Characteristics of Negative Upward Stepped Leaders in Positive Upward Lightning

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ABSTRACT: The step propagation of negative upward leaders in positive upward lightning has been analyzed using lightning current waveforms and optical images. We observed upward lightning in the coastal area of the Sea of Japan for 20 years. In the observation, we obtained positive upward lightning flashes initiated by a negative upward leader propagating from grounded structures. A negative upward leader propagates similarly to the stepped leader observed in negative cloud-to-ground lightning [Berger, et al. 1977]. In the study, we examined the step length, the interstep interval and the propagation speed of negative upward leaders. Furthermore, we compared the propagation of a negative stepped leader with the corresponding current waveform. As a result, we found that step formation corresponds to current pulses with charges of about 0.013 C.

INTRODUCTION

Positive upward lightning is initiated by the inception of a negative upward leader from a grounded structure [Rakov and Uman, 2003] and has a low rate of occurrence. Thus, few studies on positive upward lightning have been reported. Berger et al. [1977] reported the propagation of an upward negative leader and found that its propagation features are similar to those of stepped leaders observed in negative cloud-to-ground (CG) lightning. Recently, Zhou et al. [2012] examined the peak, duration and charge of the current pulse in positive upward lightning observed at the Gaisberg Tower.

A stepped leader is an important process in CG lightning flashes, because the striking point of the flash depends on the step propagation. There is not only scientific interest, but also engineering interest in stepped leaders. Thus, stepped leaders in negative CG lightning flashes have been studied for a long time. Recently, the step formation processes of stepped leaders have been measured using digital high-speed video cameras [e.g., Biagi et al. 2010;Hill et al. 2011; Petersen and Beasley 2013]. However, the current waveform of a stepped leader in CG lightning has not yet been measured, because it is difficult to measure the small magnitude of the lightning current in CG lightning flashes. Thus, the charges in a stepped leader are not yet known. On other hand, current waveforms of negative upward leaders in positive upward lightning have already been measured by several researchers [[1]e.g., Berger, et al. 1977; Heidler, et al. 2000]. Thus, if the propagation characteristics of a negative upward leader are similar to those of a negative downward leader, they could be used for the development of the propagation model of a negative downward leader.

We had observed upward lightning at a chimney in the coastal area of the Sea of Japan for 20 years.

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During the observation, we obtained current waveforms and optical images of positive upward lightning flashes. From the observation data, we found that a negative upward leader propagates intermittently similarly to a stepped leader [Miki et al., 2012]. Furthermore, we reported that the current pulse corresponds to the step of a negative leader. In this study, we evaluated the parameters of step propagation using the current data and the corresponding optical data of positive upward lightning flashes. Furthermore, we estimated the charge density of a stepped leader to clarify the mechanisms of a stepped leader in CG lightning.

OBSERVATION

We observed winter lightning flashes striking the chimney of the Fukui thermal plant located in the coastal area of the Sea of Japan from 1989 to 2008 [Miki et al., 2012]. Figure 1 shows the chimney where height is 200 m. Lightning current waveforms were measured using two shunt resistors (2 and 10 mΩ) installed at the top of the chimney. The output signals from the resistors were sent to a digital oscilloscope at the observation site through fiber optics as shown in Figure 2. The 2 mΩ resistor was used to measure large currents (5-250 kA) and the 10 mΩ resistor was used to measure small currents (0.2 - 13 kA). We used an automatic lightning progression feature observation system (ALPS) to measure the upward leaders in the observation. ALPS is a high-speed digital camera system and consists of a conventional camera lens, a pin photodiode array module, an amplifier, a multichannel digitizer and a personal computer. The space resolution of a frame in ALPS is 40x40 pixels and the maximum frame rate is 10,000,000 frames/s. The number of frames is 16,000. In the observation, we set the frame rate to 5,000,000 frames/s. ALPS was set in the observation site located 630 m from the chimney.

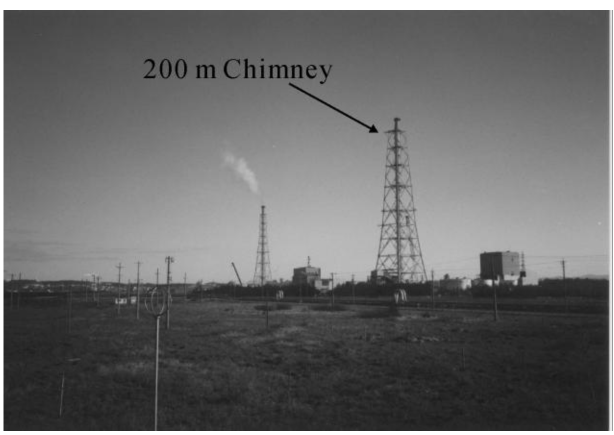

Figure 1 Observation site (Fukui chimney).

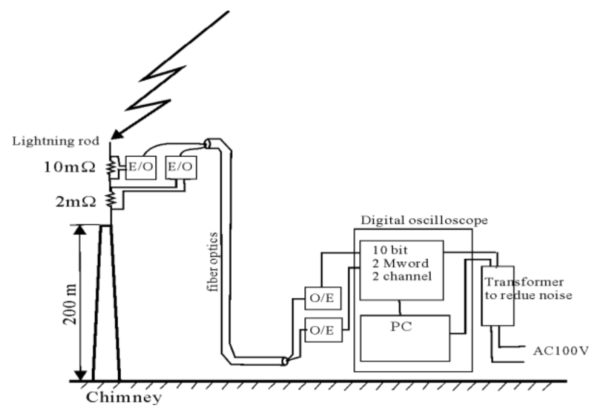

Figure 2 Current measurement system.

DATA

We successfully observed 25 positive upward lightning flashes in the observation and used three of them to analyze the step propagation of the negative upward leader.

Case 1: 21 Jan. 1997

A positive upward lightning flash occurred at the chimney on 21 January 1997. This was a single-stroke flash. Figure 3 shows the entire current waveform of the flash. The flash duration was 15.67 ms and the peak current of the flash was 13 kA. Figure 4 shows ALPS images and the corresponding current waveform of the negative upward leader in the positive upward lightning flash. A total of 3640 frames of the upward negative leader were recorded using ALPS. The current waveform, which corresponds to the propagation of negative upward leaders, consists of pulses and underlying continuous component. The number of pulses was 121. The intervals between the current pulses ranged from 3.2 to 55.6 μs with an average value of 18.6 μs. When the total length of the leader channels was more than 550 m, the continuous current component started to increase as shown in Figure 4. The average propagation speed was 1.6×10^6 m/s. Figure 5 shows the step propagation of negative upward leaders and the current waveform. The negative upward leaders propagate intermittently with the current pulses. The step extensions of the leaders are corresponding to the current pulses. ALPS measured 62 steps of the negative upward leaders in the flash. The number of the steps is smaller than that of the current pulses. The reason is that the upward negative leaders exit the field of view of ALPS. The step length in the flash ranged from 13 to 273 m with an average of 74.3 m in the flash and the average interstep interval was 12.5 μs.

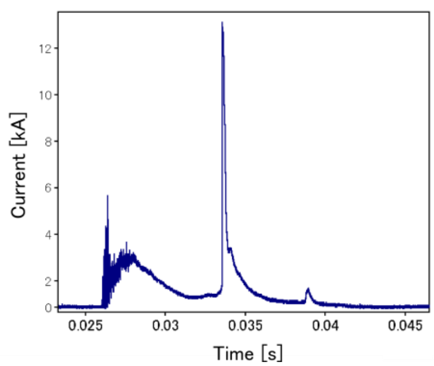

Figure 3 Entire current waveform of positive upward lightning.

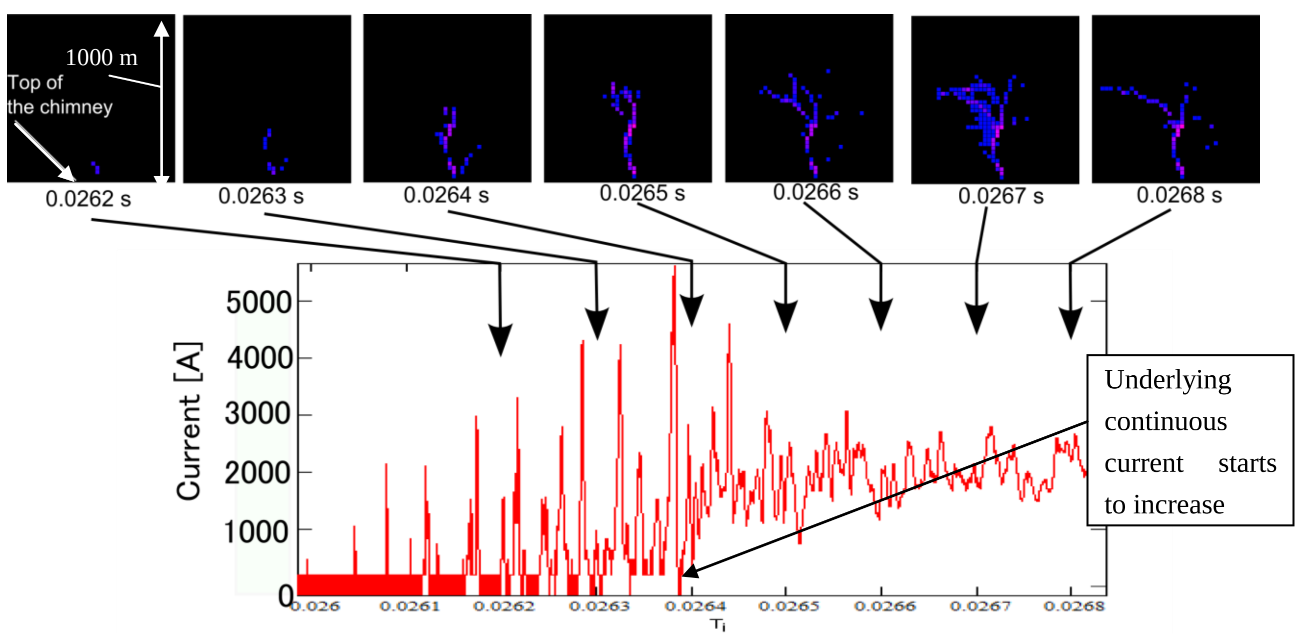

Figure 4 Negative upward leader and corresponding current waveform.

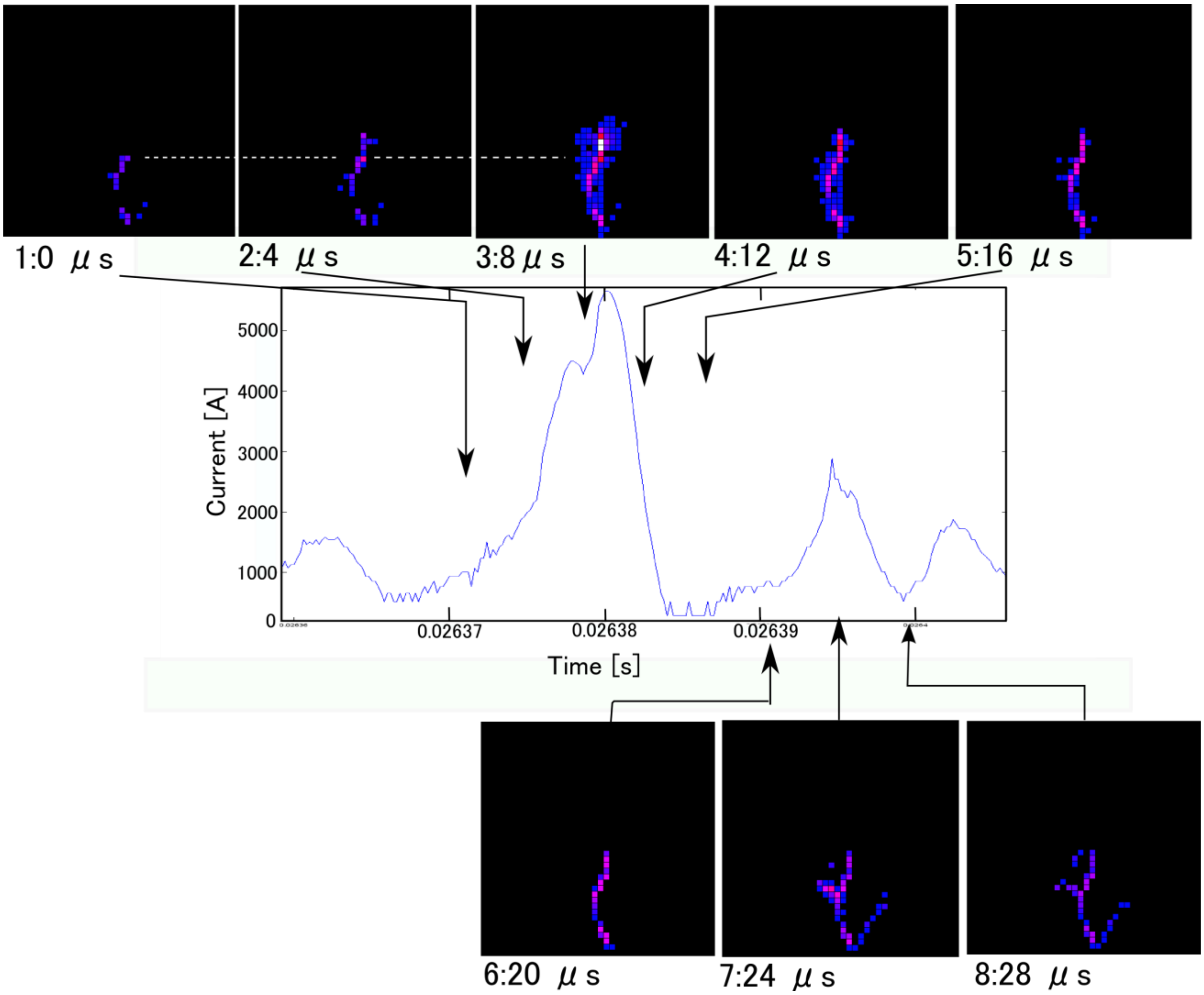

Figure 5 Step formation of upward leader and the corresponding current pulse.

Case 2: 11 Dec.1998

Another positive upward lightning flash occurred at the Fukui chimney on 11 December 1998. Figure 6 shows a still image of the flash and Figure 7 shows the entire current waveform of the flash. The flash was a single-stroke flash. The peak current of the flash was 13.5 kA and the duration of the flash was 46.5 ms. Figure 8 shows ALPS images of the negative upward leader and the leader current waveform, which consists of the current pulse and continuous current components. The number of pulses was 100. The average interpulse interval of the current pulses was 13.6 μs. A total of 1970 frames of the negative upward leader were recorded using ALPS. In the frames, the number of steps was 100. The step lengths in the flash were from 6 to 208 m with an average value of 61.5 m. The average interstep interval obtained from the ALPS was 10.8 μs. The average propagation speed in the flash was 1.6×10^{6} m/s. When the total length of the leaders was 280 m. the continuous current component started to increase.

Figure 6 Still image of positive upward lightning

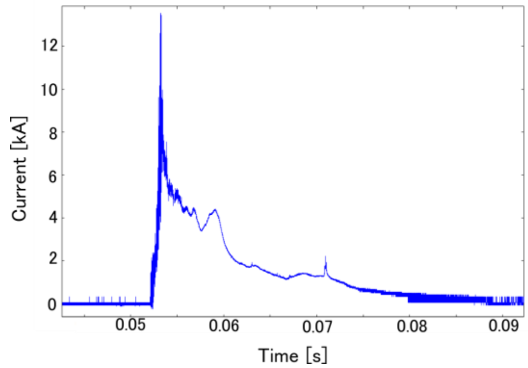

Figure 7 Current waveform of positive upward lightning

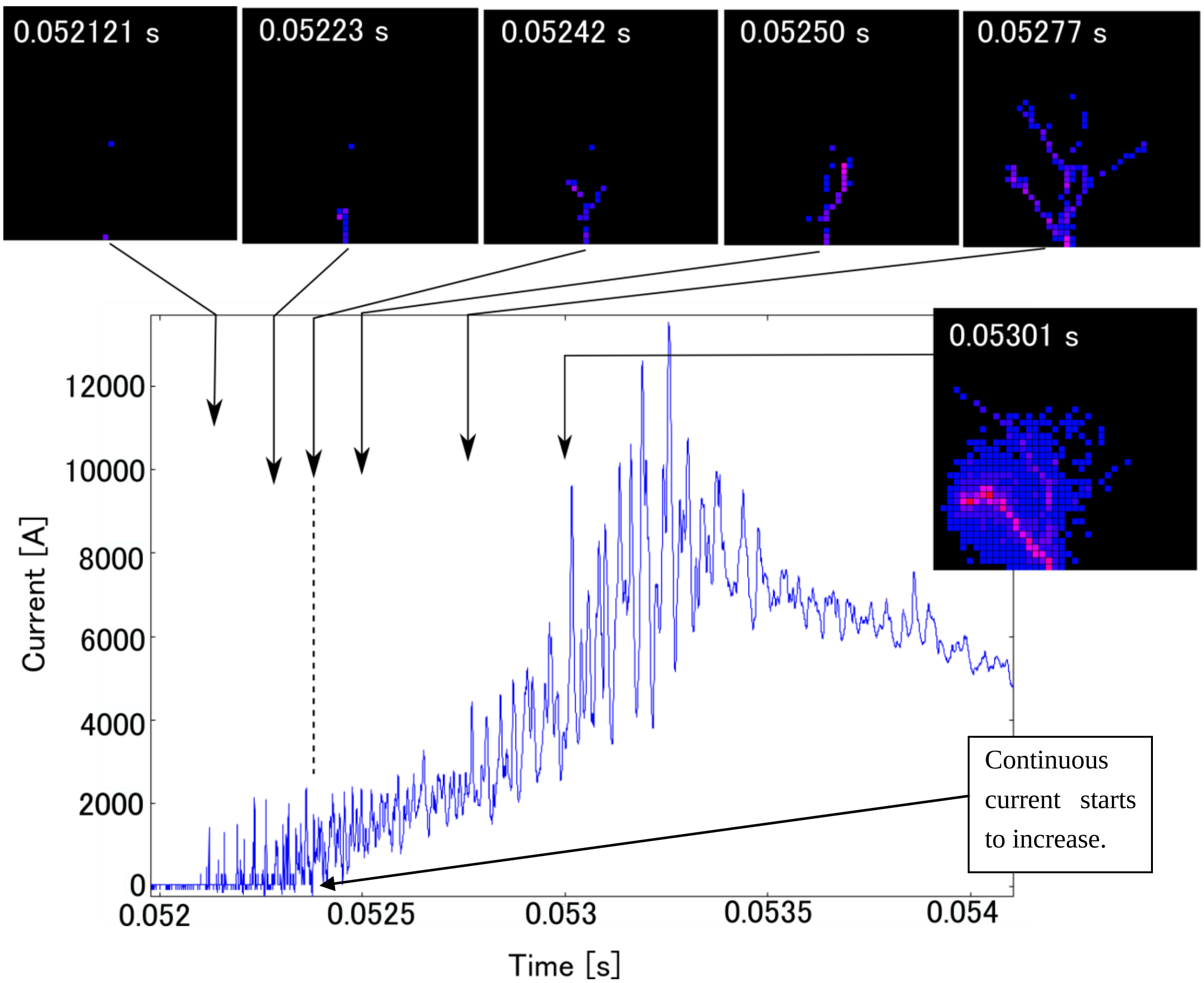

Figure 8 ALPS images showing upward negative leader and the corresponded current waveform

Case 3: 13 Jan. 1991

The third positive upward lightning flash occurred at the Fukui chimney on 13 Jan. 1991. The negative upward leader in this flash has already been reported in a previous paper [Miki et al. 2012]. Thus, here we only give the parameters of the upward negative leaders and the current. Figure 9 denotes ALPS images showing the propagation of negative upward leaders with the corresponding leader current in the positive upward flash. The number of pulses was 126. The interpulse interval ranged from 0.8 to 47.4 μs with a mean value of 11.4 μs. When the length of the leader reached about 80 m, the continuous current started to increase. A total of 6920 frames of negative upward leaders were recorded using ALPS. The number of steps was 82. The average propagation speed of the negative upward leader was 1.3×10^6 m/s. The step length was from 12.6 to 135.7 m with an average value of 51.7 m. The average interstep interval obtained from the ALPS was 16.7 μs.

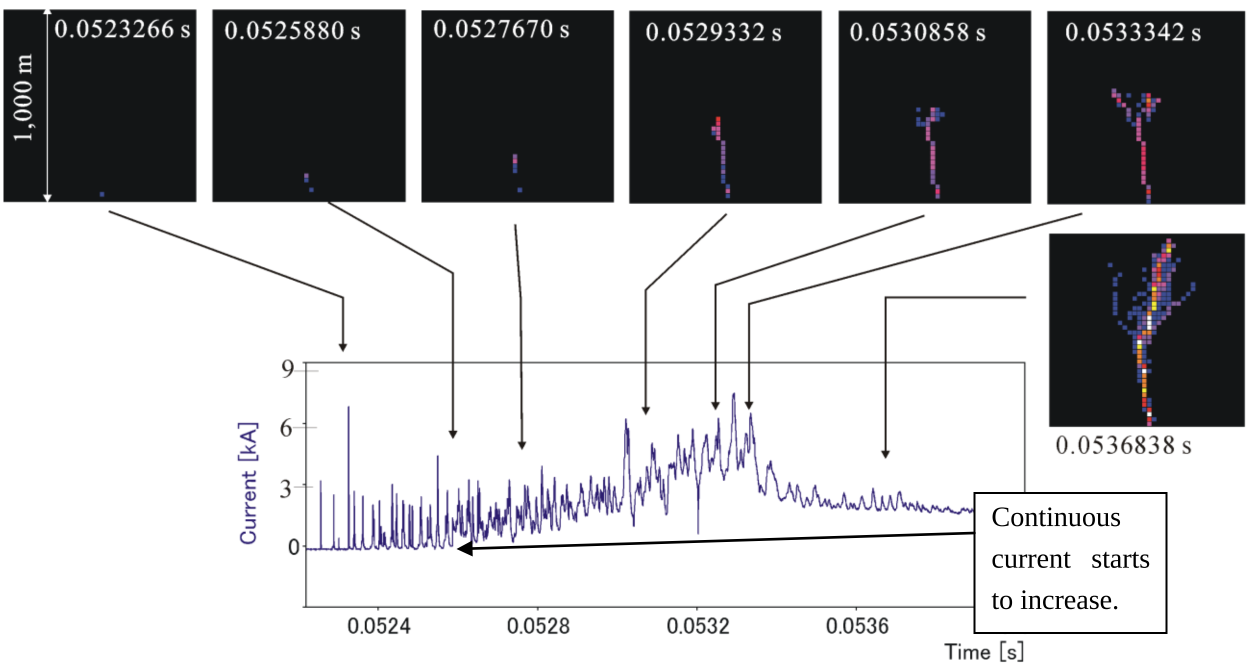

Figure 9 Negative upward leader and corresponding current waveform.

Summary of observation results

We evaluated the parameters of the step propagation of the negative upward leaders from the observation results as shown in Table 1. The interstep intervals are smaller than those of the downward leader reported by Berger et al. [1977]. However, Hill et al. [2011] recently reported a smaller interstep interval than those by Berger et al. [1977]. We consider that the differences between the interstep intervals are due to differences in the time resolution of the measurement instruments. The time resolution of ALPS is higher than that of the high-speed digital video camera used by Hill et al. [2011] and the streak camera used by Berger et al. [1977]. The step lengths in the observation were larger than those reported by Berger, et al. [1977]. This difference is due to the space resolution of the measurement instrument. The space resolution of ALPS is insufficient to measure the step length accurately. The average speed of the upward negative leaders is higher than that of downward leaders. This is likely to be due to the difference between upward and downward leaders.

Table 1 Parameters for the upward negative leaders in positive upward lightning

	Interstep interval [μs]	Interpulse interval [μs]	Step length [m]	Speed [m/s]
Case 1	12.5	18.6	13-273 : Ave. 74	1.6×10^6
Case 2	10.8	13.6	6-208 : Ave. 62	1.6×10^6
Case 3	16.7	11.4	13-136 : Ave. 51	1.5×10^6
Average	13.3	14.5	62	1.6×10^6
Downward Leader [Berger, et al. 1977]	29-47	---	3-17	$0.9\text{-}4.4 \times 10^5$

From the ALPS data, we found that the current pulse corresponds to step formation. The interstep interval obtained from the ALPS images is, however, larger than the interpulse interval obtained from the current data. This difference is due to the poor space resolution of ALPS. Furthermore, the sensitivity of ALPS is insufficient to measure the step formation because the visibility is low under thunderclouds in the coastal area of the Sea of Japan.

DISCUSSION

Step formation processes

Recently, the step formation processes of stepped leaders have been studied by several researchers using high-speed video cameras [e.g., Biagi et al. 2010; Hill et al. 2011; Petersen and Beasley 2013; Gamerota et al. 2014]. They observed the appearance of the space stem and the propagation of the space leader. In this section, we discuss the step formation of a negative upward leader using the ALPS data. Figure 10 shows the typical step formation process in positive upward flashes. First, a new luminous segment appears at a distance from the tip of the old leader channel as shown in the 2nd frame of Figure 10. In the next frame, the luminosity of the new segment increases and the new segment starts to extend toward the tip of the old leader. The peak of the current pulse corresponds to the maximum luminosity of the segment. After the new segment reaches at the old channel, its luminosity decreases gradually. These observation results are slightly different from those observed in downward stepped leaders [Hill et al. 2011][Gamerota et al. 2014]. They reported that the luminosity of the new segment produced by step propagation increases immediately after the space leaders reach the old leader. In our case, the luminosity of the new segment increased before it reaches at the old channel. We consider that this difference is due to the sensitivity of ALPS, because the visibility from the observation site to the chimney was insufficient to measure the weak luminous channel using ALPS.

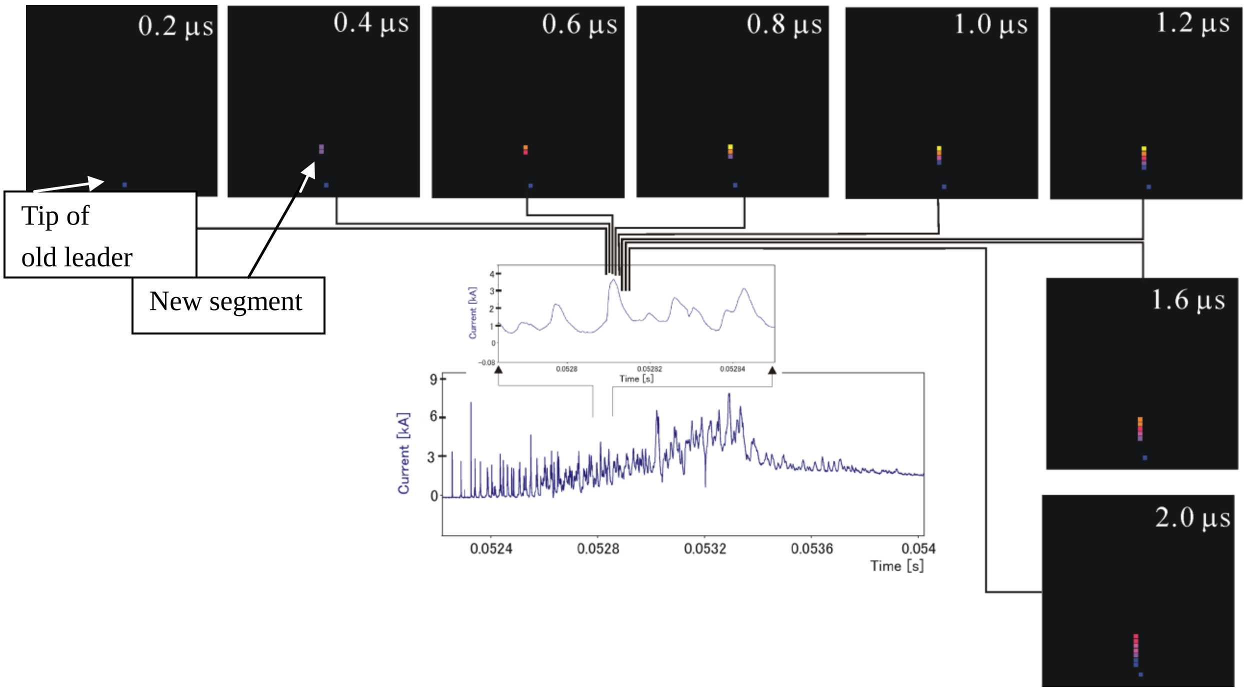

Figure 10 Step formation of negative upward leader and corresponding current waveform

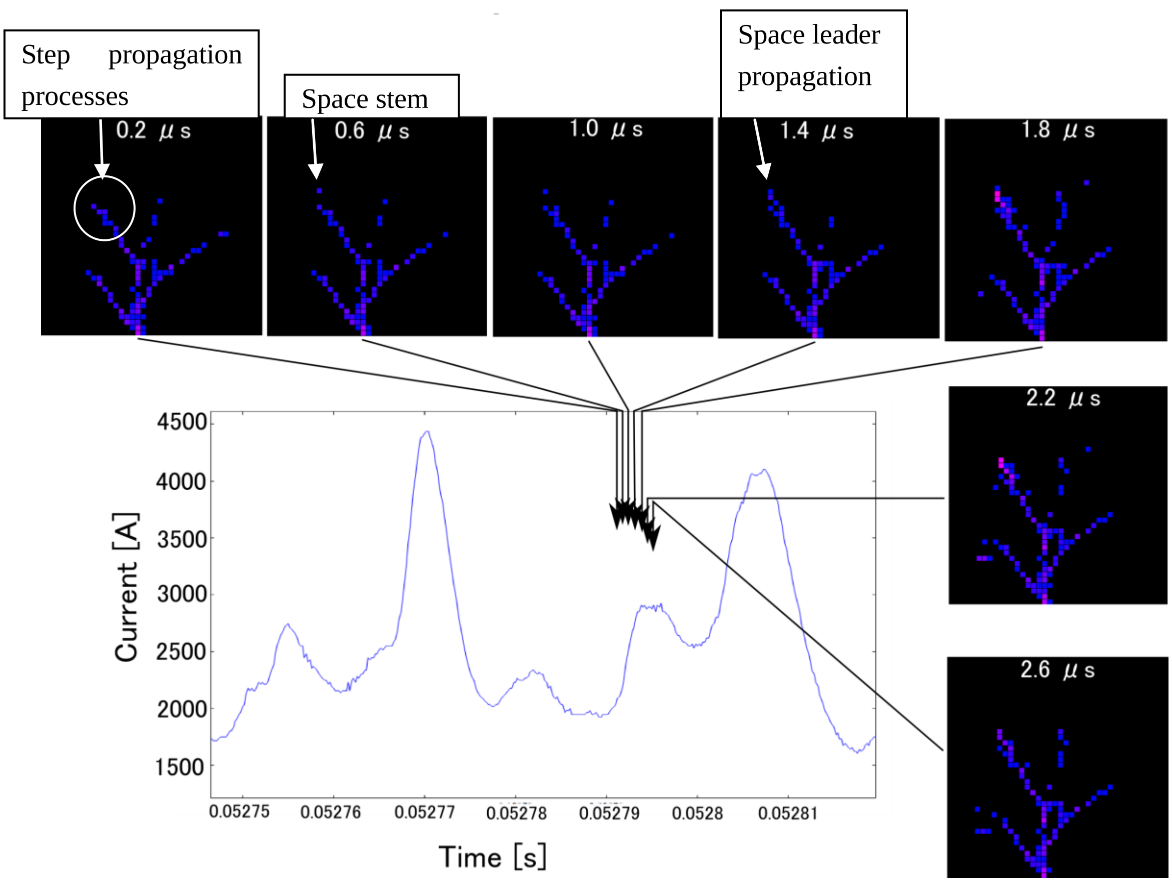

Figure 11 Stem and space leader of negative upward leader with the current pulse

However, some of our data are similar to those observed in the downward leader as shown in Figure 11. As shown in the figure, a new luminous segment appears and extends toward the old channel. After the new segment reaches the tip of the old leader channel, the luminosity of the segment starts to increase as shown in the 4th and 5th frames of Figure 11. Thus, the appearance of a new luminous segment at a distance from the old leader channel is similar to the space stem observed by Hill et al [2011]. We consider that under suitable observation conditions, good visibility around the observation site and a sufficiently large space stem, the observation results in Figure 11 are obtained.

Charges of the stepped leader

The observation results show that the step formation of the leader corresponds to the current pulse. Thus, the charge of the current pulse is the charge that flows into the new segment at the moment of step formation. We examined the average charges of the current pulse. Figure 12 shows a histogram of the charges of the current pulse. The average charge of the current pulse is 0.013 C. We obtained the line density of the new segment from the charges and step length. Figure 13 shows a histogram of the line density of the new segment produced by the step propagation. The average line density is about 3×10^{-4} C/m.

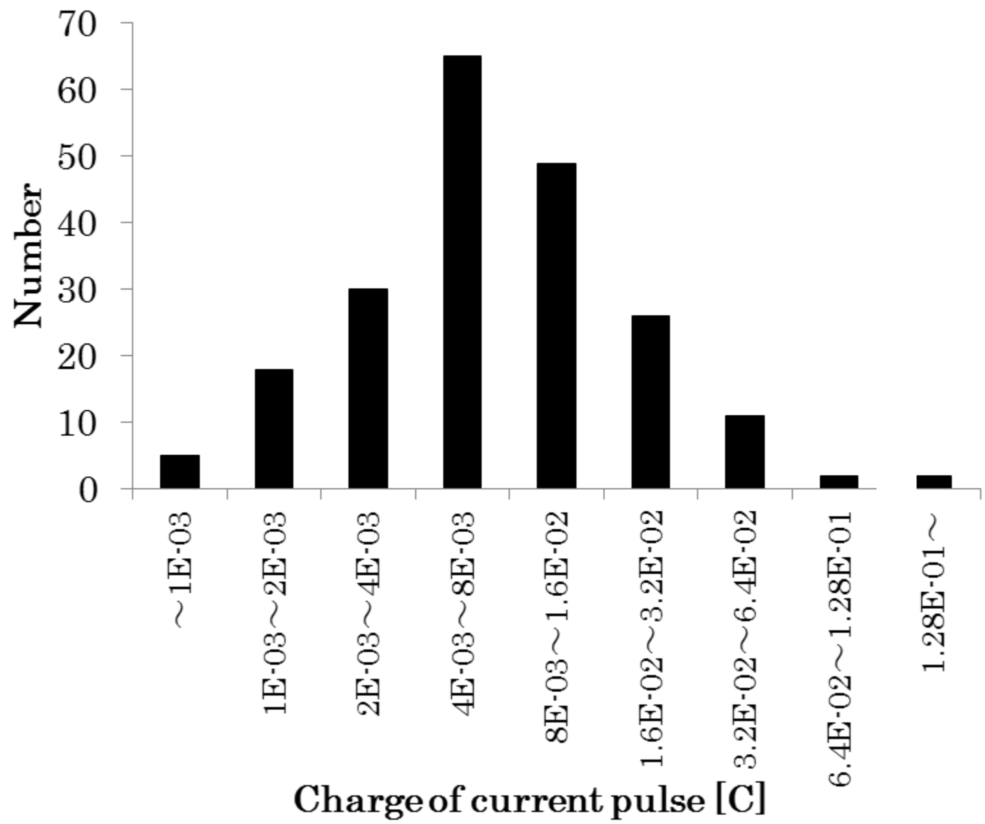

Figure 12 Histogram of the charges of the current pulse in positive upward lightning.

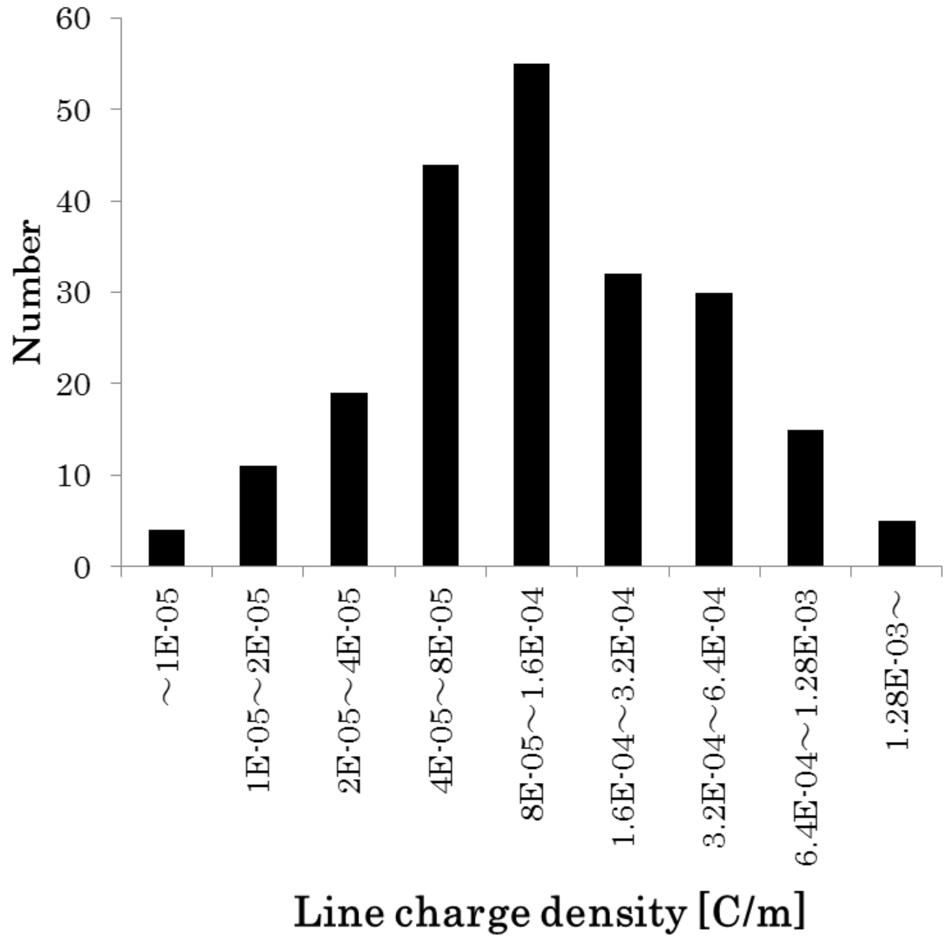

Figure 13 Histogram showing the line charge density of the extended leader segment produced by step propagation.

The continuous current component starts to increase after the pulse current starts. The Zhou et al. [2012] reported that the continuous current component in the leader current is the corona current of the leader channel. The lengths of the upward leaders at the time of initiating the continuous current are however, different each other in the three flashes. This result suggests that the values of the line charge density on the leader channels in the flashes are different from each other and depend on the discharge conditions of the individual flash.

SUMMARY

We observed the step propagation of the negative upward leaders in positive upward lightning at a chimney using ALPS and shunt resistors. In the observation, we obtained the current waveforms and propagation features of the negative upward leaders. The results show that a negative upward leader propagates intermittently with step extensions. The step formation of a negative upward leader corresponds to the pulse current. We evaluated the parameters of the step leaders using the observation results. The average step length, interstep interval and propagation speed were 62 m, 13.3 μs, and 1.6×10^6 m/s, respectively, which are not significantly different from those observed in a downward stepped leader. The charge of the new segment produced by the step propagation was 0.013 C. From this, we evaluated the line density of the new leader channel for a step to be 3×10^{-4} C/m.

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