2016 24th International Lightning Detection Conference & 6th International Lightning Meteorology Conference
18 - 21 April | San Diego, California, USA

A Short-Baseline Lightning VHF Location System in SHATLE and Observations on Lightning Discharge

Mingyuan Liu, Xiushu Qie,Zhuling Sun, Rubin Jiang, Hongbo Zhang
Key Laboratory of Middle Atmosphere and Global Environment Observation (LAGEO), Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China, 100029
lium@mail.iap.ac.cn

***Abstract*—A short-baseline lightning VHF location system has been developed during the SHandong Artificially Triggering Lightning Experiment (SHATLE) for last 5 years. The system could image the lightning channel development with high time-resolution in 2 dimensions. With the improvement on the system sensitivity and data recording method, the system successfully realized the continuous or sequential signal acquisition over the entire duration of a lightning flash. The temporal and spatial development characteristics of a negative cloud-to-ground lightning flash is discussed using the radiation location results, combining with simultaneous observations of fast/slow electric field changes. The speeds of the preliminary breakdown process and stepped leaders were about 10^5 m/s, and the speeds of the K processes after the return stroke were about 10^6–10^7 m/s.**

Keywords—lightning location; VHF; short-baseline

I. Introduction

Very high-frequency (VHF) radiation signals are generally emitted during small-scale breakdown processes in lightning discharges and can be used to locate lightning channels both outside and inside the cloud and depict the detailed evolution of lightning flashes. A short-baseline lightning VHF location system has been developed to image the lightning channel development with high time-resolution in 2 dimensions for last 5 years, and has been applied in the SHandong Artificially Triggering Lightning Experiment (SHATLE) [Qie et al.,2009]. A great deal of data on natural and rocket-triggered lightning discharges was documented by using the location system. In this paper, a brief summary of the short-baseline location system is presented, and radiation sources location result of a negative cloud-to-ground lightning flash is also analyzed in detail.

II. Short-Baseline Location System

The primary principle of the lightning location system is using generalized cross correlation time delay estimation algorithm to determine the time-difference of arrivals between a couple of antennas within a short distance, and then obtain the direction of the radiation source in two-dimensional azimuth and elevation format using at least 3 non-collinear antennas. During the time delay estimation, a parabolic interpolation algorithm was adopted in the peak estimation of the cross power spectrum to improve the time resolution of the location system [Sun et al. 2013].

In the short-baseline lightning VHF location system, four broadband discone antennas with mutually orthogonal baselines are used to receive lightning VHF radiation signals. Each antenna signal is sequentially passed through the band-pass filter, amplifier and then is transmitted to the data acquisition equipment through the coaxial cable with the same length and frequency response. Meanwhile, a fast antenna and a slow antenna were used to measure the synchronous lightning electric field changes with different bandwidth and decay time constant, and the electric signals were sampled by a digitizer. In practice, the VHF signals acquisition was externally triggered by the digitizer, and the trigger time was provided by the high-time accuracy GPS for a cooperating analysis with other observations.

In the early stages of the short-baseline location system, the bandwidth of the band-pass filter is about 125–200 MHz, and VHF signals were acquired by a LeCroy oscilloscope at a sampling rate of 1 GS/s with an 8-bit vertical resolution. Due to the so high sampling rate and the device memory limit, sequential record mode is used. In order to enhance the detection efficiency, the location system has been improved in the last three years, the bandwidth of the band-pass filter was changed to 140-300 MHz in 2013 and then changed to 35-70 MHz due to the stronger lightning radiation signals in 2015. Both a high-performance LeCroy oscilloscope and a mass memory waveform digitizer have been used for data acquisition equipment at a sampling rate of 1 GS/s with either an intermittent record mode or a continuous record mode. The orthogonal baseline length is between 7 m and 12 m due to the space restraint. By using the LeCroy oscilloscope, the data acquisition vertical resolution is 12 bits, and each channel can record up to 10000 segments with 2002 samples for each segment, and the intersegment time is 2 μs. By using the mass memory waveform digitizer, the lightning VHF radiation signals can be recorded over 1 s with a vertical resolution of 8 bits, and the whole process of a lightning flash is possible to be completely depicted. In addition, the time accuracy of GPS Disciplined Oscillator was increased and specifications of the fast/slow electric field change were also modified from 50 ns to 25 ns. By convention, the remove of negative charge in the cloud is defined to produce a positive electric field change in this paper.

III. Analysis And Results

The negative single-stroke CG lightning occurred at 21:33 UTC 2 August 2013. Using the time interval between the perception of lightning and the first sound of thunder, the lightning was estimated to be about 2 km away from the short-baseline location system. Fig. 1 shows the VHF radiation field detected by the location system and simultaneous electric field changes of the lightning recorded by the fast and slow antennas. Time zero represents the incipient moment of the fast electric field change signal. The flash lasted about 240 ms and the return stoke happened at about 81 ms, followed by a short-duration continuing current to ground lasting 3.5 ms. Finally, the flash finished with a sequence of typical K processes. The VHF radiation mainly concentrated in the phases before the return stroke and near the times of the K processes; while after the return stroke, the VHF radiation lasted just 0.2 ms and became almost quiescent in the continuing current.

Fig. 2 presents the radiation source locations for the whole CG lightning in two dimensions. The azimuth increases in a clockwise direction from the north. The color changes with time from blue to red. It can be seen that the lightning started in the south of the observation station at 68° elevation, which is marked by an “S” in Fig. 2. The whole lightning channel expanded widely, and the lightning made contact with one ground termination. Using the location result of the lightning radiation sources, the major lightning discharge developments are described in detail in the following sections.

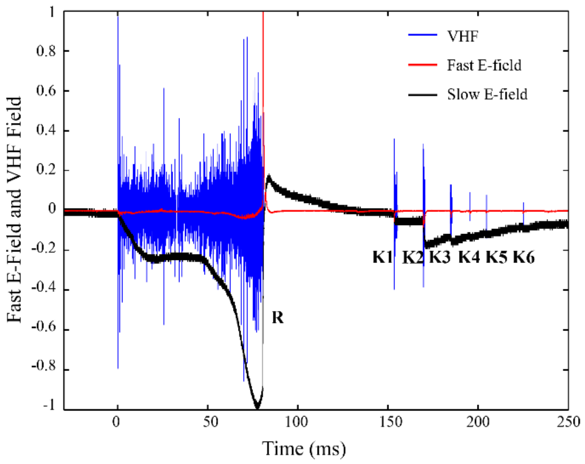

Fig. 1 The very high frequency (VHF) radiation field detected by the short-baseline location system and simultaneous electric field changes of the lightning recorded by the fast and slow antennas. R indicates the return stroke and K1–K6 indicate the six K processes.

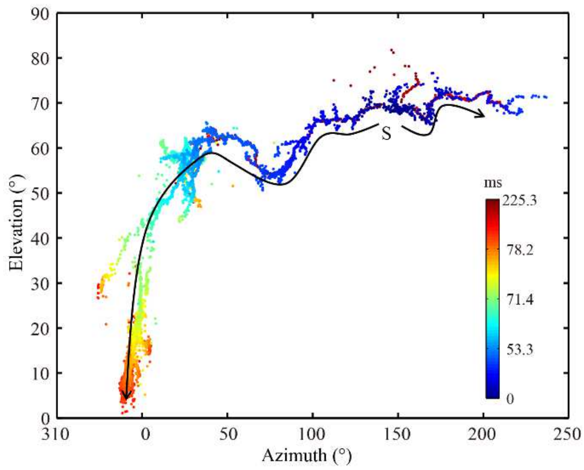

Fig. 2 2D VHF radiation source locations of the whole cloud-to-ground lightning flash. S indicates the start region of the lightning discharge.

A. The preliminary breakdown and the leader

Fig. 3a shows the electric field change of the period preceding the return stroke, which was found to be consistent with the so called BIL model defined by Clarence and Malan [1957]. In this model, the whole phase preceding the return stroke can be divided into three successive discharge processes: the preliminary breakdown (B), intermediate (I), and stepped leader (L).

The long-duration preliminary breakdown stage lasted about 26 ms. As shown in Fig. 3a, the fast electric field change was relatively small in amplitude and superimposed several negative pulses during the initial 4 ms. Meanwhile, the slow electric field change negatively increased at a steady rate, indicating that the negative charge moved toward the observation site or positive charge moved away from the observation site. As seen in Fig. 3e, the lightning began with repeated breakdowns near point S, then spread in opposite directions and developed simultaneously, as indicated by arrows b1 and b2. Subsequently, another small branch, b3, initiated from the start point S and propagated for 6 ms with increasing elevation. The propagation of these discharge channels also can be shown in Figs. 3c and 3d. Thereafter, discharge b1 extended the lightning channels downwards with several fine branches; and discharge b2 appeared to progress horizontally. The extents of discharges b1 and b2 on a spherical projection were estimated to be 4.2 km and 5.4 km. The average velocities of discharges b1 and b2 in two dimensions were 1.6×10^5 m/s and 2.0×10^5 m/s. Actual 3D extents and velocities will be larger than these, due to the possible channel slope to the observation site. Both discharges b1 and b2 had similar characteristics for VHF radiation, and the radiation sources were mainly distributed on the tips of the lightning channels. It can be inferred that the preliminary breakdown might have happened between the main negative charge region and the lower positive charge region, and the negative breakdown discharges, b1 and b2, simultaneously transferred negative charges toward the observation site in a downward sloping direction.

The intermediate period after the preliminary breakdown process lasted 21 ms. Unlike the preliminary breakdown, there was no significant change in the fast and slow electric field change, which was accompanied by discrete and weak VHF radiation during this phase as shown in Fig. 3b. Discharge arrow i1 (Fig. 3) progressed in the direction of increasing elevation upward, and the elevation ascended from about 52° to 68° with an average speed of about 2.3 × 10^5 m/s. Meanwhile, discharge b2 continued to develop horizontally, and finally extended the channel to about 246° azimuth after about 6 ms, as indicated by the arrow i2. The average speed of the radiation source progression was estimated to be 1.4 × 10^5 m/s. It can be inferred that discharge i1 transported negative charge vertically upward, and affected the electric field change with discharge i2 in common.

The leader began at about 47 ms and lasted 33 ms until the return stroke. During the leader phase, there were clusters of positive pulses in the fast electric field change, corresponding to the stepped leaders. The slow electric field change had a relatively large negative slope in amplitude, and the VHF radiation again became intense and continuous with time. As shown in Fig. 3e, the leader started from ahead of discharge i1, and was highly branched while developing to the ground. In the high-elevation region, numerous distinct branches were superimposed together on the 2D map. When the main channel descended to about 12° azimuth and 46° elevation, the leader split into three branches extending simultaneously towards the ground, as shown by arrows l1, l2, and l3. Finally, discharge l2 reached the ground and induced the return stroke. As the leader approached the ground, the radiation sources appeared more widespread, and the time interval between leader pulses became shorter and irregular, due to the increasing branches dispersed from the leader channels. The estimated velocities of the three main leader branches were 1.3 × 10^5 m/s, 1.2 × 10^5 m/s, and 1.5 × 10^5 m/s, which are similar to the speed of 1.5 × 10^5 m/s reported by Yoshida et al. [2012].

Generally, the preliminary breakdown process is considered to be necessary for the initiation of the stepped leader. Zhang et al. [2009] found that the stepped leader results from the K processes along the previously formed channel through the start point of the lighting. A similar observation, that the stepped leader is initiated by recoil streamers during the final stage of preliminary breakdown process, was reported by Cao et al. [2012]. In the present study, the stepped leader developed directly from the preliminary breakdown in the flash, and the speeds of the three successive discharge processes prior to the return stroke were in the same order of magnitude, indicating that the stepped leader might be an extension of the preliminary breakdown process propagating outside the cloud. However, more observations and studies are needed to understand the initiation mechanism of the stepped leader.

B. K processes

About 72 ms after the start of the return stroke, a sequence of typical K processes occurred with step-like changes in the slow electric field change, as shown in Fig. 1. The average time interval of the six prominent K processes was about 15 ms.

The step-like change of the K process, K1, lasted for about 1 ms, accompanied by 1.7 ms of relatively strong VHF radiation. Fig. 4a shows the radiation source location results of the K1 process. It initiated at the start of region S, and progressed quickly along the extent of discharge b2 of the preliminary breakdown toward the observation site, as shown by the arrow K1a. About 0.2 ms after the initiation of the K1a process, the other breakdown, K1b, started from the discharge channel K1a near the region S, and synchronously developed along the previous path of discharge b3. Discharge K1a terminated at the branch point of discharge b3. The average velocities of discharges K1a and K1b were about 3.2 × 10^6 m/s and 1.6 × 10^6 m/s, and are typical of those reported by other investigators [Akita et al., 2010; Winn et al., 2011]. The K1 process was considered to be a negative breakdown discharge and transferred negative charge downward from the start region of the lightning with an obviously horizontal component, like discharge b2, as evidenced by the negative field change. Meanwhile, the positive charges deposited by the return stroke were also neutralized. The results show that process K1 had the same progress direction of the positive breakdown caused by the return stroke, and was different from the negative recoil streamers mentioned by Akita et al. [2010].

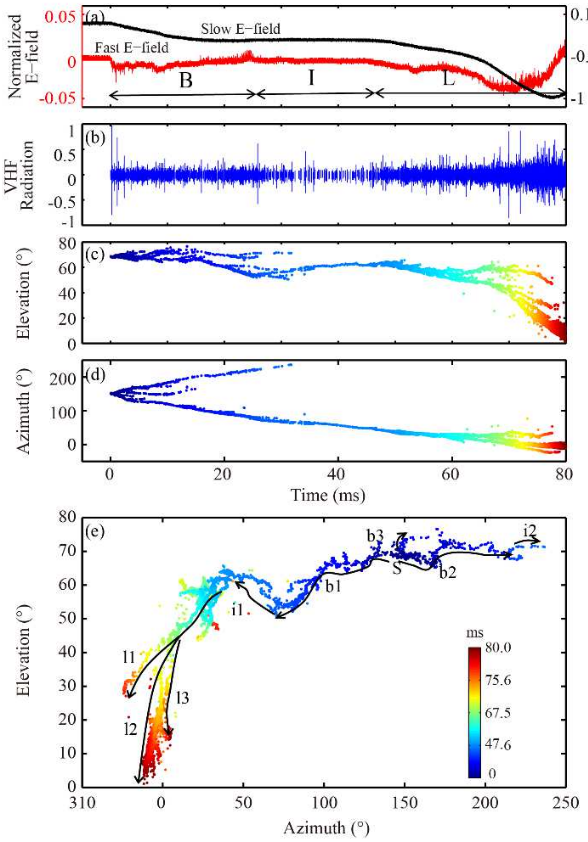

Fig. 3 Radiation sources of the discharge before the return stroke in the CG lightning: (a) electric field changes recorded by the fast and slow antenna; (b) VHF radiation field; (c) elevation versus time; (d) azimuth versus time; and (e) azimuth-elevation display. In (a), B, I, and L indicate the preliminary breakdown, intermediate, and stepped leader, respectively. In (e), the arrows b, i, and l indicate channels of the preliminary breakdown, intermediate, and stepped leader, respectively.

After a delay of 16 ms, process K2 occurred for about 1.2 ms and also radiated intense VHF radiation. Fig. 4b shows the radiation source location results of the K process, K2. The discharge began from the region of about 162° in azimuth and 75° in elevation, and spread downward to the start region, S, as shown by arrow K2a. The VHF radiation lasted 30 μs in this period, and the velocity was estimated to be 5.4×10^7 m/s. The high propagation speed and negative slow field change suggest that the fast negative streamer progressed along the existing positive breakdown channel, which might have been generated by the return stroke and could not be detected. Process K2 was considered to be a negative recoil streamer and transferred the negative discharge from another region in the cloud to the lightning start region.

After a short interruption of the VHF radiation of about 0.1 ms, the discharge resumed near region S and propagated, retracing the path of discharge b1, without branching, as shown by arrow K2b. Finally, discharge K2b stopped at 48° elevation, where the main stepped leader branched. The average velocity of discharge K2b was about 7.6×10^6 m/s. As the progression speeds of the K processes were one or two orders of magnitude faster than those of the preceding preliminary breakdown along the same paths, it can be recognized that the channels inside the cloud might still have retained good conductivity after the return stroke; while those outside the cloud had already cooled down and cut off, or there were not enough negative charges to support the channel to move forward, and the K process ultimately did not reach the ground, which was similar to the attempted leader.

Other K processes later on all developed in a similar manner, initiating from the start region of the lightning or a new region in the cloud, and propagating along the preceding electrified channel. The speeds of all the K processes were 10^6–10^7 m/s.

IV. SUMMARY

The development of the short-baseline lightning VHF radiation location system was summarized in this paper. The main discharge processes, including the preliminary breakdown process, stepped leader and K processes, of a negative single-stroke CG lightning flash were investigated using the short-baseline lightning VHF radiation location system.

The preliminary breakdown process occurred between the middle negative charge region and the lower positive charge region with bi-directional leaders, and transferred negative charges downward to the lower positive charge region. Two discharge channels developed simultaneously with a large horizontal component in different directions, both considered to be negative breakdown. The results indicate that the long-duration preliminary breakdown process likely corresponds to the lightning channels propagating horizontally with branches. The stepped leader was directly transformed from one of the branches of the preliminary breakdown process, inferred to be the further development of the latter. Abundant small branches extended away from the main leader channel in the large elevation, and three branches of stepped leader progressed simultaneously downward to the ground, with average velocities of about 10^5 m/s. All K processes presented in this paper propagated along the channel established by preceding breakdowns, and were also found to have negative polarity. The propagation velocities of K changes were about 10^6–10^7 m/s, greater than the preliminary breakdown and stepped leaders.

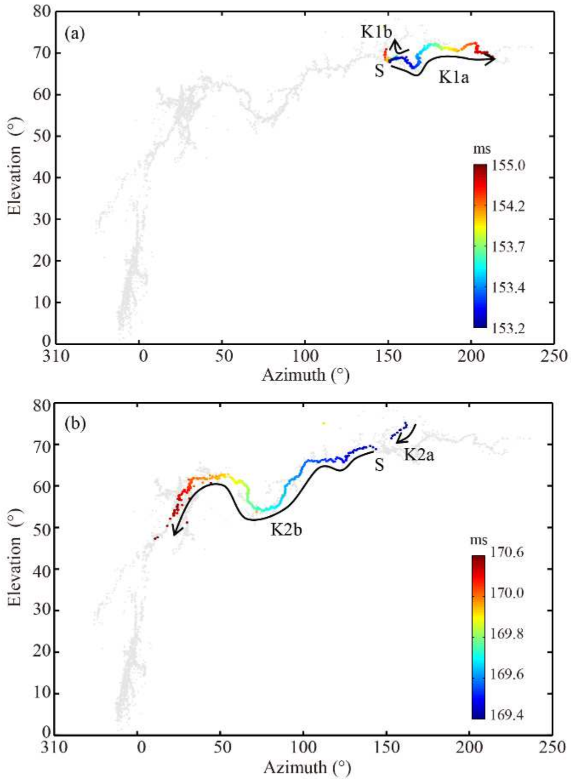

Fig. 4 2D VHF radiation source locations of the K processes in the CG light ning: (a) processes of K1; (b) processes of K2. The arrows K1a, K1b, K2a, and K2b indicate channels of the K processes K1 and K2.

The short-baseline lightning VHF radiation location system shows good performance in locating simultaneous radiation sources, and provides an effective approach to infer the distribution characteristics of electric charge inside the thunderstorm.

ACKNOWLEDGMENT

The research was supported by the National Key Basic Research Program of China (Grant No. 2014CB441405), and the National Youth Natural Science Foundation of China (Grant No. 41505002).

REFERENCES

Akita, M., Y. Nakamura, S. Yoshida, et al. (2010), What occurs in K process of cloud flashes? J. Geophys. Res., 115, D07106, doi: 10.1029/2009JD012016.

Cao, D., X. Qie, S. Duan, et al. (2012), Lightning discharge process based on short-baseline lightning VHF radiation source locating system, Acta Phys. Sinica, 61(6), 069202, doi:10.7498/aps. 61.069202.

Clarence, N. D., and D. J. Malan (1957), Preliminary discharge processes in lightning flashes to ground, Quart. J. Roy. Meteor. Soc., 83, 161–172.

Qie, X., Y. Zhao, Q. Zhang, et al. (2009), Characteristics of triggered lightning during Shandong artificial triggering lightning experiment (SHATLE), Atmos. Res., 91(2), 310–315.

Sun, Z. L., X. Qie, M. Y. Liu, et al. (2013), Lightning VHF radiation location system based on short-baseline TDOA technique—Validation in rocket-triggered lightning, Atmos. Res., 129, 58–66.

Winn, W. P., G. D. Aulich, S. J. Hunyady, et al. (2011), Lightning leader stepping, K changes, and other observations near an intracloud flash, J. Geophys. Res., 116, D23115, doi:10.1029/2011 JD015998. .

Yoshida, S., M. Akita, T. Morimoto, et al. (2012), Propagation characteristics of lightning stepped leaders developing in charge regions and descending out of charge regions, Atmos. Res., 106, 86–92.

Zhang, Y. J., Q. Meng, W. T. Lu, et al. (2009), Positive charge region in lower Part of thunderstorm and preliminary breakdown process of negative cloud-to-ground lightning, Acta Meteor. Sinica, 23(1), 95–104.