A Rocket-triggered Lightning Flash with more-than-usual Dart Leader-return Stroke Sequences

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ABSTRACT: A negative lightning flash with 16 leader-return stroke sequences was triggered in the summer of 2013 by using the classical triggering technique. The peak current of 16 return stroke ranged from 5.8 kA to 32.5 kA with a geomean of 14.1 kA. A total of 28.0 C charge was transferred by the whole flash. The progression of upward positive leader and downward negative (dart or dart-stepped) leaders was reproduced visually by using a new developed short-baseline time-difference of arrival (TDOA) VHF lightning location system. The upward positive leader developed with a speed of about 10^4 m/s without branches. A total of 14 negative leaders propagated in the same channel with few branches inside the cloud. The dart leaders may transform into dart-stepped leaders after a long time interval between successive strokes.

INTRODUCTION

A conventional negative rocket-triggered lightning usually goes through several stages, such as: the initial stage (IS) that involves the upward positive leader and the initial continuous current, one or more negative leader-return stroke sequences, and some processes between the return strokes like the nature lightning flashes [Rakov et al,.1998]. Shandong Artificially Triggering lightning Experiment (SHATLE) has been conducted continuously since 2005 [Qie et al.,2009]. The installation of the experiment during SHATLE 2013 is shown in Figure 1. A negative lightning flash with 16 leader-return stroke sequences was triggered in the summer of 2013 by using the classical triggering technique. It was the triggered flash with the most return stroke numbers in SHATLE. The newly developed lightning VHF radiation location system based on short-baseline time-difference of arrival (TDOA) technology had observed the IS and the first 14 leader-return stroke sequences.

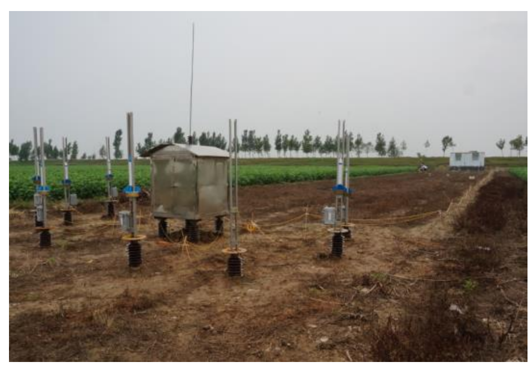

Figure 1 The installation of the experiment during SHATLE 2013.

In this paper, the short-baseline location system which realized the continuous acquisition of lightning radiation signals is present. Then, the progression of positive and negative leaders is analyzed, combining

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with simultaneous observations of channel base current, high-speed camera and fast/slow electric field changes.

BRIEF DESCRIPTIONS ON THE (TDOA) SYSTEM

The basic principle of this technique is the TDOA estimations for the lightning broadband VHF radiation signals received by the orthogonal 8 m-baseline antenna array with four identical broadband discone antennas. The location of lightning radiation sources in two dimensions (elevation and azimuth) can be determined by the geometric relationship among the antenna array [Sun et al. 2013]. The system received the lightning broadband VHF radiation signals over a range of frequencies from 140 to 300 MHz and acquires signals of 4 channels continuously over 1s using the mass memory waveform digitizer. The data sampling rate is 1 GS/s and the data vertical resolution is 8 bits. The VHF location system is triggered by the synchronous measurement of the electromagnetic field changes signals, and the trigger time is provided by the high-time accuracy GPS for a cooperating analysis with other observations.

During the summer of 2013, the short-baseline TDOA VHF lightning location system, the electromagnetic field changes, and the high-speed camera were located 970 m away from the rocket launcher.

ANALYSIS AND RESULTS

The triggered flash occurred at 05:37:21, August 02, 2013, and exhibited a long duration of 1095 ms from the inception to the end of discharge. The peak current of 16 return stroke ranged from 5.8 kA to 32.5 kA with a geomean of 14.1 kA. The relatively weak initial continuous current (ICC) lowered only 4.9 C negative charge from cloud to ground in a period of 139 ms, and the whole flash realized a total charge transfer of 28.0 C, which is less than expected in view of a large number of return strokes.

The TDOA location system depicted the progression of lightning radiation sources in 2-D during a period of 0.8 s, including the upward positive leader and the first 14 negative leader-return stroke sequences. Figure 2 shows the image of the upward positive leader and first return stroke captured by high-speed video camera and the radiation source locations of the triggered lightning in two-dimensions.

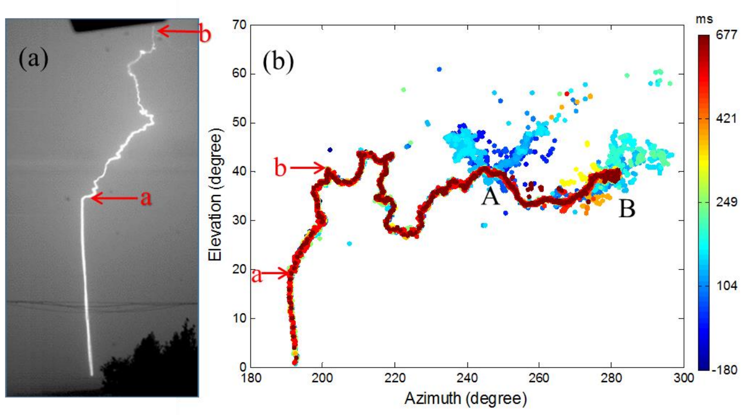

Figure 2 Discharge channel of the triggered flash. (a) One frame from high speed video images, (b) 2-D VHF radiation source locations. The north direction is the reference azimuth with increasing clockwise. Time zero represents the triggering moment of the recorded signal. Color of radiation sources changes with time from blue to red.

As labeled by arrows *a* and *b*, the radiation sources positions in the Figure 2(b) correspond to the top of the trajectory of metal wire after evaporation and the top of the visual channel outside the cloud captured by the high-speed video camera, respectively. The curved channel between *a* and *b* was corresponding to the natural discharges by the upward positive leader and downward negative leaders. It can be seen that the discharge channel determined by radiation source locations was generally in good agreement with the optical observation. The channel outside the sight of the camera was sinuous and expanded widely from about 200 °to 300 °azimuth only with obvious branches at regions A and B.

The upward positive leader

Figure 3 shows the channel base current and the radiation sources result of the IS. At the time T0, the current started as a cluster of several pulses, and the upward positive leaders were located to initial from the top of the metal wire. It can be inferred that the upward positive leaders at the beginning might develop in the stepped manner. Unfortunately, the luminance of the leader was too weak to be recognized from the optical observation, while the discrete stepped progression was also observed by Wang et al.[2012] using the high-speed video camera and electric field changes. Subsequently, the channel base current increased steadily, and the leader propagated upward to the cloud. After about 14 ms, the leader reached position of the arrow *b*, and the average two dimensional speed of the radiation source progression was estimated to be 3.8×10^{4} m/s, which agrees with the result got through the high-speed video camera [Biagi et al., 2009]. With the progression of the leader, the channel became sinuous and the VHF radiation turned to be sparse. At time T1, there was the current oscillation associated with the vaporization of the metal wire. About 9 ms after the time T1, VHF radiation signals decreased to the background noise level, and no more positive leader radiation was detected, while the small current indicated that the positive leader kept propagating forward to the negative charge region. The positive leader path can be deduced by dart leaders which followed the path created by the positive one.

After a VHF silence duration of about 25 ms, the radiation sources initiated from the space beyond the region A and extended towards the main channel. Then, negative breakdowns occurred frequently and transiently near the regions A and B until the initiation of the first negative dart leader.

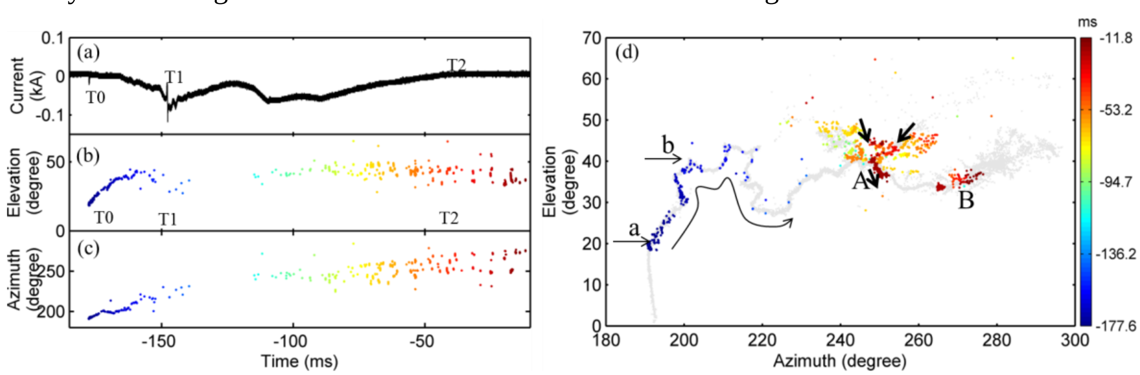

Figure 3 The channel base current and radiation sources location of initial stage (IS). (a) Channel base current, (b) elevation versus time, (c) azimuth versus time, and (d) azimuth-elevation display.

Negative leaders

Most of the downward negative leaders initiated from the same region B and traversed a single channel, even in the cloud, except for the severest one with stroke peak current of about 32.5 kA, which was from the region A and might be influenced by the charge from main channel and a branch channel together. The in-cloud channel associated with the negative leaders was found to be not higher than 4.0 km, and involved a significant horizontal spanning with few branches. The time interval between successive strokes may influence the in-cloud streamer breakdown, and the radiation sources became relatively discrete along the channel with high conductivity.

With a long time interval, the dart leaders may transform into dart-stepped leaders. Average speeds of dart leaders from the 30 °elevation down to 20 °were of the order of 10^5-10^7 m/s, and those of dart-stepped leaders were 10^5 m/s magnitude. All of the negative leaders were found to have a greater speed as they approached the ground.

CONCLUSIONS

Based on the location of lightning radiation sources, the progression of the triggered lightning discharge channel can be reconstructed continuously. Although the VHF radiation of the upward positive leader was weak, the VHF radiation sources were located immediately from the initiation of the upward positive leader. The positive leader developed upward with a speed of about 10^4 m/s. The downward negative leaders propagated in a single channel deviously. Few branches of the leader channel inside the cloud might be the reason of weak ICC and small total charge transfer for the whole flash, which potentially lead to a more-than-usual return stroke sequences.

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