LEADER AND RETURN STROKE SPEED OF UPWARD-INITIATED LIGHTNING

Atsushi Wada, Akira Asakawa, Takatoshi Shindo, Sigeru Yokoyama
Central Research Institute of Electric Power Industry, Tokyo, Japan

ABSTRACT: Leader and return stroke speeds of upward-initiated lightning were measured at a 200m-high chimney in winter in Japan by using a 40x40 pin photodiode array system. The mean value of upward positive leader speeds was 3.6x10^6 m/sec with a range from 0.6x10^5 to 14x10^5 m/sec without any appreciable stepped motion. Upward negative leader was observed with stepped motion. The average speed of an upward negative leader was 6x10^6 m/sec and the mean value of each step speeds was 3x10^7 m/sec. In the rare case, downward return stroke was observed at average speed of 1.6x10^8 m/sec after the upward positive leader developed at a speed of 2.3x10^6 m/sec. The downward return-stroke decreased the speed from 2.5x10^8 m/sec to 2.5x10^7 m/sec as it developed towards the ground. In the subsequent discharge following the upward positive leader development, the negative downward dart leader with speed of 5.1x10^7 m/sec and the upward return stroke with speed of 1.7x10^8 m/sec sequences were observed.

INTRODUCTION

The return stroke speed is one of the most important parameters in the various lightning return stroke models to estimate the lightning current from the electromagnetic field measurements. However, it is very hard to collect many data of return stroke speed of natural lightning because the striking point is not known in advance. We have been observing the lightning discharge at the 200m-high Fukui chimney in winter in Japan /1/. About thirty events of the lightning discharge are observed using still cameras in a winter season. About ninety percent of all the recorded events were the lightning discharge initiated by an upward moving positively charged leader. About ten percent was the lightning initiated by an upward moving negatively charged leader. Some of the lightning produced the subsequent discharge composed of downward leader and upward return stroke sequences following the upward leader development. The leader and return stroke speeds were determined by a pin photodiode array system. We will report the properties of leader and return stroke speed of the upward-initiated lightning.

INSTRUMENTATION

When the lightning strikes the 5-m lightning rod on top of the chimney, lightning currents are measured by using a 10 mΩ and a 2 mΩ coaxial shunt-resistor installed at the base of the lightning rod. The progressive characteristics of lightning are measured by ALPS (Automatic Lightning Discharge Progressing Feature Observation System) /2/. The ALPS records luminosity changes in the lightning channel by measuring the differences between signals from different photodiodes. The transient recorder of ALPS is a sampling time of 200 ns, a recording capacity of 12.8M bytes, a resolution of 4 bits, and a recording time of 3.2 ms. At a distance of 630 m from the chimney, a vertical lightning channel of 1000 m is divided by using 40 diode elements. Electromagnetic field changes that accompany lightning discharges are also measured by using several types of antennas. These simultaneous measurements classify the behavior of winter lightning initiated by an upward leader.

CLASSIFICATION OF UPWARD-INITIATED LIGHTNING

In the three years from 1996 to 1998, lightning discharge of 40 events were recorded at the chimney in winter. All recorded event was the upward-initiated lightning (upward positive leader 87.5 percent). In the lightning initiated by the upward positive leader, the lightning discharge processes are categorized in four types as follows. Type a: upward positive leader only. Type b: upward positive leader and downward return stroke sequences. Type c: downward negative leader and upward return stroke sequences following the upward positive leader development. Type d: downward positive leader and upward return stroke sequences following the upward positive leader development. Most upward-initiated lightning was observed without return strokes as type A. Such discharge is classified in the “slow” case of rocket-triggered lightning /3/. Type b is a rare case. Type c is similar to the lightning from the Empire State Building /4/, the “classical triggered lightning” of the rocket-triggered lightning /3/, and the model proposed by Mazur and Ruhnke /5/. Type d is a new type of lightning discharge process from the tall structure in winter.

UPWARD LEADER SPEED

Positive leader
The cumulative frequency distribution of two-dimensional average speed of upward moving positive leader was reported /6/. The mean speed was 3.6x10^5 m/sec with a range from 0.6x10^5 to 14x10^5 m/sec. Most positive leader progressed upward without any appreciable stepped motion. The speed of the upward positive leader is similar to the leader speed of reviews given by Uman /7/ and MacGorman and Rust /8/.

**Negative leader**

The upward negative leader is rare case (about 10 percent) and it is very hard to observe it. One example was observed with a good condition in 2000. The average speed of the upward leader was 6x10^6 m/sec and the mean value of each step speeds was 3x10^7 m/sec /9/. The upward leader moved with stepped motion like a downward stepped-leader of natural lightning in summer. Interestingly, the step length, the speed, and the peak current increased as the upward leader development. Table 1 shows the comparison between upward negative leader and downward negative leader properties. The leader average speed, pause time between steps and step length of the upward leader observed at the chimney are similar to the downward leader properties, but the upward leader current is big compared to the downward leader current.

Table 1. Negative stepped-leader properties

<table>
<thead>
<tr>
<th>Upward leader from tall structures</th>
<th>Leader average speed (10^5 m/sec)</th>
<th>Pause time between steps (µs)</th>
<th>Step length (m)</th>
<th>Leader current (kA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Berger et al. /10/</td>
<td>1.2 - 1.9</td>
<td>33 - 50</td>
<td>4.5 - 8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.1 - 4.5</td>
<td>40 - 47</td>
<td>5.0 - 18</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8.7 - 12.0</td>
<td>4 - 6.5</td>
<td>3.5 - 7.5</td>
<td></td>
</tr>
<tr>
<td>Wada et al. /9/</td>
<td>60</td>
<td>2 - 32</td>
<td>10 - 311</td>
<td>0.7 - 20</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Downward leader from thundercloud</th>
<th>Leader average speed (10^5 m/sec)</th>
<th>Pause time between steps (µs)</th>
<th>Step length (m)</th>
<th>Leader current (kA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Many researchers /7/</td>
<td>1.0 - 26.0</td>
<td>30 - 125</td>
<td>3 - 200</td>
<td>0.05, 0.06</td>
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<td>Williams and Brook /11/</td>
<td></td>
<td></td>
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<td>0.2 - 3.8</td>
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<td>Krehbiel /12/</td>
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<td></td>
<td>0.1 - 5</td>
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<td>Thomson et al. /13/</td>
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</tbody>
</table>

**RETURN STROKE SPEED**

**Downward return stroke**

In the rare case, downward return stroke was observed after the upward negative leader development. Figure 1 (a) shows the streak image of the luminosity observed by ALPS. The altitude represents the height from the top of the 200 m-high chimney. The color differences indicate the relative intensity of light. The luminosity continues to brighten with little change in brightness without a obvious upward propagation of light in the time of 154.8µs ((3) to (4)). The luminosity propagates to the thunderclouds without any appreciable stepped motion at a traveling time of 306.6µs. ((4) to (6)). The average speed was 2.3x10^6 m/s. After that, very strong luminosity was observed 850 m above the chimney. The luminosity then drops to 50 m above the chimney at a traveling time of 5.0µs ((7) to (9)). The average speed was 1.6x10^8 m/sec. Figure 2 shows the downward return stroke speed at different altitudes. The speed decreased from 2.5x10^8 m/sec to 2.5x10^7 m/sec as it developed towards the ground. Due to the difference in the propagation speed of downward luminosity, a difference in conductivity at the top and bottom of the upward positive leader is assumed. Because the conductivity of channel decreases rapidly over time, the upper part of the channel is assumed to possess high conductivity, while the lower part has low conductivity. The characteristics of the downward return-stroke speed which decreases with propagation are similar to those of the upward return-stroke reported by Idone and Orville /14/, Nakano et al. /15/, Mach and Rust /16/, and Wang et al. /17/.
Upward return stroke

Upward return stroke was observed in the subsequent discharge following the upward positive leader development. Figure 3 shows the lightning progressing feature observed by ALPS. At the height of 900 m from the top of the chimney, the luminosity in the space is first observed. The part of brightness becomes stronger and the tip of the luminosity propagates to the chimney. The luminosity reaches the top of the chimney with a traveling time of $12.8\mu$s. The two-dimensional average speed is $5.1\times10^7$ m/sec. The speed belongs to the category of high value of dart-leader velocity which was observed in summer /8/. After that, in the time of $2.0\mu$s, relative light intensities in the center of channel dose not change and the only part of the around of channel brightens. The time corresponds to the part of rise of current wave front. It is considered that the lightning channel is heated with flowing of current in the time. After that, the luminosity of the part of height of 50 m above the chimney increases, and the luminosity propagate to the thundercloud with traveling time of $7.4\mu$s. The two-dimensional average speed of the luminosity is $1.7\times10^8$ m/sec. It is considered that the upward luminosity is return stroke because the strong brightness returns from the chimney to the cloud with a high speed of the order of $10^8$ m/sec.

SUMMARY

We described the leader and return stroke speed of upward-initiated lightning observed at the 200m-high chimney in winter in Japan. The mean speed of upward positive leader was $3.6\times10^5$ m/sec and the upward negative leader developed at the average speed of $6\times10^6$ m/sec with stepped motion at the mean value of each step speeds of $3\times10^7$ m/sec. In the rare case, a downward return stroke was observed after the upward negative leader development. The average speed of the upward positive leader is $2.3\times10^6$ m/sec, and that of the downward return stroke is $1.6\times10^8$ m/sec. The downward return stroke decreased the speed from $2.5\times10^8$ m/sec to $2.5\times10^7$ m/sec as the return-stroke propagates to the ground. The downward return-stroke is believed to occur when the upward positive leader reaches the negative charge region but the attachment process that combines the upward and downward leaders near the thundercloud was not confirmed. This is a future topic. The ALPS recording memory is 3.2 ms and it is not enough to observe the multiple stroke after the upward leader development. We started to observe the lightning discharge last year by using the new type of ALPS, which is able to measure the multiple strokes.

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Fig. 3. Downward leader and upward return stroke.

REFERENCES

/9/ Wada, A., A. Asakawa, and T. Shindo, Luminous phenomenon during upward leader development - Lightning observational results at 200m-high chimney-, 26th Int. Conf. on Lightning Protection, 1a.1, Cracow, Poland, 2002.

Corresponding author e-mail address: Dr. Atsushi Wada
lun@criepi.denken.or.jp