Stepped leader characteristics in developing horizontally within thunderclouds and in descending out of thunderclouds

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Abstract

We examine VHF and optical images of cloud-to-ground flashes to study IC leaders that propagated within thunderclouds and CG leaders that descended outside thunderclouds. It is shown that IC leaders developed smoothly and CG leaders propagated in a heavily branched manner. We speculate that, in the case of IC leaders, only the leader tip having the highest charge density in the channel could propagate in E-field intensified by local positive charge. In the case of CG leaders, not only leader tips but also lower parts of the leader could initiate new branches due to higher charge density.

1. Introduction

Charge structures in thunderclouds have a significant effect on lightning leader development [1, 2]. *Mazur and Ruhnke* [1] showed with numerical solutions of a cloud charge model that lightning current continued to flow, both when the leader expanded bi-directionally in the initial stage of a flash, and when it expanded uni-directionally in the later stage as long as a breakdown process took place at least at one tip. When E-field at the both leader tips was near threshold breakdown values, the propagations stopped. Thus *Mazur and Ruhnke* [1] suggested that the leader progressions are determined by the ambient potential distribution along the entire leader's length in the thunderclouds.

These results imply that charge located around lightning leaders has a large effect on propagation characteristics of the stepped leaders within thunderclouds. In the case of a CG flash, after a stepped leader develops within thunderclouds, it gets out of the thunderclouds, propagates toward ground, and touches the ground, resulting in the first return stroke. The stepped leader out of thunderclouds is less likely to be affected by positive charge region in thunderclouds. It is expected that descending stepped leaders out of thunderclouds have different propagation characteristics from those within thunderclouds. Although stepped leader characteristics at very low altitudes (up to a few hundred meters from the ground) have been carefully studied, stepped leader propagation characteristics out of thunderclouds at high altitude (a few kilometers) have been less paid attention to.

In this paper, we examine VHF and high speed video images of stepped leaders within thunderclouds (IC leaders) and out of thunderclouds (CG leaders), and compare the characteristics of IC and CG leaders.

2. VHF broadband digital interferometers

The lightning observation campaign has been conducted in Darwin, Australia, using VHF broadband digital interferometers (DITFs) in November and December since 1995. The DITF located sources of wideband VHF radiation in two dimensions [3]. The VHF broadband DITF consisted of capacitive antennas that were equipped at three apexes of a level isosceles right-angled triangle with proper separations (5m - 10 m). The basic idea of the broadband digital interferometry is to estimate phase differences between the impulsive electromagnetic wave received by a pair of two antennas. In this system, two independent phase differences were acquired. If an arrival direction meets the two incident angles, the direction of an electromagnetic source is estimated in terms of elevation and azimuth [3]. For the VHF radiation detected by both DITFs, 3D locations were determined by first triangulating a single horizontal (x-y) location, and the resultant horizontal location was used to calculate a source for each DITF [3].

3. Results

Figure 1 shows VHF source locations of a CG flash before the first return stroke, (a) altitudes estimated by two DITFs, (b) (c) azimuth and elevation estimated by a DITF, and (d) E-field change recorded by a capacitive antenna with a decay time constant of 10 s. This flash was recorded at 07:22:33 (GMT) on 16 December 2006 and the same event

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reported by *Akita et al.* [4]. The negative leader was initiated about 8 km in altitude and traveled more than 10 km almost horizontally [4]. The negative leader changed its propagation direction toward ground and began to descend around 700 ms. It touched the ground at 761 ms, resulting in the first return stroke (indicated by the fast rise of the waveform of the E-field change). This CG flash involved an IC leader (before changing the propagation direction around 700 ms) and a CG leader (after 700 ms).

It is recognized that the channel of the IC leader located by the DITF is much sharper than that of the CG leader in Figure 1. The broadening of the channel of the CG leader is a rather common result in the VHF source locating by DITFs. Another example is seen in Figure 15b of *Morimoto et al.* [3]. Figure 2 shows the number of the VHF pulses per 10 ms and the standard deviations of azimuth located by the DITF for the event. The standard deviations are calculated every 10 ms. The number of located VHF pulses per 10 ms and the standard deviations begin to increase after the stepped leader began to descend toward the ground around 700 ms. These results also indicate that the channel of the VHF source locations for the CG leader is broader than that for the IC leader.

Figures 3 shows 2D mapping of the VHF sources associated with a CG flash recorded at 19:54:12 (GMT) on 14 December 2007 in an azimuth-elevation format. This event had an IC, a CG, and a dart leaders. As well as the event seen in Figure 1, this event exhibits the same characteristic that the channel of the CG leader located by the DITF broadened. Figure 3 shows that the dart leader developed the same channel that the IC leader propagated along and, then, it developed one part of the area occupied by the VHF source locations for the CG leader. Although the dart leader propagated almost the same channel as the CG leader, the downward dart leader is much more sharply located.

4. Discussion and summary

As seen in Figure 3, the IC leader and the dart leader progressions could be clearly located. Therefore, it does not seem that the broadening of VHF source locations for the CG leader is caused by DITF locating error. We speculate that the CG leader developed with having many branches in a complicated manner while the IC leader and dart leader developed without many branches.

In order to confirm our speculation, we examine high speed video camera images (20kfps) of a CG leader recorded in Darwin, Australia, on 19 November 2010 (Figure 4). The field of view of this high speed video camera is about 20 degree in azimuth. The typical altitude of cloud bases in Darwin is about 4 km. The series of the high speed video images shows

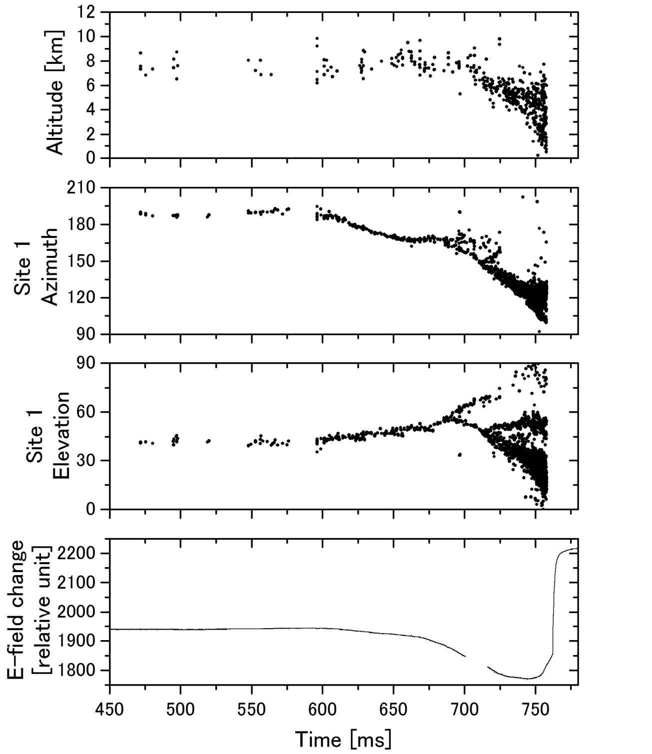

Figure 1: VHF sources locations of a CG flash before the first return stroke, (a) altitudes estimated by two DITFs, (b) (c) azimuth and elevation estimated by a DITF, and E-field change recorded by a capacitive antenna with a decay time constant of 10 s.

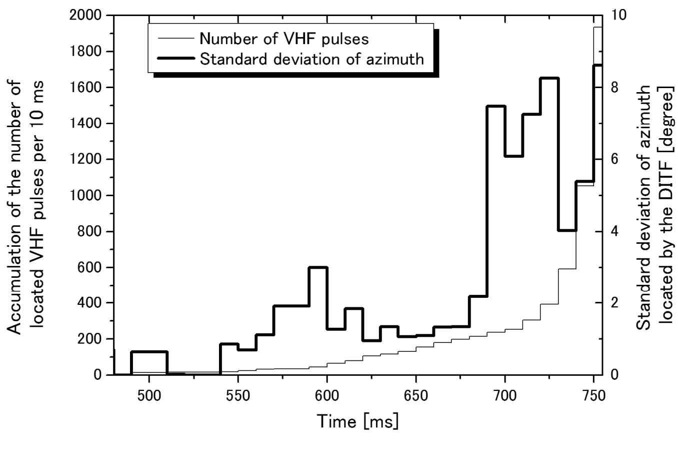

Figure 2: The number of VHF pulses per 10 ms and standard deviations of azimuth located by the DITF for the event shown in Figure 1.

that the CG leader descended with heavily branching. In Figure 4, the tips of the branches are recognized as luminous segments. The number of the tips of the branches increases with the development of time. At 0 ms one tip is seen, and at 2.5 ms (one flame before the return stroke) over 40 luminous leader tips are recognized. The tips of the branches appeared not only around the lower end of the descending leader but also just below the cloud base, which is a few kilometers above from the lower end of the CG leader. Taking into account that most VHF source locations correspond to the tips of the negative leaders [4], it seems that the broadening of the VHF source locations for the CG leaders implies complicated and heavy branches of the CG leaders similar to the branching seen in Figure 4. This fact is also well consistent with the result that the number of the VHF pulses increase as the CG leader descended shown in Figure 2. Figure 5 shows images of the high speed video camera for the dart leader followed by the second return stroke. Unlike the CG leader seen in Figure 4, the dart leader propagated downward rather smoothly without heavy branches and only the tip of the main channel is luminous. This fact is consistent with the result that the channel of the dart leader in Figure 3 is sharper than that of the CG leader. It is apparently that CG leaders propagated downward with complicated and heavy branches, while IC leaders and dart leaders developed without such heavy branches.

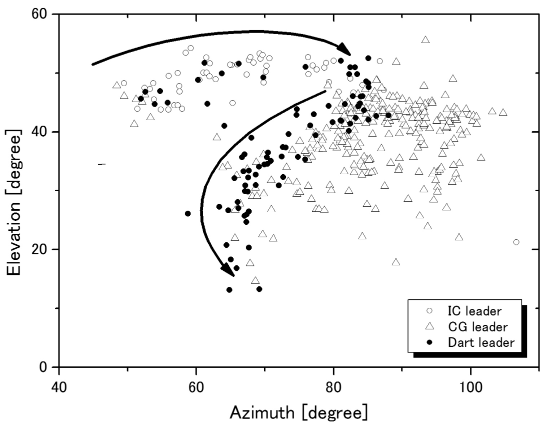

Figure 3: 2D mapping of VHF sources associated with a CG flash recorded at 19:54:12 (GMT) on 14 December 2007 in an azimuth-elevation format.

According to *Akita et al.* [4], the IC leader shown in Figure 1 propagated horizontally in dense dry snow layer (more than 10 dBz), where positive charge is apparently to have been dominant, within thunderclouds. In a lightning leader propagation simulation reported by *Mazur and Ruhnke* [1], for a CG flash, charge density along the stepped leader channel increased as the stepped leader descended. The charge density along the leader channel at the initiation was at least by a factor of 2 lower than the charge density near the ground. These results imply that the charge density of the IC leader was lower than that of the CG leader.

In the case of the IC leader, positive charge regions might have been located just ahead of the leader tip. We presume that the IC leader could propagate due to E-field near the tip intensified by the local positive charge regions, although the charge densities at the leader tips were not high enough to proceed to propagate without the local positive charge. The only IC leader tip that had the highest charge density in the channel could propagate along the line of electric force. Therefore, the IC leaders did not involve many branches. On the other hand, in the case of the CG leaders, the charge density of the lower part of the leader (some hundreds meters) as well as the leader tip might have been high enough to proceed propagation without local positive charge. This fact implies that the CG leader could involve complicated and heavy branches since a new branch could be launched from not only the tips but also the lower part of the leader, having high enough charge densities.

6. Acknowledgments

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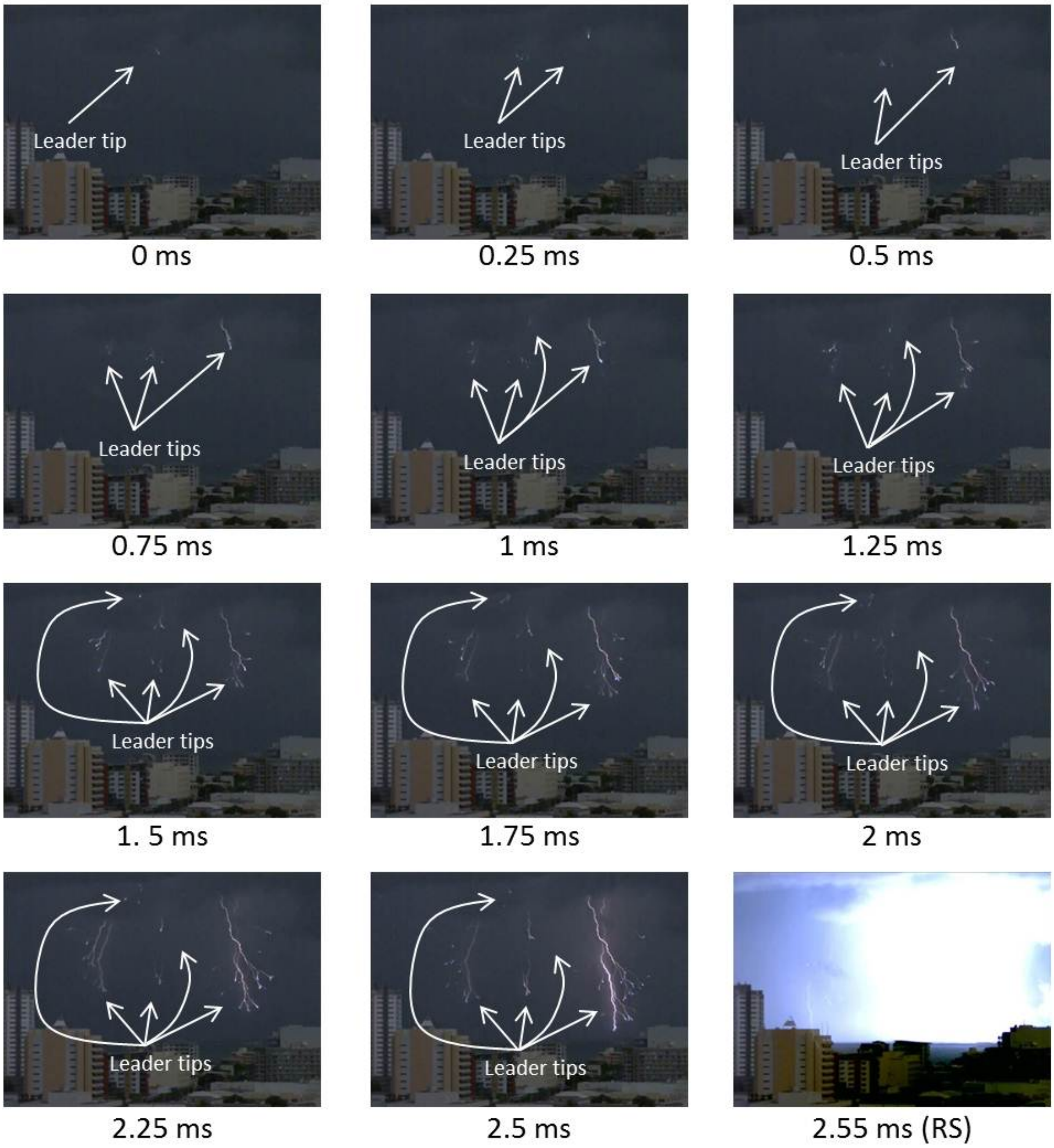

Figure 4: High speed camera images of the CG leader development recorded in Darwin, Australia, on 19 November 2010.

Figure 5: High speed camera images of the dart leader following the stepped leader shown in Figure 4.