Three-Dimensional VHF Observations of Positive Cloud-to-Ground Flashes in Summer Thunderstorm Season

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***Abstract*— Lightning Research Group of Osaka University (LRGOU) and Chubu Electric Power Company (CEPCO) have been conducting a cooperative thunderstorm observations during the last few summers in Tono Aria (Gifu Pref., Japan). LRGOU has been developing two- (2D) and three-dimensional (3D) VHF source mapping system for electromagnetic (EM) waves emitted in association with lightning discharge progression based on a unique technique of the broadband digital interferometry. CEPCO has improved the location accuracy of lightning strokes by the lightning location and protection system (LLP system). At 2028:59 JST on 8 August, 2008, we observed the 3D spatiotemporal development channels of positive cloud to ground (CG) lightning flash with the VHF broadband digital interferometer (DITF) and the return stroke with the LLP system. This flash is divided before and after the return stroke. In the first stage, the lightning channel progresses about 16 km horizontally between 6 and 10 km high. The LLP system detects the return stroke near the initiation point of that channel. In the last stage, the negative breakdown run through the same channel before the return stroke. This positive lightning is accompanied by the bidirectional leader.**

Key words: Positive CG Lightning, Bidirectional Leader, Three-dimensional Imaging, Broadband Digital Interferometry

I. Introduction

Positive CG lightning flashes are defined as the discharge lowering positive charges in cloud. As is widely alleged, the number of positive CG lightning flashes is less than one tenth of global CG lightning. Positive discharges have attracted attention for the substantial volume of neutralizing charges, the highest lightning current (over 200 kA) and the association with luminous phenomena in the middle atmosphere known as sprites. By contrast, it have not be revealed obviously that the 3D spatiotemporal structure of positive CG lightning flashes with VHF-UHF measurement systems because the average intensity of VHF-UHF radiation by a positive breakdown is about 20 dB weaker than that by a negative breakdown [1], [2], [3].

Kasemir introduced the "bidirectional leader" concept in 1960s [4]. According to the bidirectional leader model, a lightning discharge is initiated with both positive and negative leaders traveling simultaneously in opposite direction from its origin. This concept was overlooked or ignored by most researchers in field observations of lightning. In recent years, video pictures of triggered lightning by an ascending airplane were reported [5] [6]. In these pictures, the upward and downward lightning branching are exist together. This phenomenon indicates that both upward and downward lightning are started simultaneously, and is the correctness proof of a bidirectional leader concept for natural lightning. Then many lightning investigators have discussed about this concept based on various field observations. Mazur *et al.* [7] developed this concept based on the observation results for the artificially triggered lightning. Sumi and Horii [8], and Rakov *et al.* [9] report the optical observations for the rocked triggered lightning and altitude triggered lightning with the bidirectional leader. Although Kawasaki *et al.* [5] observed this concept's leader by the UHF interferometer in winter nature positive CG lighting, there are few observation about the nature lightning.

In this paper, we report the 3D spatiotemporal structure of summer nature positive CG lightning flashes with the VHF broadband digital interferometer (DITF) and the return stroke with the lightning location and protection system (LLP system).

II. Instruments and Field Sites

LRGOU and CEPCO have been conducting lightning observations in Tono area during summer seasons from 2004 to 2008. Two systems of the VHF broadband DITF are installed at the Mizunami (35.41N, 137.33E) and the Ena (35.43N, 137.37E) sites (Figure 1). At the Ena site, an L-band (1.3575 GHz) tropospheric radar (L-28, developed by Sumitomo Electric Industries) is operated as well. We have

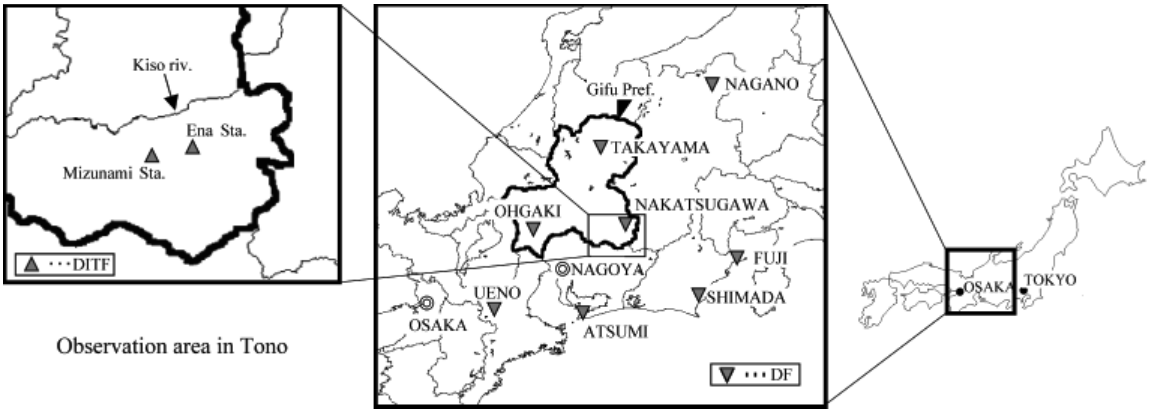

Fig. 1 Location of the observation

developed a VHF broadband DITF with specially manufactured analog-to-digital converter (ADC) of 200MHz sampling rate, 10-bit resolution and 1us dead time that means mechanical minimum time interval between data acquisitions for each pulse [10]. One VHF broadband DITF system locates angular position, namely azimuth and elevation, of VHF impulse sources. 3D localizations of VHF impulse sources need at least two time synchronized systems of DITFs with a proper separation. With two or more pairs of azimuth and elevation provided for each site, the VHF impulse sources are able to be localized in 3D. A more detailed method for 3D localization is explained by Morimoto *et al.* [10], [11].

The LLP system has been observed lightning strike points since 1986. It is composed of two or more Direction Finders (DFs) detect the electromagnetic radiation by a lightning return stroke, and a Position Analyzer (PA) calculates the position and the current of the lightning based on the detection data. The LLP system was owned by CEPCO in 1998. Then we have tried to combine a time-of-arrival method in the DF algorithm based on the intersection method to improve its accuracy [12]. The CEPCO LLP system is currently composed of eight DFs in central Japan (shown in Fig. 1).

III. Observation Results

Figs. 2 and 3 show the two-dimensional (2D) mappings of lightning discharge process drawn in time domain by VHF broadband DITFs installed at Mizunami and Ena, respectively. The azimuth 0° means north and increases anticlockwise. This event which was recorded at 2028:59 JST on 8 August, 2008, is recognized as a positive CG lightning flash by the LLP system.

At 375 msec, first VHF pulse is received at both sites. The azimuth increases from the northwest. In Figs. 2 and 3, a number of leaders are noticeable. We pay our attentions to the two leaders (Leader 1 and Leader 2) circled in Figs. 2 and 3. Fig. 4 is the enlarged view of Leader 2 shown in Fig. 2. Leader 1 initiates from the azimuth of 58° and the elevation of 50° at 375.5 msec, and reaches at the azimuth -172° and the elevation of 58° at the time of 551.0 msec. Leader 2 initiated from the azimuth of 50° and the elevation of 47° at 551.9 msec, and reaches at the azimuth -173° and the elevation of 59° at the time of 552.8 msec. Furthermore Leader 2 progresses beyond the end of Leader 1. In Fig. 3, Leaders 1 and 2 are identified as well as in Fig. 2.

The return stroke of this positive CG occurred at 551 msec with the peak current of 76.5 kA. Fig. 5 shows the azimuth-elevation plots of VHF lightning radiation sources in Leaders 1 and 2 by VHF broadband DITFs and direction of the return stroke by the LLP system at Mizunami. From Fig. 5, it can been seen that Leader 2 develops through the same channel as Leader 1 and that the return stroke detects near the initiation point of Leader 1.

Fig. 6 is the 3D imaging of Leaders 1 and 2 by a conventional triangulation scheme from the 2D mappings shown in Figs. 2 and 3. Each panels of Fig. 6 show the north-south vertical projections (a), plan views (b), east-west vertical projections (c) of the VHF impulse sources. "×" indicates the location of the return stroke detected by the LLP system. Leaders 1 and 2 start at 6 km high and developed upward to 9 km. These lengths of these channels are about 16 km. The estimated propagation velocities of them are 9.1×10^4 m/s, 1.6×10^7 m/s, respectively. At least two similar positive CG lightning flashes are observed in this campaign.

IV. Discussions

What's interesting in this positive CG lightning discharge is that we cannot see the leader propagation toward the ground in Fig 5. Leader 2 proceeded through the Leader 1's path and beyond the end point of Leader 1 almost as soon as the positive return stroke occurred. Because the positive return stroke start from the ground to the initiation point of Leader 1 at 551 msec, a downward positive leader must be developed in the Leader 1 period. But the positive downward leader is not visualized. To explain this result, we need to apply the bidirectional leader progression concept proposed by Kasemir [4]. Once we have a breakdown, both negative and positive leaders should be initiated and progress simultaneously to reverse directions to conserve the net charge at the inception point. Since it is known that the average intensity of VHF radiation by a positive breakdown is about 20 dB weaker than that by a negative breakdown, the VHF broadband DITF mostly visualizes the channel of negative leader. In other words, visualized breakdowns are negative leaders if we have both positive and negative breakdown "simultaneously."

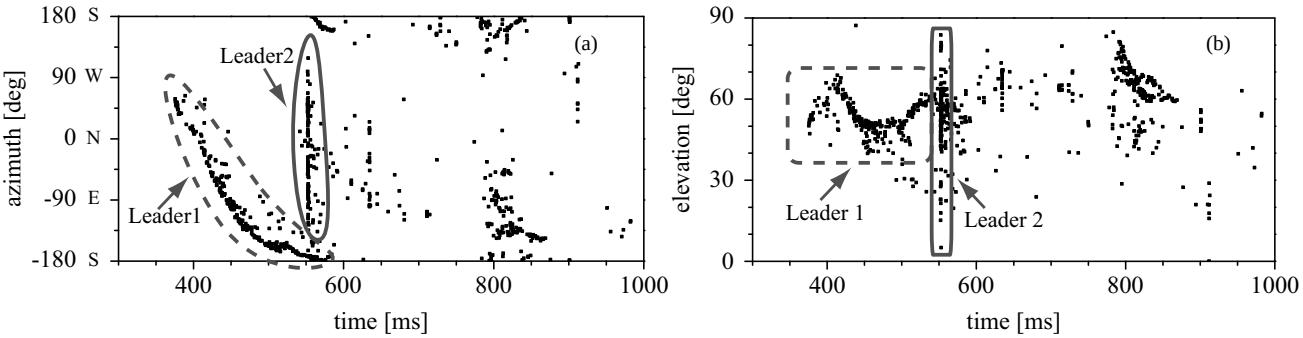

Fig. 2 The 2D mapping of the positive CG flash recorded at 2028:59 JST on 8 August, 2008 at Mizunami.
(a) azimuth and (b) elevation. Leaders 1 and 2 are circled.

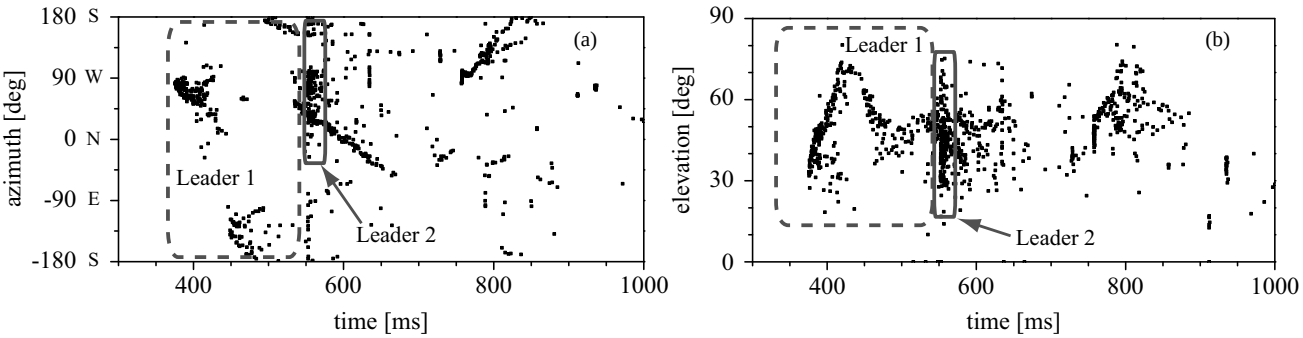

Fig. 3 The 2D mapping of the positive CG flash recorded at 2028:59 JST on 8 August, 2008 at Ena.
(a) azimuth and (b) elevation. Leaders 1 and 2 are circled.

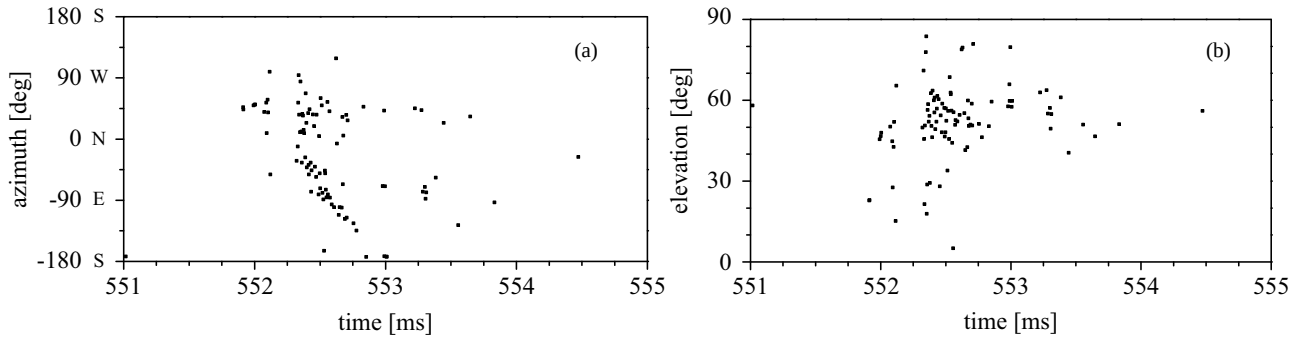

Fig. 4 The enlarged view of Leader 2 shown in Fig. 2. (a) azimuth and (b) elevation.

Therefore we cannot see this positive downward leader propagation.

In the Leader 1 period, from 375.5 msec to 551.9 msec both downward positive and in-cloud negative leaders progress, and only negative Leader 1 is visualized. At the time of 551.9 msec, the positive leader touches to the ground and the positive return stroke current propagates and penetrates in the opposite direction as Leader 2.

According to the tropospheric radar observation, the bright band height in this case is 3.7 km and there is snow region dotted with positive charges around 7 km high. Leaders 1 and 2 proceeded into the snow regions neutralizing the positive scattered charges. Developing velocity of Leader 2 is about 175 times faster than that of Leader 1. To assume the path of the positive leader is straight line, the length of this is 6.8 km

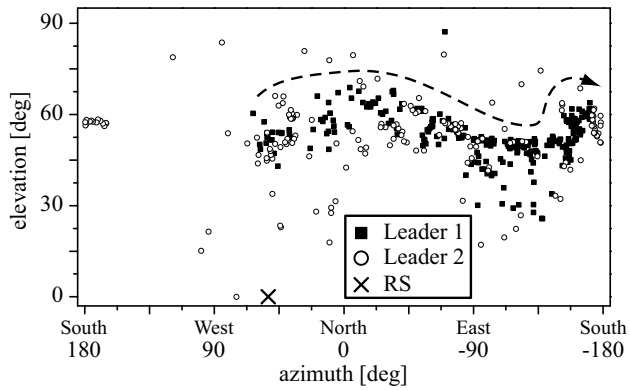

Fig. 5 Azimuth-elevation plots of VHF lightning radiation sources in Leader 1 and 2 at Mizunami. "×" indicates the direction of occurrence of return stroke from the LLP system.

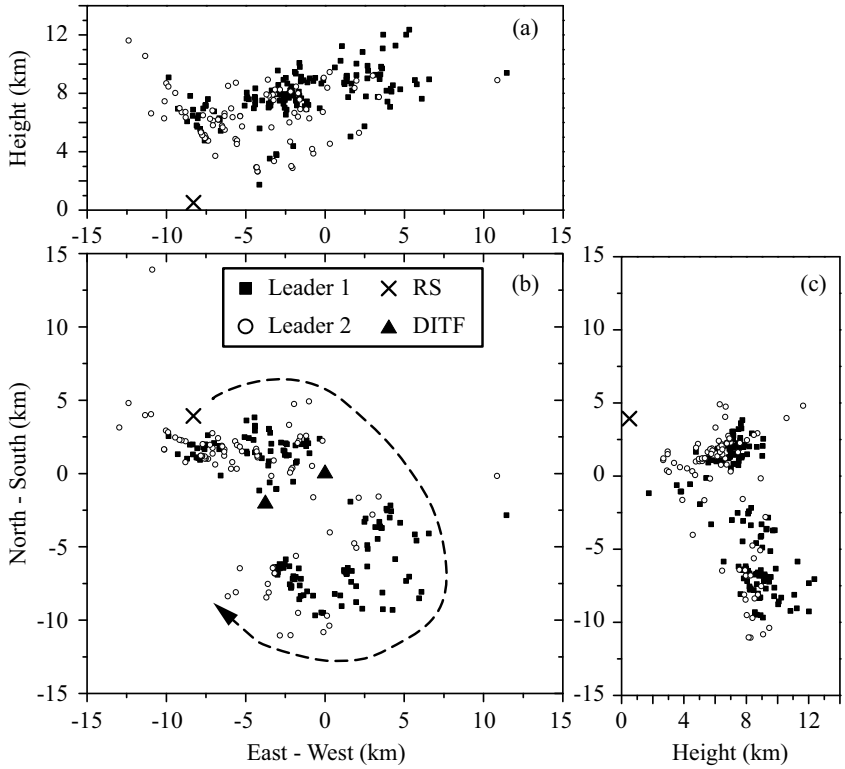

Fig. 6 Spatiotemporal distributions of radiation event for the Leaders 1 and 2 occurred the positive CG lightning flash at 2028:59 JST on 8 August, 2008. The different panels show north-south vertical projections (a), plain views (b), east-west vertical projections (c) of the lightning radiation sources. × indicates the position of occurrence of return stroke from the LLP system. ▲ shows the location of the DITF's station.

and this velocity is 3.8×10^4 m/s.

V. Conclusions

We observed the 3D spatiotemporal structure of summer nature positive CG lightning flashes with the VHF broadband DITF and the LLP system. First, both downward positive and in-cloud negative leaders progress, and only negative leader is visualized. The positive leader touches to the ground and the positive return stroke current propagates and penetrates in the opposite direction as visualized subsequent negative leader. This suggests the negative breakdown process occurrence during positive leader progression phase strongly. To realize this situation, we conclude the necessity to apply the bidirectional leader progression concept. In a word, we observed bidirectional leaders in summer nature positive CG lightning flashes.

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