Research on chaotic leader in cloud-to-ground lightning

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ABSTRACT: Based on the data of optical and electromagnetic signals detected during the comprehensive observation experiment on lightning discharge in Guangdong province in 2012 and 2013, the comprehensive characteristics of chaotic leader (CL), including multi-scale entropy of electric field change, optical radiation, wideband radiation (bandwidth 300M) and occurrence regularity, have been analyzed in detail. The results show that two types of CL can be identified. One type exhibits the chaotic pulse connecting to RS, the other type begins with chaotic pulse followed by regular pulse before RS. According to our statistics, near 50% of subsequent return strokes (SRS) are preceded by CL. At the same time, almost all of CLs are accompanied by obvious optical signal, which indicates that CLs tend to occur below the cloud, and near 80% CLs also show a large change of electric field profile. One case shows that CL pulse is a typical discharge signal of obvious attempted leader. The average power spectral density of CL shows substantially higher radiation power in the frequency range of 0-300MHz than that of non-chaotic subsequent leaders. In addition, we found that multi-scale entropy may be used as characteristic parameter to describe CL pulses. There are different entropy values for different leaders such as stepped leader and CL. The value for CL is larger than 1.5 with the scale of over 3(the average value of multi-scale entropy, from 2.0 to 2.1).

INTRODUCTION

Leader process, as an important discharge process of lightning, has drawn continuous attention. In addition to those conventional leader processes, such as stepped leader and dart leader, there is a somewhat controversial class of events usually known as 'chaotic leader (CL)' (as shown in figure1). CL had been presented firstly by Weidman et al. [1982]. He found the irregular pulse train before subsequent RS, and termed these return strokes as 'Chaotic subsequent strokes' or subsequent strokes preceded by 'Chaotic Leaders'. In general, Chaotic leader has been used to refer to a relatively continuous sequence of irregular electric field pulses occurring within about 2 ms preceding a subsequent return stroke in natural lightning [Lan et al., 2011] or triggered lightning [Hill et al., 2012], but no consistent definition has yet emerged.

The previous research about CL has focused on the waveform characteristics of electric field, such as pulse width, duration and pulse interval [Weidman et al., 1982; Makela et al., 2007; Gomes et al., 2004]. However, as continuous sequence of irregular electric field pulses, it is difficult for CL pulses to be accurately described only by pulse parameters. At the same time, considering the characteristics of high

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frequency radiation, it is also difficult to give a sufficient information of CL due to the limit frequency range in the previous research. In addition, there is also little report about the detailed process of CL discharge. Up to now, the research on chaotic leader is still not adequately detailed.

In the work, the comprehensive characteristics, including multi-scale entropy of electric field change, optical radiation, wideband radiation (bandwidth 300M) and occurrence regularity, have been analyzed in detail by the comprehensive data of optical and electromagnetic signals which has been observed during the comprehensive observation experiment on lightning discharge in Guangdong province in 2012 and 2013.

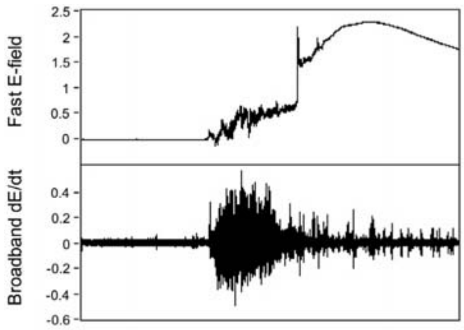


Figure 1 Classical chaotic leader shown by Lan [2011]

EXPERIMENT AND DATA

The electromagnetic radiation, optical radiation, and high-speed video images were detected by optical-electromagnetic observation system during summer season. The measurements were conducted at Conghua of Guangzhou province (latitude 23.34N and longitude 113.36E) in the periods of May to August, 2012 and 2013. The detection focus on the close lightning discharge (0–20 km), so that the optical-electromagnetic signal can be fully recorded. The detection sensor include optical detector (200-3 MHz), fast antenna (200 Hz-3 MHz), broadband biconical antenna (0.1M-300MHz) and high-speed video (3000 fps). The record method was designed as a segmented collection. The waveforms of optical radiation (200Hz-3MHz), low-frequency electromagnetic filed (200Hz-3MHz), high frequency radiation (3-30MHz), and VHF radiation (30-300MHz) had been recorded by the data acquisition cards with 10MS,100MS and the high speed oscilloscope with 1Gpt. The video images were recorded by the special computer. And the acquisition equipment was synchronized by the same trigger resource and GPS timestamp.

RESULTS

Occurrence regularity

According to our statistics, 72 cases out of 140 subsequent stroke is accompanied by chaotic leader. The percentage of subsequent stroke preceding to CL is near 50%. At the same time, two types of chaotic pulse (type I and type II) preceding RS can be identified. Figure 2 and Figure 3 show the electric field waveforms of Type I, II and expand scale waveforms. 58 type I and 14 type II have been found out of 72 chaotic leaders. The percentages are 81% and 19%, respectively. The first type of chaotic leader (defined as type I) exhibit continuous irregular pulses before return stroke, however the second type of chaotic leader (defined as type II) begins with chaotic pulses and then followed by some relatively regular pulse train (last for several hundred μs and the interval some μs) before RS. According to Krider et al. [1977], when referring to the statistics for dart-stepped leader pulses, the average pulse interval is 6.5 and 7.8μs for subsequent strokes as measured in Florida and Arizona, respectively. Thus, it is reasonable to believe that the regular pulse train in type II indicates a discharge process of dart-stepped leader. Therefore, the type II can be considered as a hybrid leader.

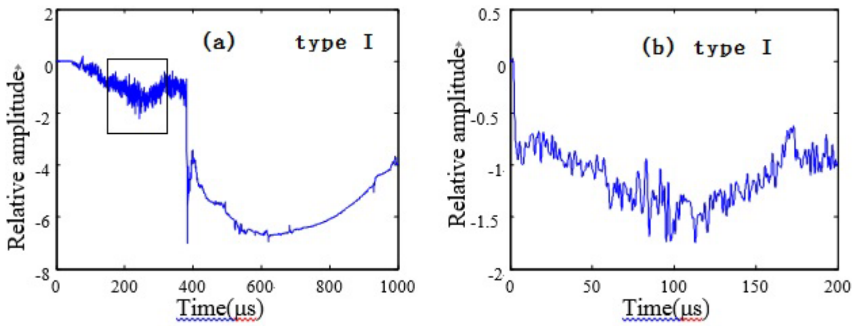


Figure 2 Electric field waveform of chaotic leaders (a) type I and (b) an expand scale

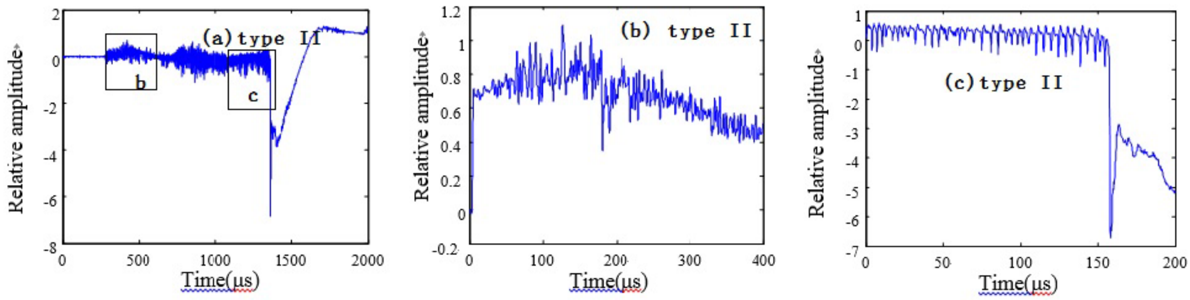
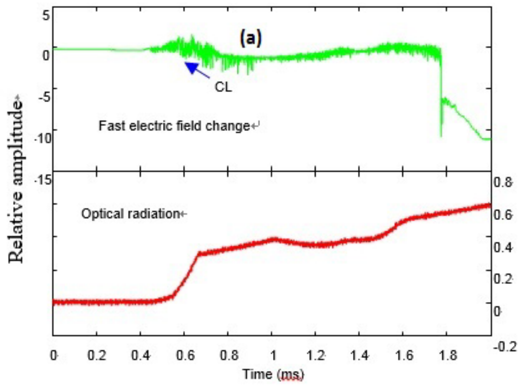


Figure 3 Electric field waveform of chaotic leaders (a) type II and (b，c) an expand scale

Characteristics of CL

1) Optical radiation and high-speed video

As shown in figure 4, the chaotic leader (CL) exhibits obvious optical signal in the corresponding position of electric field waveform, which indicate that the discharge signals occur below the cloud. According to the relative position between the pulses and return stroke, it is reasonable to believe that the chaotic pulses occur in a leader process. Therefore, we define the pulse chaotic leader. According to our statistics, almost all of the CL pulses are accompanied by the obvious optical radiation. Based on the synchronous data of high-speed video and electric field change in a case, we found that the CL pulse is a typical discharge signal of obvious attempted leader.



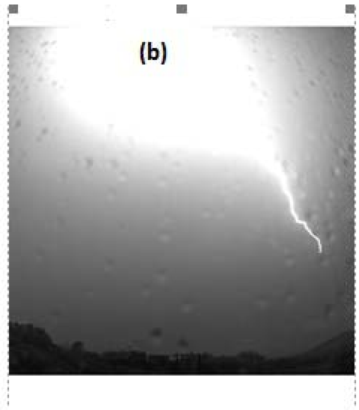


Figure 4 (a)Waveforms of optical radiation and electric field change for chaotic leader and (b) high-speed video image accompanied by CL

2) Irregular characteristics

In order to represent the irregularity, we propose multi-scale entropy to analyze the chaotic leader. The multi-scale entropy method, which develops from sample entropy, has been applied in the analysis of noise signals. About the method of multi-scale, if the sample entropy increases monotonically on the scale, then the time series is complex. Conversely, if the sample entropy decrease monotonically on the scale, then the time series is less complex.

In our work, multi-scale entropy are applied to the analysis of three kinds of leader signals: dart leader signal, stepped leader signal and the chaotic leader signal .The sample number of each leader is 30. In Figure 5, the average value of multi-scale entropy in 10 scale are shown. The entropy values of chaotic leader, stepped leader and dart leader increase with scale and then stabilized. Furthermore, after statistical analysis of 30 cases of the three leaders, we can see that there are obvious difference in the entropy values of chaotic leader, stepped leader and dart leader. Especially when the scale is greater than 3, the three leader can be clearly distinguished by its entropy value. Entropy value greater than 1.5 may be typified as chaotic leader, entropy value less than 1.5 are typified as stepped leader or dart leader.

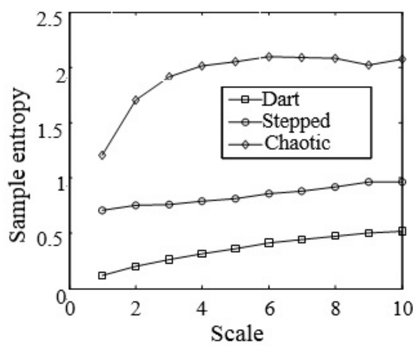


Figure 5 Multi-scale entropys of dart leader, stepped leader and chaotic leader

3) Power spectral features

In order to calculate the intensity of radiation, an average spectrum was analyzed in terms of the PSD (power spectrum density). The PSD of CLs shows a well agreement with the spectral of chaotic leaders obtained by Willett et al. [1990]. According to the broadband observation, the dart-stepped leader always present as a weak radiation source in many cases. Nevertheless, the chaotic leader have stronger broadband radiation. Figure 6 compares the average PSD (20-300MHz) of chaotic leaders (30 samples) with that of dart-stepped leaders (30 samples), the spectrum has been normalized to a range of 50 km. As shown in Figure 6, the radiation energy of chaotic leader decreases rapidly with an increase of signal frequency when the signal is less than 50MHz. When the signal is over 50MHz, the decrease tendency begins to change slowly. And the radiation energy of dart-stepped leader is smaller than that of chaotic leader. Power spectrum density of dart-stepped leader is lower than about 1-8 dB than that of chaotic leader over the entire band.

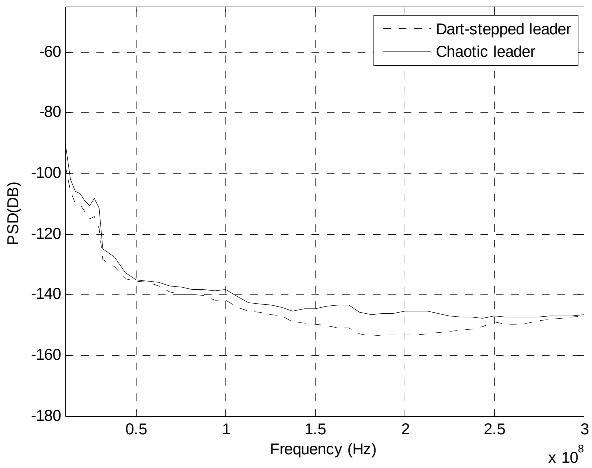


Figure 6 Average power spectrum density (PSD) of chaotic leader and dart-stepped leader.

CONCLUSIONS

The comprehensive characteristics of chaotic leader (CL), including multi-scale entropy of electric field change, optical radiation, wideband radiation (bandwidth 300M) and occurrence regularity, have been analyzed in detail. The result is as follows.

(1)According to the statistical results, near 50% of subsequent return strokes (SRS) are preceded by CL and two types of CL also has been identified. One type exhibits the chaotic pulse train connecting to RS, the other type begins with chaotic pulse, followed by regular pulse before RS. The percentage of the two types are about 81% and 19%, respectively. It is reasonable to believe that type II is a hybrid leader which include chaotic leader and dart-stepped leader.

(2) Almost all of CLs are accompanied by obvious optical signal, which indicates that CLs tend to occur below the cloud. At the same time, near 80% CLs also show a large change of electric field profile. The average power spectral density of CL shows substantially higher radiation power in the frequency range of 0-300MHz than that of non-chaotic subsequent leaders. In addition, one case shows that the CL pulse is a typical discharge signal of obvious attempted leader.

(3) The multi-scale entropy as a characteristic parameters can be used to distinguish the chaotic leader and the other leader processes (such as stepped leader and dart leader). The value for CL is larger than 1.5 with the scale of over 3(the average value of multi-scale entropy, from 2.0 to 2.1,). Entropy value less than 1.5 are a criteria of stepped leader or dart leader.

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REFERENCES

Weidman, C. D. 1982: The submicrosecond structure of lightning radiation fields, Ph.D. dissertation, Univ. of Ariz., Tucson.

Makela, J. S., M. Edirisingheb, M. Fernandob, R. Montano, and V. Cooray,2007: HF radiation emitted by chaotic leader processes, J. Atmos. Terr. Phys., 69, 707–720

Gomes, C., V. Cooray, M. Fernando, and R. Montano, 2004: Characteristics of chaotic pulse trains generated by lightning flashes, J. Atmos. Terr.Phys., 66, 1733–1743

Lan, Y., Y. Zhang, W. Dong, W. Lu, H. Liu, and D. Zheng, 2011: Broadband analysis of chaotic pulse trains generated by negative cloud-to-ground lightning discharge, J. Geophys. Res., 116, D17109

Krider, E. P., C. D. Weidman, and R. C. Noggle, 1977: The electric fields produced by lightning stepped leaders, J. Geophys. Res., 82(6), 951–960

Willett, J. C., J. C. Bailey, C. Leteinturier, and E. P. Krider, 1990: Lightning electromagnetic radiation field spectra in the interval from 0.2 to 20 MHz, J. Geophys. Res., 95(D12), 20367–20387

Hill, J. D, M.A. Uman, D. M. Jordan, J.R. Dwyer and H. Rassoul, 2012: “Chaotic” dart leaders in triggered lightning: Electric fields, X - rays, and source locations. J. Geophys. Res., 117(D3), D03118