightning.

2. Instrumentation

For our study, the observation experiment was conducted in the mountain area of Taer Town, Datong County in the Xining City of Qinghai Province, China in the summer of 2015; in this area, there are many natural tips on the mountains. Multiple-grounding-points lightning was observed at 17:35:06 on August 29, 2015. The camera was set at 9060 fps with an image resolution of 896×400 pixels. In addition, the frequency bandwidth of the fast and slow antenna was 100 Hz–3.2 MHz and 0.18 Hz–3.2 MHz with the time constant of 2 ms and 5.6 s, respectively. The dynamic output range was ±3 V. We used a 12-bit analog-to-digital card with a sampling rate of 10 MS s^{-1} to record the data for lightning flashes. Furthermore, the fast and slow antenna system and high-speed camera were temporally synchronized using GPS.

Based on the initial peak E_{max} in the observed electric field change waveform (Haddad et al., 2012; Li et al., 2017), and transmission attenuation effect of the electromagnetic wave along the surface of the ground (Cooray et al., 2000), the peak current I_{max} of the return stroke can be estimated using the transmission line model (Rakov and Uman, 2003; Qie et al., 1998).

3. Data analysis

The lightning is estimated to be about 10.5 km from the observation point based on the arrival time differences between the observed light and first sound produced by the lightning. The flash lasted for about 501.2 ms and was composed of six return strokes (as is shown Figure 1). By convention, R1 represents the first return stroke, and R2–R6 represent the other subsequent strokes, respectively. The time when the first return stroke occurred is set as 0 ms. As shown in Figure 1a, the discharge of this lightning was considerably strong, because the waveform of the slow electric field change after the fifth stroke is saturated.

The images of each return stroke channel are shown in Figure 2; it can be observed that the lightning has two main channels: the left channel and right channel. Furthermore, the first return stroke has five sub-branches and the main discharge channel is on the left, while the discharge of all the five subsequent return strokes is along the right channel.

3.1 Grounding behavior

3.1.1 First return stroke

Figure 3 shows the high-speed video images of the discharge channels before and after the first return stroke. The height of cloud base is about 1.5 km. Unfortunately, the starting points of the two main branches are blocked by the cloud and the stepped leader cannot be recorded until 16.225 ms before the first return stroke occurred. In particular, the first stroke has two main branches d and e at the beginning. The sub-branches a–c on the left branch d appeared at about 500, 290, and 200 m above the ground, respectively. In addition, the sub-branch f on the right branch e occurred at about 220 m above the ground. As can be seen in Figure 3, 0.110 ms before the first return stroke, only two main branches were observed. However, in the image at 0 ms, the five branches b–f near the

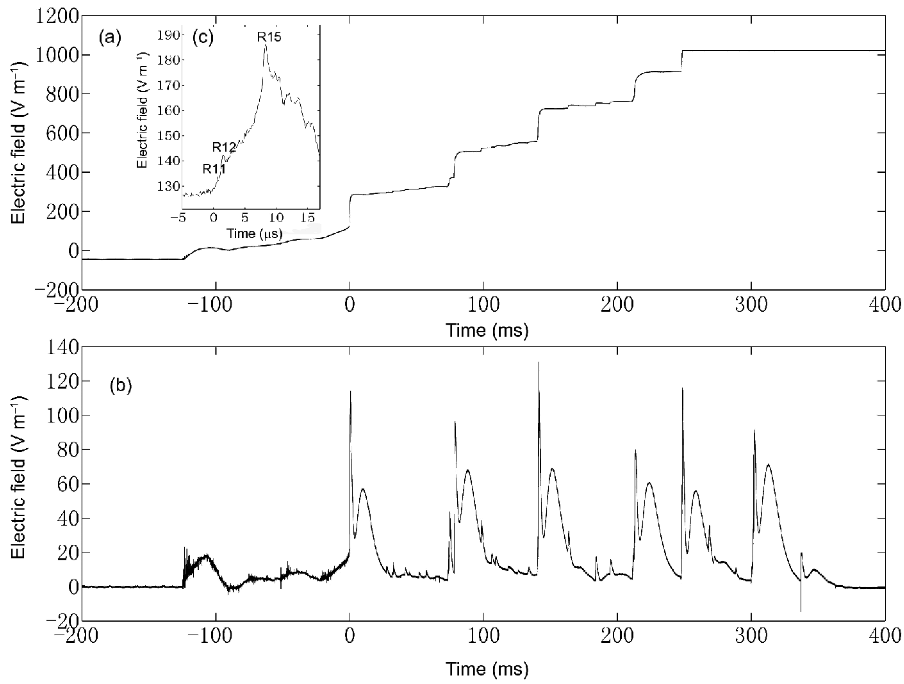

Figure 1 Waveforms of the synchronous fast and slow changes of the electric field caused by lightning. (a) Waveform of slow electric field changes, (b) waveform of fast electric field changes, and (c) amplifying waveform of the initial peak for the slow change of the first return stroke. The *x*-axis represents time, while the *y*-axis represents the electric field change.

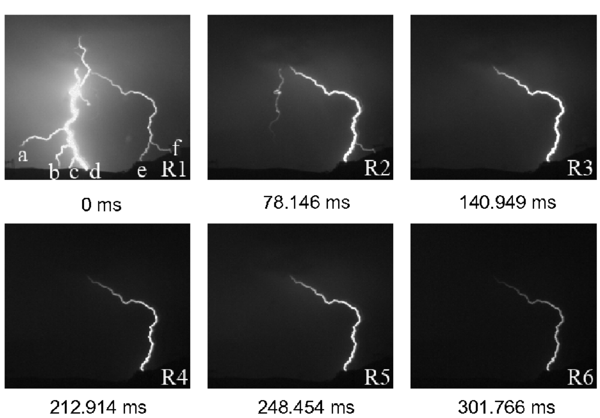

Figure 2 Images for each return stroke channel.

ground in the first return stroke are visible. Furthermore, the channels d and e continue to glow from the stepped leader to the return stroke (as seen in Figure 3); in particular, they are the main channels of the first return stroke discharge. From the images at 0, 0.111, 78.035, and 78.146 ms, it can be seen that branches e and f are glowing near the ground in the first return stroke as well as in the subsequent return strokes, which indicates that they were grounded. Because the branches b and c are observed reaching the ground only at 0 ms, it is difficult to confirm whether they are grounded. The grounding order of the branches cannot be distinguished using the high-speed video, because its exposure time is only 1/9060 s. As can be observed from the outline of the mountain in Figure 3, the ground surface on the right is higher than that on the left. Furthermore, from the image at −1.876 ms, it can observed that the right branches are closer to the ground; in particular, the sub-branch f reached the ground first. Based on the luminous intensity (Wang et al., 2005; Idone and Orvill, 1985), the discharge intensity of the right branch e should be weaker than that of the left branch d. In addition, from the amplifying waveform in Figure 1c, it can be seen that the amplitude of the electric field variation of R12 is larger than that of R11, and less than that of R15; moreover, the interval time between R12 and R11 is only 0.9 μs, which can be attributed to the multiple branches grounding (Kong et al., 2003). Based on the above characteristics, the electric field change pulse in the case of R12 and R15 should correspond to the discharge of the right branch e and left branch d, respectively; furthermore, R11 might be responsible for the discharge of the sub-branch f. The other small electric field pulses between R12 and R15 might be related to sub-branches b and c; however, their corresponding relationship is not certain. The time intervals between branches f and e, and e and d reaching the ground are 0.9 and 6.8 μs, respectively, with an average value of 3.8 μs, which is less than the values reported by Kong et al. (2005, 2003); this difference might be attributed to the distances between the grounding points.

Based on the distance between the lightning channel and observation site, the two-dimensional distances between the

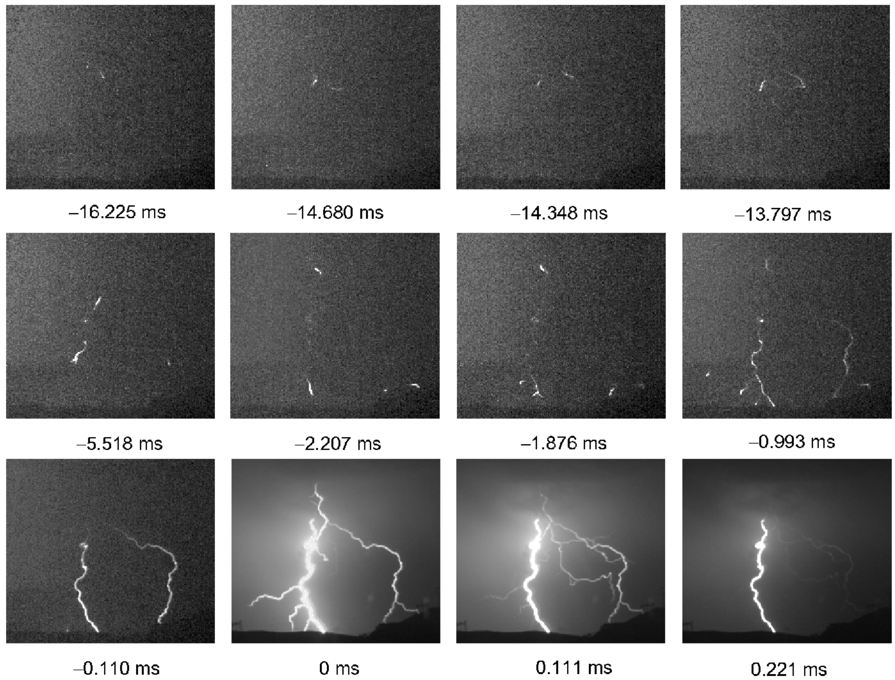

Figure 3 High-speed video images of the discharge channels before and after the first return stroke.

three grounding points are estimated to be about L_{de}=670.5 m and L_{ef}=355.0 m, respectively, with an average distance of 512.7 m. Thottappillil et al. (1992) reported that the distance between the grounding points in the case of multiple-grounding-points lightning is usually in the range of 0.3–7.3 km. From our observations, it can be seen that sub-branch a fails to reach the ground and eventually develops into an attempt leader; this can be attributed to the fact that its main branch connects to too many sub-branches, which leads to an instantaneous decline in the potential difference between the sub-branch a and ground (Jiang et al., 2015). In contrast, this might also be related to the propagation direction of this sub-branch in that it is almost perpendicular to the direction of the atmospheric electric field, which is not conducive to downward charge transfer. In theory, the negative charge in the cloud is transported downward and stored in the leader channel during leader downward propagation. However, because the direction of the atmospheric electric field is approximately perpendicular to the ground, the smaller the angle between the directions of propagation for the sub-branch and atmospheric electric field during the downward propagation process of the negative leader is, the larger the electric field force experienced by the negative charge in the channel, the faster the velocity of charge, and the higher the amount of negative charge in the tip of the sub-branch. Therefore, the electric field between the tip of leader and ground becomes stronger, which is conducive to downward charge transfer. On the contrary, a larger angle between the direction of propagation of the sub-branch and electric field is not conducive to the development of a charged channel. When the tip of sub-branch a was still about 280 m from the ground surface, the return stroke occurred in the channel d, which causes it to develop into an attempt leader.

The formation of multiple grounding points should be associated with the surrounding terrain. In particular, this formation can be attributed to the lightning occurring on undulating hills, where there are many trees, grass, and other natural tips. During strong thunderstorm conditions, a strong corona discharge on these natural tips might release many corona ions, which can easily form multiple pocket charge regions between the cloud and the ground (Qie et al., 2003), and further induce the multiple grounding discharge channel.

3.1.2 Subsequent return stroke

As seen in Figure 4, similar to the stepped leader, the dart leader in the case of the subsequent return stroke R2 developed along both the main channels; in addition, the luminous intensities of the channels are clearly brighter than that of the stepped leader. Kong et al. (2003) reported that whether the dart leader will reach the ground depends on its velocity; the faster the velocity of the dart leader, the easier it will be for the dart leader to reach the ground and become the grounding channel for the subsequent return stroke. Because the two-dimensional propagation velocity of the right branch is higher, it reaches to the ground first and becomes the grounding channel of the subsequent return stroke R2. In most cases, the return stroke occurs immediately after the leader (Sun, 1982). However, in our case, R2 is an exception. In particular, at 75.718 ms, the right channel e reaches close to the ground, but fails to achieve a return stroke; then, at 75.938 ms, the left channel d also reaches close to the ground, after which, both channels stop glowing, until at 78.035 ms, when the subsequent return stroke R2 occurs in the right branch e. The high-speed video images of the discharge channels in the subsequent return stroke R2 are shown in Figure 5. From the change waveform of the corresponding electric field, it can be estimated that the return stroke happened about 2.1 ms after the leader reaches the ground. In addition, in the nonluminous period specified above, there is no electric field change information recorded. During the entire stage of R2, the left channel d never achieved a return stroke. A leader along the left channel reappeared between 78.146 and 78.256 ms; however, it still failed to generate a return stroke (as seen in Figure 5). The characteristics discussed above might be related to the discharge intensity of the left channel in that it is too strong in the first return stroke. As can be seen from Figure 4, the leader reached the ground, indicating that the amount of negative charge in the cloud is sufficient; however, the return stroke did not follow in a timely manner, which can be attributed to the shortage of charges around the grounding points. Large positive charges near the grounding points are neutralized because of the over-discharged first return stroke, and subsequent charges accumulation requires time. Furthermore, the discharge of the right channel in the first return stroke is relatively weaker than that of the left channel, and there is a certain distance between the grounding points of the two channels; therefore, the return stroke can occur in the right channel. In addition, the upper part of the left channel d has a considerably strong luminous node (Figures 3 and 4), which will also consume a considerable electric charge.

3.2 Development characteristics

Based on the number of pixels added along the transmission direction of the channel in each frame image captured by the high-speed video system, the two-dimensional velocities of the stepped leader can be estimated to be about 1.23×10^5 and 1.16×10^5 m s^{-1} for the left and right branch, respectively, which is in agreement with the range of values of 1×10^5–3.8×10^5 m s^{-1} reported by Li et al. (2010), Wang D H et al. (2000), and Qie et al. (2002). The two-dimensional velocities of the left and right branches for dart leader in the subsequent return stroke R2 are about 0.61×10^6 and 1.17×10^6 m s^{-1}, respectively. The reported value for single grounding lightning is in 5.5×10^6–1.9×10^7 m s^{-1} (Jordan et al., 1992; Mach and Rust, 1997; Kong et al., 2008). Wang et al. (1999) reported the values of 2×10^6–1.3×10^7 m s^{-1} for artificially triggered lightning. Recently, Saba et al. (2008) and Zhang et al. (2008) reported that the velocities of the dart leader for single

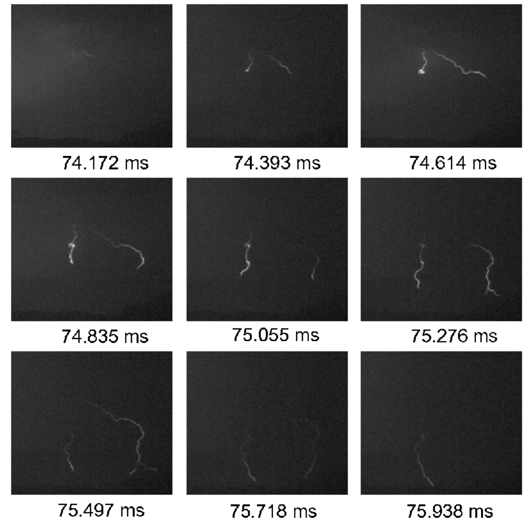

Figure 4 Images of the discharge channels for the dart leader before the subsequent return stroke R2.

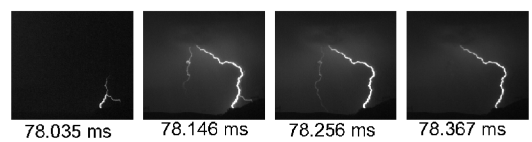

Figure 5 Images of the discharge channels during the subsequent return stroke R2.

grounding lightning as 1.3×10^6–4.1×10^6 m s^{-1}. In this study, the two-dimensional velocities of the dart leaders for five subsequent return strokes are observed to be all in the normal range; this indicates that the two-dimensional velocities of the stepped leader and dart leader for multiple-grounding-points lightning have no obvious differences in magnitude compared with those of the normal single-grounding-point lightning (Wang D H et al., 2000; Wang et al., 1999).

Figure 6 displays the changes in the two-dimensional velocities of the two main channels for the dart leader in the subsequent return stroke R2. The two-dimensional velocities of the left channel and right channel are represented as v_l and v_r, respectively; their change trends are relatively similar. As the dart leaders propagate downward, their two-dimensional velocities decrease gradually, which is consistent with the results of Campos et al. (2014).

The characteristic parameters of a strong lightning discharge process have recently garnered the most interest in the field of lightning protection research. Some characteristic parameters of the investigated lightning are listed in Table 1. t_i is the time interval between the return strokes (in particular, the time interval between the initial peaks of the electric field for the return strokes), t_p is the luminous duration of the return stroke channel (which is approximately the duration of the return stroke current); in particular, the luminescence duration of the left and right channels for R1 was about 3.41

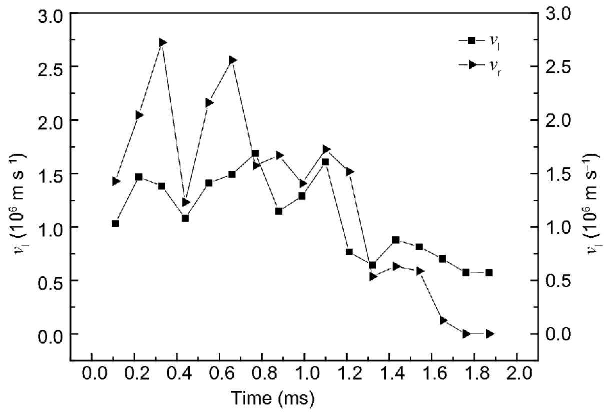

Figure 6 Changes in the two-dimensional velocities between the two main channels for the dart leader in the subsequent return stroke R2.

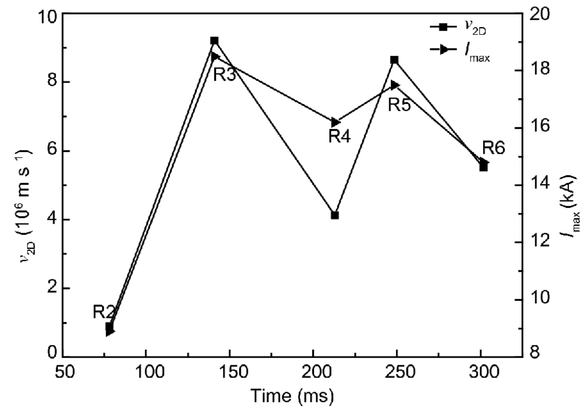

Figure 7 Relationship between the two-dimensional velocity of the dart leader and peak current of the corresponding subsequent return stroke.

and 0.55 ms, respectively. E_{max} is the initial peak value of the electric field change normalized to 100 km in the return stroke (Haddad et al., 2012; Li et al., 2017), and I_{max} is the peak current of the corresponding return stroke. Furthermore, v_{2D} is the two-dimensional velocity of the corresponding leader.

The peak current of the return strokes for this lightning varied from 8.9 to 19.9 kA with a mean of 16.0 kA as shown in Table 1. Qie et al. (2012) found that the peak current of the return stroke for artificially triggered lightning is in the range of 4.4–41.6 kA with a mean of 12.1 kA. Wang D H et al. (2000) reported that the average peak current of the first return stroke for negative cloud-to-ground lightning is between 20–40 kA; in addition, the peak current of the subsequent return stroke is around half of the first return stroke. Li et al. (2017) analyzed the peak of the electric field change of 421 and 789 first return strokes and subsequent return strokes, respectively, and found that the average values normalized to 100 km were 7.2 and 5.0 V m^{-1}, respectively.

The relationship between the two-dimensional velocity of the dart leader and the peak current of the corresponding subsequent return stroke is shown in Figure 7; it can be seen that they are approximately linearly correlated, which is in agreement with the conclusion for artificially triggering lightning reported by Idone et al. (1984). This can be theoretically explained considering that the strong electric field produced by more charges in the cloud can accelerate the propagation velocity of the leader; in particular, the faster the propagation velocity of the leader is, the more the charges stored in the channel and the greater the peak current of the corresponding subsequent return stroke.

There exists a rough inverse correlation between the two-dimensional velocity of the dart leader and the time interval between the return strokes (Figure 8). Similar to R2, R4 is in agreement with the characteristic of the single-grounding-point lightning reported by Kong et al. (2003). In theory, if the time interval between two adjacent return strokes is long, the conductivity of the lightning channel will decrease, which leads to a decrease in the velocity of the subsequent dart leader.

3.3 Electric field changes for the leaders

3.3.1 Electric field changes of the stepped leader

The waveform analysis shows that the duration of the stepped leader is about 23 ms; and there are many pulses (Figure 9) with polarities in accordance with that of the return stroke. The pulse interval is in 1.5–29.9 μs with a mean of 11.4 μs (Figure 9b). These pulses might be generated by the stepped process (Beasley et al., 1982). In particular, it has been reported that the pulse interval of the stepped leader for single grounding negative cloud-to-ground lightning using electromagnetic field change recorder is in 13.9–23.9 μs (Qi et al., 2016; Hill et al., 2011; Krider et al., 1977; Cooray and

Table 1 Characteristic parameters of the investigated lightning

Return stroke order	t_i (ms)	t_p (ms)	E_{max} (V m^{-1})	I_{max} (kA)	v_{2D} (10^6 m s^{-1})
R1		3.410	5.96	19.9	0.12
R2	78.119	3.774	2.67	8.9	0.89
R3	62.817	3.201	5.56	18.5	9.22
R4	71.955	3.422	4.86	16.2	4.13
R5	35.534	3.104	5.25	17.5	8.66
R6	53.321	4.525	4.43	14.8	5.51

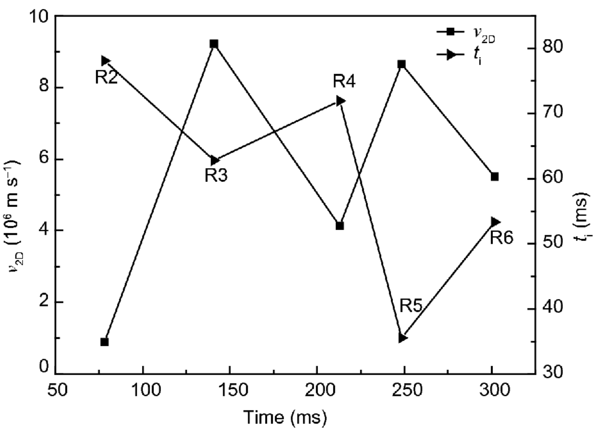

Figure 8 Relationship between the two-dimensional velocity of the dart leader and time interval between the return strokes.

Lundquist, 1982). In our study, the average time interval of the stepped leader pulses for multiple-grounding-points lightning is shorter than that reported for normal single-grounding-point lightning. This can be attributed to the two branch channels and four sub-branches of the stepped leader, all of which follow a stepped process and are responsible for the pulses. The pulse change, which is generated by the two main channels and its four sub-branches together, can be recorded simultaneously using an electric field observation device; however, the location of the radiation source cannot be distinguished.

3.3.2 *Electric field changes of the dart leader*

In Figure 10a, L2 is the corresponding dart leader process, which lasted for about 2.67 ms; this value is greater than that of 1.766 ms, which was obtained using the high-speed video. The primary reason for this difference is that the time resolution of the electric field change recorder is higher than that of the high-speed video system, and some weaker luminescence channels in the far-distance cannot be recorded via optical observation. T is the time interval between the dart leader grounding and the occurrence of the corresponding subsequent return stroke, which is about 2.1 ms. There are several pulses with a time interval in 1.6–20 μs with a mean of 5.3 μs (Figure 10b). The polarity of these pulses is in accordance with that of the subsequent return stroke. In addition, there is no obvious strong pulse in the electric field waveform for nearly 75.938 ms, which is consistent with the characteristics observed from the optical image. When the two main channels reach the ground successively, the corresponding electric field drastically decreases from 19.75 to about 8.92 V m^{-1}.

A similar trend was observed in the case of the electric field change waveform of the dart leaders before the subsequent return strokes R3–R6. In addition, as the dart leaders reach close to the ground, the electric field pulses became more symmetric and their time intervals clearly increased.

Table 2 lists the characteristic parameters of the corresponding leaders in the lightning evaluated in our study. Δt_{Li} is the time interval between the leader pulses, Δt_L is the average time interval between leader pulses, and Δt_{LR} is the time interval between the final pulse of the leader and corresponding return stroke. The average time interval between electric field pulses of the dart leader is in the range of

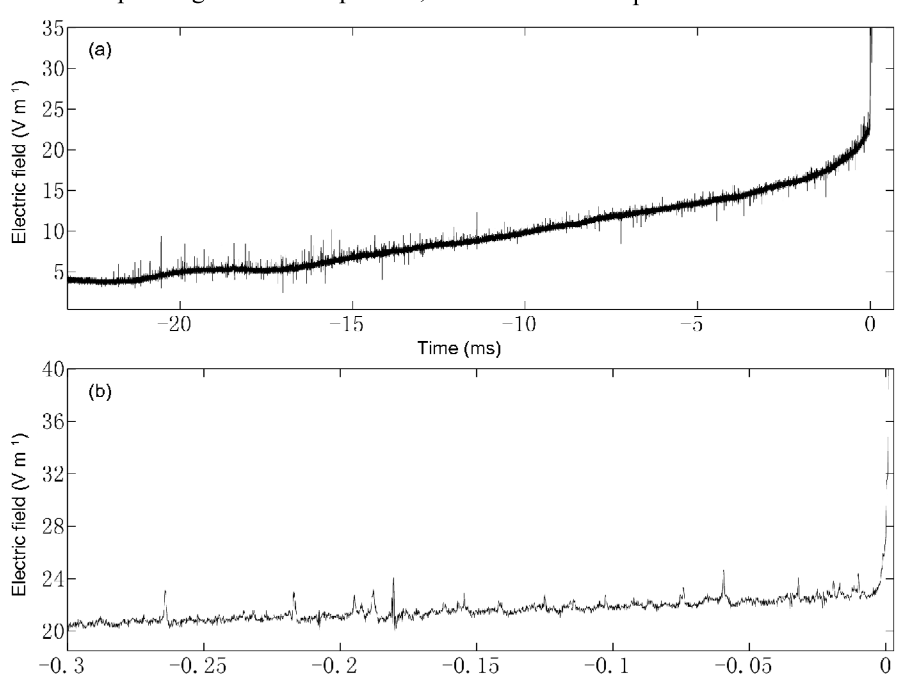

Figure 9 Amplified waveforms showing (a) electric field changes for the stepped leader and (b) electric field changes within 300 μs before the first return stroke.

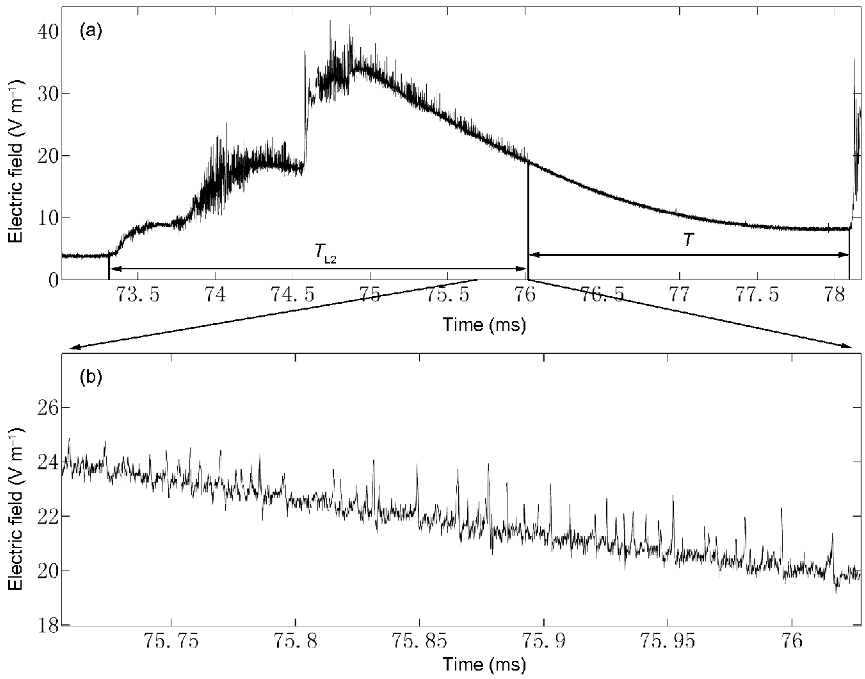

Figure 10 Change of the electric field before the subsequent return stroke R2. (a) Change of the electric field from the start of the dart leader to the corresponding subsequent return stroke and (b) electric field change for the dart leader.

Table 2 Characteristic parameters of the corresponding leaders in the evaluated lightning

Leader order	Δt_{Li} (μs)	Δt_{L} (μs)	Δt_{LR} (μs)	t_i (ms)
L1	1.5–29.9	11.4	10	
L2	1.6–20	5.3	2100	78.119
L3	1–20.3	3.2	1.7	62.817
L4	1.5–14.6	3.6	9.6	71.955
L5	0.5–12.7	3.7	1.3	35.534
L6	1–8.9	2.7	2.4	53.321

2.7–5.3 μs (Table 2), which is in accordance with the result for normal single-grounding-point lightning. Wang et al. (1999) reported that the average time interval between dart leader pulses is in the range of 1.7–7.2 μs for the normal single-grounding-point lightning. The average time interval between the dart leader pulses for multiple-grounding-points lightning is similar to those of the normal single-grounding-point lightning and is smaller than that of the stepped leader. With the development of the lightning, the conductivity of the channel is enhanced; therefore, the average time interval decreases gradually.

4. Conclusions

The average time interval between the stepped leader pulses for multiple-grounding-points lightning is smaller than that of normal single-grounding-point lightning. The two-dimensional velocities of the two main channels for the stepped leader are about 1.23×10^5 and 1.16×10^5 m s^{-1}. The average distance between the three grounded points of the first return stroke is estimated to be about 512.7 m; in addition, the average time interval between the pulses of the corresponding electric field change is 3.8 μs. The sub-branch a of the stepped leader for the left channel fails to reach the ground and eventually develops into an attempt leader; this might be attributed to the fact that the main branch connects considerably many sub-branches, which leads to an instantaneous decline in the potential difference between the sub-branch and the ground. Furthermore, it might also be because the propagation direction of this sub-branch is almost perpendicular to the atmospheric electric field direction, which is not conducive to charge transfer. There is a long time interval between the dart leader and corresponding subsequent return stroke R2, which may be related to the special property that, when the discharge intensity of the preceding first return stroke is especially strong, it might result in the charges near the grounding points not being supplemented in a timely manner. The two-dimensional velocities of the dart leader are in the commonly observed numerical range and are positively correlated with the peak current of the subsequent return stroke.

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