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Some features of stepped and dart-stepped leaders near the ground in natural negative cloud-to-ground lightning discharges

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Abstract. Characteristics of the electric fields produced by stepped and dart-stepped leaders 200 μs just prior to the return strokes during natural negative cloud-to-ground (CG) lightning discharges have been analyzed by using data from a broad-band slow antenna system with 0.08 μs time resolution in southeastern China. It has been found that the electric field changes between the last stepped leader and the first return stroke could be classified in three categories. The first type is characterized by a small pulse superimposed on the abrupt beginning of the return stroke, and accounts for 42% of all the cases. The second type accounts for 33.3% and is characterized by relatively smooth electric field changes between the last leader pulse and the following return stroke. The third type accounts for 24.7%, and is characterized by small pulses between the last recognizable leader pulse and the following return stroke. On the average, the time interval between the successive leader pulses prior to the first return strokes and subsequent return strokes was 15.8 μs and 9.4 μs, respectively. The distribution of time intervals between successive stepped leader pulses is quite similar to Gaussian distribution while that for dart-stepped leader pulses is more similar to a log-normal distribution. Other discharge features, such as the average time interval between the last leader step and the first return stroke peak, the ratio of the last leader pulse peak to that of the return stroke amplitude are also discussed in the paper.

Key words. Meteology and atmospheric dynamics (atmospheric electricity; lightning) – Radio science (electromagnetic noise and interference)

1 Introduction

Most of the negative cloud-to-ground (CG) lightning discharges start with preliminary breakdown activities inside the cloud, the time duration of which varies from several milliseconds up to a few hundreds of milliseconds. Then a stepped or initial leader starts to progress from cloud to ground. The stepped leader usually takes tens of milliseconds to reach the ground and initiates the first return stroke. The name of the stepped leader comes from the step-like nature of the air breakdown from photographic observations when it progresses downward to the ground. When the stepped leader approaches the ground (within a distance of several tens to a few hundred meters), an upward progressing leader is emitted from the ground, which bridges the leader tip and the ground and is usually called attachment process. The connecting leader initiates a return stroke, which propagates upward along the leader channel and effectively adds positive charge along the channel and in the cloud, thereby neutralizing the existing negative charge there. A normal negative CG lightning discharge usually consists of several return strokes to the ground.

Understanding the initiation mechanisms and propagation of a leader during CG lightning discharges is essential for designing of structure protection against lightning. In the last few decades, the millisecond-scale electrostatic field of stepped leaders has been reasonably well understood and has been adequately modeled. In the 1940's, stepped leaders and dart leaders were first studied photographically by Schonland and Collens (1934). They stated that all return strokes were induced by one of the three initial processes: stepped leader, dart leader and dart-stepped leader. These photographic measurements were supplemented by Clarence and Malan (1957), Krider (1974), Krider and Radda (1975). Kitagawa (1957) studied the electric field change due to the leader processes. It has been made clear that the leader to the first return stroke is always a stepped leader. The most frequent pulse intervals are 40–60 μs; they are generally longer in the initial part and gradually become shorter towards the final part, where they have the minimum value of 13 μs immediately before the initiation of the return stroke. It has been confirmed that the time interval of stepped leader pulses is between 5–20 μs, with a mean value of 15 μs by measuring the electromagnetic fields radiated by individual leader steps with microsecond and sub-microsecond resolu-

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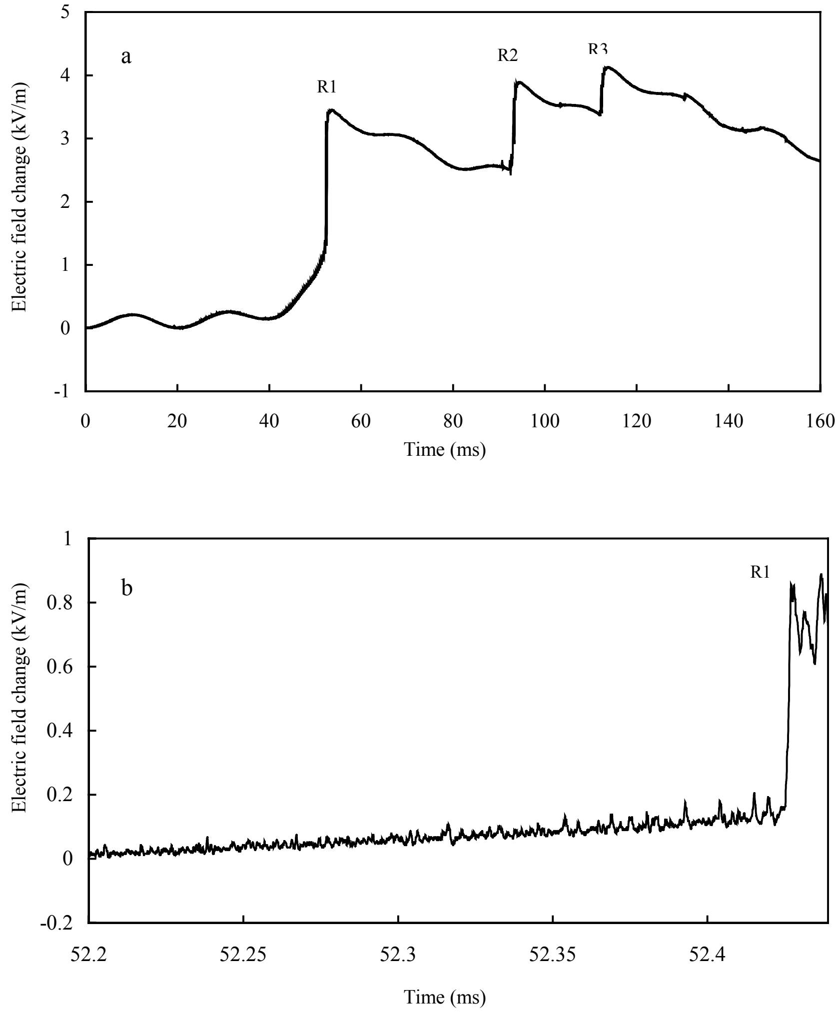

Fig. 1. Electric field produced by a negative CG lightning discharge that occurred at 12:33:44 (Beijing time) on 25 July 1999 by using the wideband slow antenna system. **(a)** for about 160 ms time scale, **(b)** time expanded electric field change about 250 μs just before $R1$.

tion (Orville and Idone, 1982; Beasley et al., 1982, 1983; Cooray and Lundquist, 1985). Thomson et al. (1985) theoretically discussed the propagation behavior of a leader for different charge distributions by analyzing waveforms of dE/dt. More recently, characteristics of current and electric fields produced by a leader have been extensively studied by using small rocket-triggered lightning discharges (Laroche et al., 1991; Lalande et al., 1998; Wang et al., 1999). In this paper, we present the results on the characteristics of the stepped and dart-stepped leaders 200 μs before the first return stroke in natural negative CG lightning discharges with sub-microsecond resolution, to help the understanding of the related physical processes.

2 Instrumentation

The experimental site is located at the Guangzhou area, in southeastern China, about 180 km north of the South China Sea. The altitude of this area is close to sea level. Electric fields produced by natural CG lightning discharges were measured with a "wideband slow antenna" system, which is similar to the slow antenna system originally developed by Brook et al. (1982). It consists of a capacitive antenna connected to a charge amplifier. In order to measure the fast electric field changes in the lightning discharges for several tens of milliseconds, the system has been modified with a decay time of about 100 ms, and a 3 dB frequency bandwidth of 4 Hz–1.5 MHz, which is much higher than that of the original slow antenna system. The output signals were digitized at a sampling frequency of 12.5 MHz with an amplitude resolution of 12 bits. The digital data were recorded with a personal computer. The recording length is 2 Mbytes, providing a recording duration of 160 ms. The data acquisition is triggered by the fast field variation of the return stroke with a pre-triggered mode. During the observation period, the sensor of the wideband slow antenna system was installed on the top of a 3-story building which is about 18 m high.

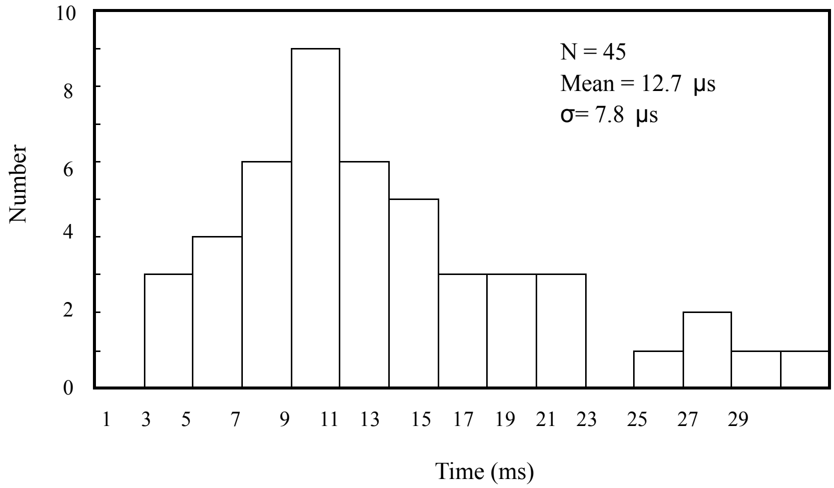

Fig. 2. Histogram of the time interval between the peak of the last leader pulse and the following first return stroke peak.

Table 1. Time interval ΔT_{LR} and ratio R_{LR} between the last stepped leader pulse peak to the following first return stroke peak.

Author	Region	Rang (km)	Mean ΔT_{LR} (μs)	R_{LR}
Krider and Radda (1975)	Florida, USA	100–200	14.9	0.1
Krider et al. (1977)	Arizona, USA	30–100	11.0	0.13
	Arizona, USA	20–50	–	0.07
Corray and Lundquist (1985)	Sri Lanka	100–200	9.8	0.1
Qie et al. (this paper)	Guangdong	6–10	12.7	0.1

3 Features of electric field changes produced by a natural negative-stepped leader

All the data analyzed in this paper were obtained on 25 July 1998. An example of the electric field recorded by using the wideband slow antenna system is shown in Fig. 1a. It was produced by a negative discharge that occurred at 12:33:44 (Beijing Time) at a distance of about 7 km. Three return strokes are marked with $R1$, $R2$, and $R3$ with time intervals of 41 ms and 60 ms, respectively. Figure 1b shows the time-expanded waveform before the first return stroke $R1$ in Fig. 1a. The abrupt changes in the first return stroke $R1$ are shown together with small pulses due to the stepped leaders.

It can be noted in Fig. 1b that the individual pulses of leader steps can be more easily distinguished when they are near the initiation of return strokes, especially within 200 μs of the return strokes. This may be due partly to the longer distance from the observation site to the upper part of the channel and the relatively low breakdown electric field needed for leaders propagating along the upper part of the channel with relatively low atmospheric pressure.

Forty-five negative CG lightning discharges to ground with obvious impulsive electric field changes preceding the first return strokes have been analyzed. The distance of these lightning discharges was about 6–10 km. In this paper, the stepped leader pulses within 200 μs prior to the initiation of first return stroke have been analyzed.

3.1 Characteristics of electric field changes produced by a stepped leader prior to the first return stroke

Detailed analysis was processed based on time-expanded electric field waveforms produced by stepped leaders of 45 negative CG lightning discharges. Figure 2 shows a histogram of the time interval between the peak of the last leader pulse and the following return stroke peak. The time interval between the first return stroke and the last step leader pulse ΔT_{LR} is from 2 to 30 μs , with a mean value of 12.7 μs and a standard deviation of 7.8 μs. The value agrees very well with the result given by Krider et al. (1977) of 11.0 μs. The results from different authors at different areas are listed in Table 1. It can be noted that mean ΔT_{LR} is not very different among different areas and different ranges. The biggest value is 14.9 μs by Krider and Radda (1975) in Florida, and the smallest is 9.8 μs by Cooray and Lundquist (1985) in Sri Lanka. Our result is in between.

The electric field variation between the last step pulse and the following first return stroke can be classified in three categories. Examples of time expanded electric field change from the three different types of stepped leaders are shown

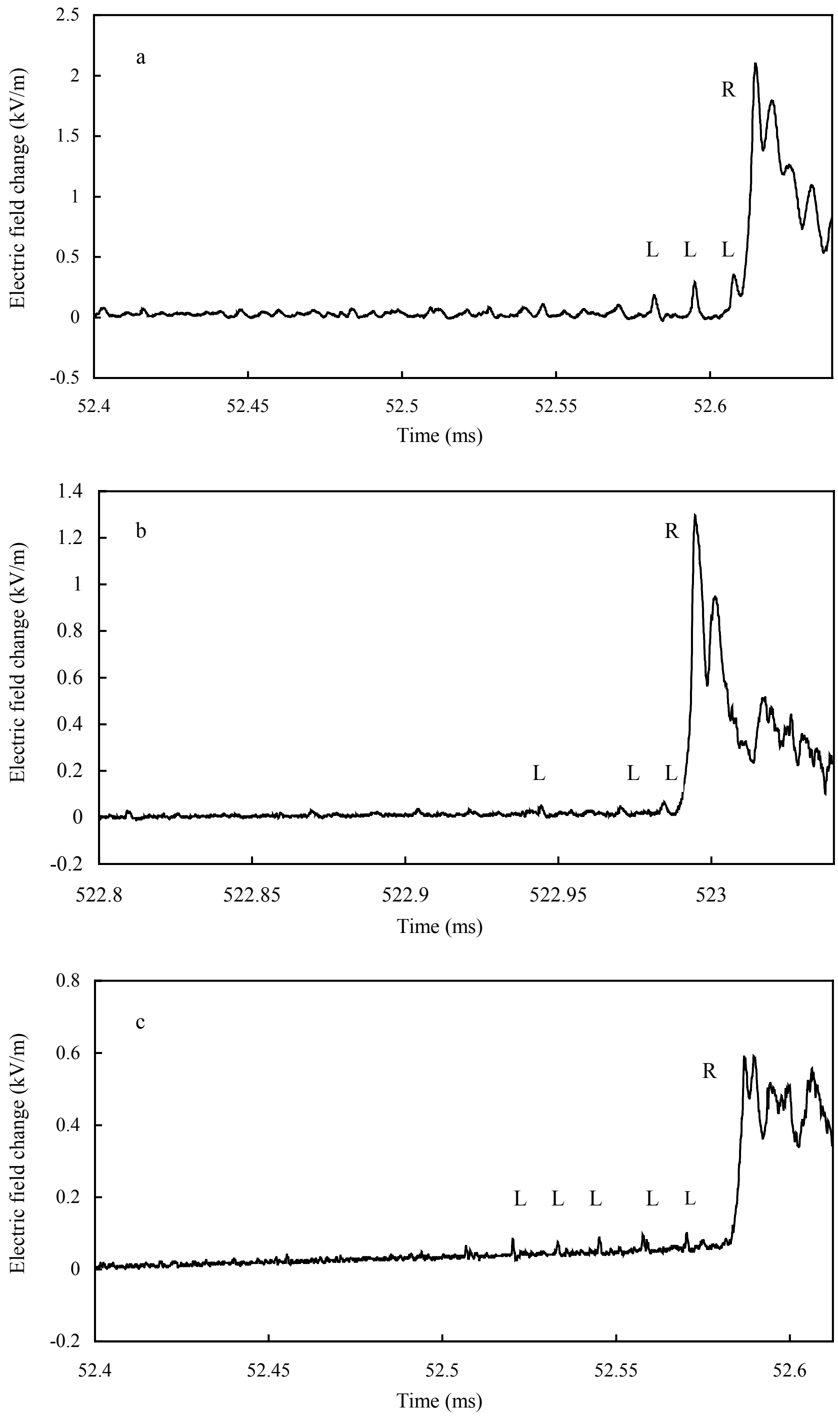

Fig. 3. Three categories of electric field changes between last stepped leader and the first return strokes.

in Figs. 3a–c. The first return stroke is marked with R, and the leader pulses are marked with L. All of the three negative discharges occurred in the same thunderstorm. The first type is characterized by a small pulse superimposed on the abrupt beginning of the return stroke, as shown in Fig. 3a, and accounts for 42% of all the cases. The second type, as shown in Fig. 3b, accounts for 33.3% of all the cases, and is characterized by relatively smooth electric field changes between the last leader step and the following return stroke. The third type, as shown in Fig. 3c, accounts for 24.7% of all the cases, and is characterized by several small pulses between the last recognizable leader pulse and the following return stroke. The time intervals between the peak of the last leader pulse and the following return stroke peak are 6.5 μs, 13.15 μs and 20.4 μs, respectively. The average peak of an electric field change caused by a return stroke, measured on top of a

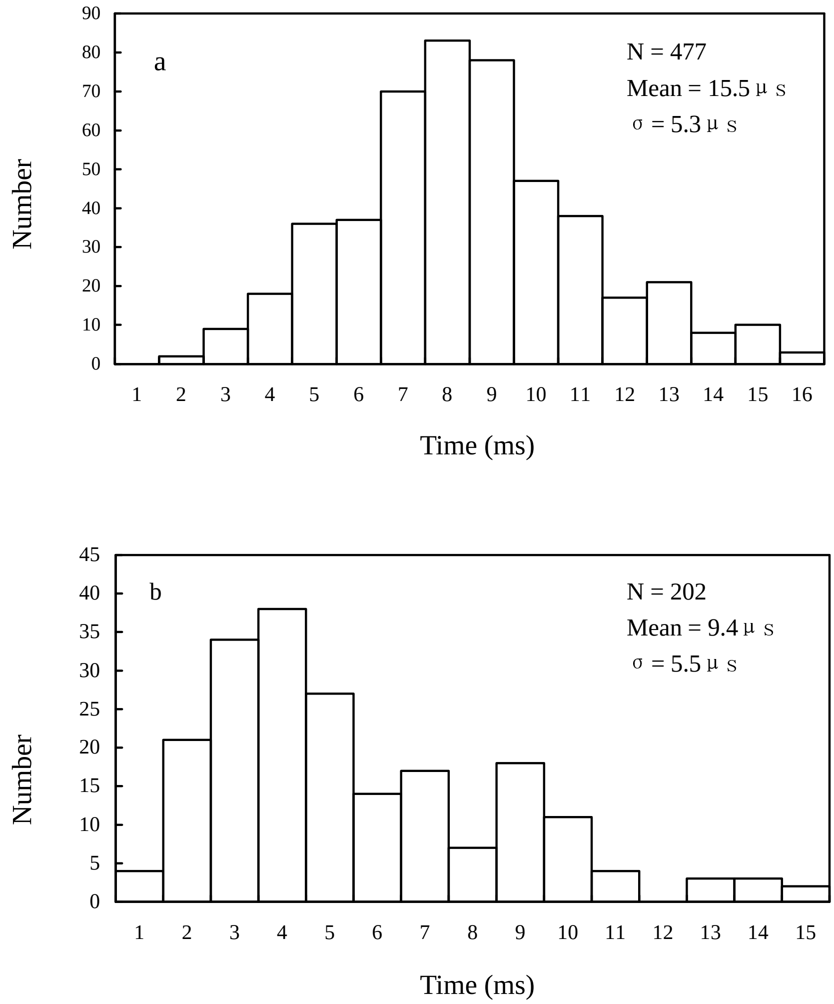

Fig. 4. Histograms of the time interval between successive step pulses, **(a)** for stepped leader, **(b)** for dart-stepped leader.

18-m high building, for each of the three stepped leader categories is 1.027 kV/m, 1.067 kV/m and 1.089 kV/m, respectively. These three types may be correlated with different channel branches, different upward connecting leaders from the ground and so on. Further studies are needed, such as by combining of the simultaneous optical observations, to clarify their mechanisms.

3.2 Statistic features of stepped leader pulses before the first return stroke

As mentioned above, it is difficult in our case to distinguish an individual leader step from an electric field waveform when it is far prior to the initiation of a return stroke. Therefore, the stepped leader pulses were analyzed primarily during a 200 μs period just prior to the start of the first return stroke in negative CG lightning discharges. Leader pulses of the stepped leader in Fig. 3 usually increase in amplitude as they become close to the initiation of the first return stroke, and the largest leader pulse is the last or next to the last pulse prior to the first return stroke. As can be noted in Fig. 3, most of the leader step pulses are unipolarity and symmetric, and have the same polarity as the following return strokes. The width of these pulses is 1.6–10 μs, with an average value of 4.6 μs. Figure 4a shows a histogram of the time interval between 477 successive leader steps for 45 negative CG lightning discharges. The distribution is quite similar to a Gaussian distribution. The time interval ranges from 2 μs to 31 μs, with a mean value of 15.8 μs and a standard deviation of 5.3 μs, which agrees well with the results of Beasley et al. (1983) in Florida, Krider and Radda (1975) in Florida and Krider et al. (1977) in Arizona.

The ratio of the last stepped leader pulse peak to the following first return stroke peak was analyzed for 45 CG lightning discharges. Since the distances of all analyzed ground discharges in this paper are 6–10 km, the effect of propagation on electric field waveforms was ignored for preliminary estimation. The ratio of the last leader pulse peak to the corresponding return stroke peak (R_{LR}) ranged from 0.04 to 0.19, with a mean value of 0.1 and a standard deviation of 0.04 for 45 cases. The results obtained by other authors are shown in Table 1. It can be noted from Table 1 that our result

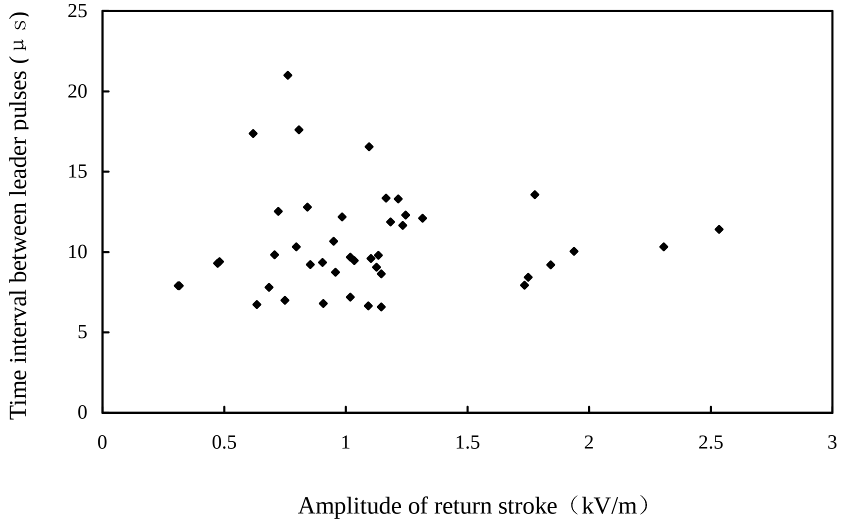

Fig. 5. Scatter plot of the time interval between leader step pulses versus amplitude of the following return stroke pulse.

agrees rather well with that obtained by other authors.

Figure 5 shows the scatter plot of the average time interval between leader step pulses versus the amplitude of the following return stroke pulse. It can be noted that the average time interval of a stepped leader does not change very much with an increase in the return stroke peak. This suggests that the average stepped leader interval in different CG lightning discharge processes does not retain obvious changes, although an individual stepped leader interval in a certain CG lightning discharge could vary from 2 μs to 31 μs.

3.3 Pulsating electric field waveforms produced by dart-stepped leader

Forty-six percent of the 45 negative discharges that contain more than one return stroke, in which 38% contain second return strokes and 34% contain third return strokes, exhibit impulsive electric field features called dart-stepped leaders. These percentages agree well with that obtained by Rakov et al. (1994) for the second return stroke of lightning discharges, which was 36%. Figures 6a and b show the time expanded electric field waveforms of two leader-return stroke processes that occurred at 12:28:41 and 13:10:43 (Beijing Time), respectively. The stroke intervals preceding the two return strokes are 30 ms and 85 ms, respectively. It can be noted in Fig. 6a that the leader waveform is smooth with little step-like pulses, while that of Fig. 6b is characterized by step-like pulses, possibly indicating that leaders of subsequent return strokes corresponding to a long stroke interval are more likely to show stepping. The leader pulses in Fig. 6b are quite similar to a stepped leader in amplitude and the interval between successive leader pulses is shorter than that of a stepped leader. The average time interval between subsequent return strokes with a dart-stepped leader is about 74.7 ms, while that of the other 62% of the second return strokes and 66% of the third return strokes not corresponding to dart-stepped leaders is about 26.7 ms. These indicate that leaders before subsequent return strokes corresponding to a relatively long stroke interval are more likely to be dart-stepped leaders. In addition, there are 4 subsequent return strokes preceded by impulsive electric field changes, which is similar to that preceding the first return strokes, and the corresponding stroke interval is 16.9 ms. These leader signals are probably produced by the formation of a new leader channel.

The pulses produced by a dart-stepped leader process are quite similar to that of a stepped leader in amplitude, while the time interval between successive dart-stepped leader pulses is quite different from that of a stepped leader. Figure 4b shows a histogram of the time interval between 202 successive dart-stepped leader pulses for 29 negative ground discharges. The mean time interval between successive leader pulses is 9.4 μs, with a standard deviation of 5.5 μs, which agrees well with the results of Krider et al. (1977) obtained in Florida and Arizona. On the average, the time interval between successive dart-stepped leader pulses is shorter than that between successive stepped leader pulses. The studies of Orville and Idone (1982) indicated that the stepping part of a dart-stepped leader propagated with a velocity greater than that of a stepped leader preceding the first return strokes, and had a shorter time interval between successive leader steps, which agrees with our results.

The distribution of the time interval between successive dart-stepped leader pulses is different from that of stepped leaders, as shown in Figs. 4a and b. The distribution in Fig. 4a is quite similar to a Gaussian distribution, while that in Fig. 4b is more similar to a log-normal distribution.

4 Discussion

The time domain electric field changes produced by 45 natural negative CG lightning discharges have been used to analyze the electric field characteristics produced by stepped

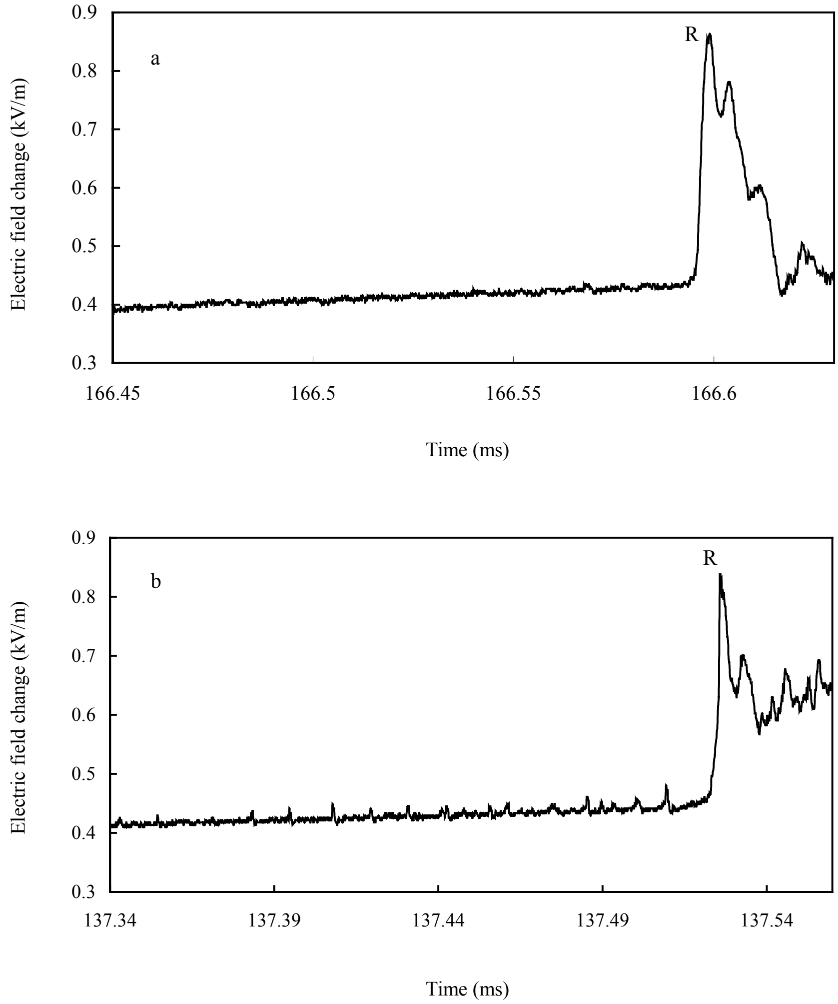

Fig. 6. Electric field produced by a leader just before the initiation of a subsequent return stroke, **(a)** dart leader occurred at 12:28:41 (Beijing Time), and **(b)** dart-stepped leader occurred at 13:10:43 (Beijing Time) on 25 July 1999.

and dart-stepped leaders 200 μs prior to the initiation of return strokes of negative lightning discharges to ground. The time interval between successive stepped-leader pulses is 1.7 times larger than that of dart-stepped leaders. The dart-stepped leader preceding the subsequent return strokes propagates completely or partly, following the previously formed channels with relatively good conductivity, high temperature and so on, which facilitates the propagation, while stepped leaders preceding the first return strokes have to develop a new channel by air breakdown. Therefore, a long interval is needed for stepped leaders to develop a new step. The better the channel conditions are, the less charge is required in the tip of a stepped leader to drive the leader propagating through the channel to ground. Observations of Rakov et al. (1994) also indicated that leaders of lower-order subsequent return strokes following previously formed and relatively young (100 ms or less) channels were more likely to show no stepping at all.

The relationship between the average time interval of successive steps of dart-stepped leaders and the corresponding stroke interval preceding the subsequent return strokes is shown in Fig. 7. It can be noted that the distribution of the time interval between successive steps of dart-stepped leaders is discrete when the stroke interval is shorter than 25 ms, but is positively proportional to the stroke interval when it is longer than 25 ms. Dart-stepped leaders preceded by a short stroke interval (less than 25 ms) are more likely to create a new path similar to the stepped leader before the first return stroke. The time interval between successive steps of dart-stepped leaders relates closely to the previous channel status, such as the number density of ions, the temperature, or the pressure in the previous channel and so on. The longer the time interval is between successive steps of dart-stepped leaders, the worse the conditions of the previous channel for leader progression. Therefore, the time interval discrepancy between the stepped and dart-stepped leaders might be mainly due to the difference in the channel conditions.

The classification of stepped leader-return stroke electric field change based on the characteristics of electric fields immediately preceding first return strokes has not been

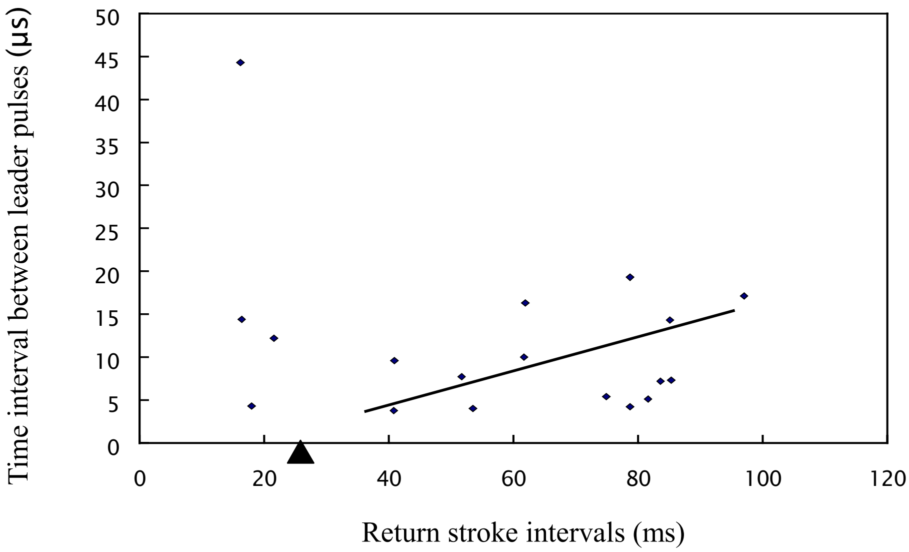

Fig. 7. Distribution of time interval between successive leader pulses for different stroke interval.

mentioned in previous literature. In a paper by Krider et al. (1977), they found that the abrupt beginning of a return stroke is preceded by a string of small pulses associated with the stepped leader and the last such step is visible in the record just before the beginning of the return stroke which is similar to the first type in this paper. Due to the absence of other simultaneous observations, the conclusions presented in this paper need to be further confirmed. To better understand these processes, we should employ more extensive and comprehensive observations.

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