Broadband Interferometer Observations of Lightning in China

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[Abstract] The bi-directional propagations of the lightning channel within clouds have been observed by use of a lightning broadband interferometer system. After a lightning flash is initiated within the negative charge region of clouds, its channel developments show bi-directional propagations with two concurrent breakdown processes extending in opposite directions from the extremities of the lightning channel. Radiation field spectra of the two concurrent breakdown processes at the extremities of the lightning channel are quite similar, indicating that the both may be negative breakdown and may be caused by the same mechanisms. During the period of the channel bi-directional propagations, the electric field change indicates that the negative charge moves upward along the channels.

Introduction
The concept of bi-directional propagations of the lightning channel was firstly proposed by Kasemir\cite{1,2} in the 1960s. Later in the 1990s, with the development of the altitude-triggered lightning technique, bi-directional propagation leaders initiated from the two ends of a floating conductive wire were confirmed based on the high-speed camera photographs and the measurements of the current and electric field\cite{3}. It is easy to be accepted that a positive leader and a negative leader are initiated respectively from the upper and lower ends of the floating wire in the altitude-triggered lightning, but it is disputed whether the bi-directional propagation leaders are initiated within clouds in natural lightning. Techniques of locating and tracking the radiation events from lightning flashes have been the most important methods to study the inception and development of a lightning flash. Because of the limitation of equipments used, however, evidences of the bi-directional propagation channel in natural lightning have not been observed by using the early time-of-arrival technique and the VHF radio interferometer\cite{4,5}. Mazur et al. considered the reason that the phenomena of the bi-directional propagation leaders were unable to be observed could be the weakness of VHF radiation produced by the positive leaders or/and the interferometer’s limited capability to discriminate simultaneous multiple sources \cite{6}. In recent years, the phenomenon of the bi-directional propagation of the lightning channel in natural flashes has been observed by us with a broadband interferometer system in southern China. This paper presents our observation results of the bi-directional propagations of the lightning channel and discusses the characteristics of the bi-directional propagations.

Observation and Results
The broadband lightning interferometer system used in this study employed three identical broadband flat plane antennas, which were separated horizontally with a baseline’s length of 10 meters. These antennas were located at three apexes of a square and connected via three 50-meter-long coaxial cables terminated with characteristic impedance of 50 ohms to a four-channel digital storage oscilloscope (DSO) through 25 MHz high pass filters. The record length of each channel is 2 M samples. In the experiment, the oscilloscope sample rate was set at 1 GHz and its memory of each channel was divided into 2000 segments so as to record the whole discharge process of a lightning flash. Each segment could record 1000 sample points and was pre-triggered by 400 sample points. Along with the broadband interferometer, outputs of a slow electric field change antenna with a decay time constant of 6 seconds and a fast electric field change antenna with a decay time constant of 100 microseconds were recorded concurrently with a sample rate of 1 MHz and a recording length of 1 M samples for each channel. The hardware configuration and the theory of radiation source location of the broadband interferometer system have been described in detail by Dong et al. \cite{6}. In this paper, the sign convention of the electric fields is that a negative change corresponds to the removal of a positive charge above the observation site. The azimuth increases clock-wise from North (0').
The bi-directional propagation of channels in the initial period of a CG flash

Fig.1a is the overview of radiation source locations in azimuth-elevation format for a CG flash observed China. The progression direction of the lightning radiation sources is marked with the arrow. The location at which the lighting initiated is marked with S. This flash lasted about 300 ms with single stroke from cloud to ground. Figure 1b and 1c show the expanded waveforms of the fast electric field change (\(\Delta E_F\)) and slow electric change (\(\Delta E\)) for preliminary breakdown process from 0 to 40 ms, respectively. As seen in the figure, there are 6 obvious positive pulse trains in the waveform of \(\Delta E_F\). The short vertical lines in Fig. 1c, which mark the time sequence of occurrence of the broadband lightning electromagnetic pulses, mainly are emerged in the phase of each pulse train, indicating that the intermittent pulses characterize the radiation in the preliminary period of the CG. Figure 1d to 1f show respectively the locations of the lightning radiation sources with the elevation (El) and the azimuth (Az) of radiation sources in time sequences and the azimuth-elevation format. The progression directions of the lightning radiation sources are marked with arrows. As seen in Figures 1d and 1f, the elevations of the radiation sources are increasing and its azimuths are decreasing during the occurrences of pulse trains 1 to 3. The lightning channel in this period show an upward extension from the start region S in general with little reverse extension (the arrow A in Figure 1f). The positive electric field changes in Figure 1c suggest that these breakdown processes transfer net negative charges upward. During the occurrence of the pulse trains 4 to 6, however, the radiation sources appear alternately at both sides of the previously formed channel, showing a bi-directional extension of the channel (see Figure 1d and 1e, and arrows A, B1 and B2 in Figure 1f). The positive electric field change in this period means that negative charges are transferred upwards during this bi-directional propagation period. During the initial 15 ms of the breakdown process, the lightning channel develops upwards obliquely and negative charges are transferred away from the start region of the lightning. This is consistent with the results obtained by Rhodes with the narrowband interferometer [7]. During the period of 16 ~ 36 ms, the radiation sources appear alternately at the two ends of the earlier formed channel. This phenomenon belongs to a new result observed firstly by using the broadband interferometer, which has not been observed by using the early time-of-arrival techniques and the VHF radio interferometer systems. The manner of the lightning channel propagation observed here is similar to the description of the bi-directional propagation of the lightning channel proposed by Kasemir. The positive electric field change in this period means that negative charges are transferred upwards along the previously formed channel. In this point, it differs from the conception of Kasemir’s theory, in which the leader channel is supposed to be electrically neutral.

![Fig.1](image.png)

Fig.1 Radiation source locations and electric field change in azimuth-elevation format of a CG flash
(a) Radiation source locations in azimuth - elevation format
(b) Fast electric field change (\(\Delta E_F\));
(c) Slow electric field change (\(\Delta E\));
(d) Elevation of radiation sources in time sequences;
(e) Azimuth of radiation sources in time sequences;
(f) Radiation source locations in azimuth-elevation format.
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Figure 2a and 2b show respectively the overall time waveform of the electric field change (ΔE) and overview of the radiation source locations in azimuth-elevation format for a CC flash. This flash lasted about 260 ms. The region where the flash began is marked with S.

Figure 2c and 2d show respectively the locations of the lightning radiation sources with the elevation (El) and the azimuth (Az) of radiation sources in time sequences during the period of 0 ~ 110 ms. For the initial 5 radiation sources, their azimuths have a little variety and elevations vary from 38˚ to 43˚. The lightning channel develops upwards nearly vertical. The positive electric field change in this phase means that negative charges are transferred upwards and the breakdown processes are of negative polarity. During the period of 5 ~ 28 ms, the lightning channel extends horizontally from the start region S, as the arrow B shown in Figure 2b. The positive electric field change means that negative charges are transferred upwards along the early formed channel A during the extension of the horizontal channel B. During the period of 28 ~ 110 ms, the radiation sources appear alternately at the two ends of the channels A and B, forming two channels developing simultaneously in different directions, as the arrows B1 and B2 shown in Figure 2b. This also can be seen obviously in Figure 2c and 2d. During the period of 28 ~ 40 ms, the channel B2 proceeds almost along the early channel A. The positive electric field change implies that negative charges are transferred upwards and away from the observation site. The reason that the strong radiation sources have been detected in the early formed channel A again cloud be the declination of the A channel conductance with time. Some strong breakdown processes may occur when the electric charge flows along the old poor channel A during the B2 development. The negative electric field change during period of 40 ~ 76 ms implies that the channel extends horizontally in a direction towards the observation site in this period. From time 76 to 110 ms, the channels B1 and B2 extend in a zigzag manner, which may be related to the complex distribution of the positive and negative charges within the thunderstorm. General speaking, for the period of 28 ~ 110 ms, the lower channel B1 propagates horizontally inside the main negative charge region, while the upper channel B2 propagates firstly from the lower negative charge region towards the upper positive charge region and then inside the upper positive charge region of the thunderstorm. Consequently, the lightning channel behaves as a bi-directional propagation and negative charges are transferred along the channel upward from the main negative charge region to the upper positive charge region of the thunderstorm. This is approved by the waveform of ΔE recorded synchronously.

Conclusion and Discussion

On observations by using a broadband interferometer, the developments of lightning channels within clouds have the characteristics of bi-directional propagations for both CC and CG lightning. The phenomena of bi-directional propagations in natural flashes could be confirmed with the broadband interferometer system is apparently due to that the broadband interferometer system is able to partially locate and discriminate noises from simultaneous multiple sources [6]. We conclude that the breakdown processes occurring at both ends of the bidirectional propagating channels of the lightning flashes in this study are of negative polarity. As the channel formed at the very beginning of the lightning near the start region has a high conductivity, it can be viewed as a conductor with equal potentials and there is an increasing potential difference between the channel and the charged particles around it. The breakdown process at one end of the channel is of negative polarity as usual. For the breakdown process at another end of the channel, the process may be as follows. Under the effects of strong local electric filed, a short negative breakdown process occurs firstly in front of the channel tip, and then it propagates backward to the tip of the channel. Such a negative breakdown process occurs repeatedly, resulting in that the lightning channel extends forward like a positive streamer but negatively charged in actual. Such a phenomenon of reverse propagation of the lightning channel was observed by Shao et al. also by using the VHF radio interferometer [5,8]. The physical mechanism of
breakdown processes relevant to this reverse propagation of the lightning channel and its distinction from the positive breakdown processes need to be investigated further.

References