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Characterization of the initial stage of upward-initiated lightning

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Abstract: We compare the characteristics of the initial stage (IS) in natural upward lightning as observed on (1) the Gaisberg tower (100 m, Austria), (2) the Peissenberg tower (160 m, Germany), and (3) the Fukui chimney (200 m, Japan) with their counterparts in rocket-triggered lightning in Florida. All current records in Japan and some of the current records in Germany and Austria were obtained in winter, whereas all triggered-lightning data were obtained in summer. All lightning events analyzed here effectively transported negative charge to ground. The geometric mean (GM) values of the overall characteristics of the IS, duration (T), charge transfer (Q), average current (I), and action integral (AI), for rocket-triggered lightning (T = 305 ms, Q = 30.4 C, I = 99.6 A, AI=8505 A^2s) are similar to their counterparts for Gaisberg-tower flashes (T = 235 ms, Q = 29.6 C, I = 126 A) and Peissenberg-tower flashes (T = 290 ms, Q = 38.5 C, I = 133 A, AI=3540 A^2s), while the Fukui-chimney flashes are characterized by a somewhat shorter GM initial-stage duration (T = 77.1 ms), a larger average current (I = 505 A) and a larger action integral (AI=46440 A^2s). The GM initial stage charge transfer for the Fukui-chimney flashes is 38.9 C. The observed differences in the IS duration is probably related to the difference in the lower current measurement limits: about 200 A for the Fukui data set vs. 15 to 20 A for the other three data sets. Thus the actual Fukui charge transfer is underestimated along with the IS duration, while the actual average current is overestimated. The characteristics of the initial continuous current (ICC) pulses in object-initiated (Gaisberg, Peissenberg, and Fukui) lightning are similar within a factor of two to three, but differ more significantly from their counterparts in rocket-triggered lightning. Specifically, the ICC pulses in object-initiated lightning exhibit larger peaks, shorter risetimes, and shorter half-peak widths than do the ICC pulses in rocket-triggered lightning.

Keyword: Upward lightning, Rocket-triggered lightning, Initial stage, ICC pulses, Action integral

1. Introduction

Upward lightning discharges are initiated by a leader that originates from the object and propagates upward toward the charged cloud overhead. Upward lightning discharges involve an initial stage (IS) that is characterized by a continuous current with a duration of some hundred millisecond and an amplitude of some tens to some thousands of amperes. The initial stage is often followed by one or more downward leader/upward return stroke sequences. Since direct current measurements are usually performed on towers that experience primarily upward discharges, there has been considerable interest lately in characterizing upward lightning flashes. Specifically, there is the question of whether current pulses superimposed on the long-lasting, low-level continuous current, are due to return strokes or due to an M component-type lightning processes. Additionally, a better understanding of upward lightning is needed for developing adequate lightning protection methods for tall man-made objects, such as TV towers, high-rise buildings, and UHV transmission lines.

The phenomenology of upward lightning is similar to that of rocket-triggered lightning. P. Hubert was the first to compare the characteristics of rocket-triggered lightning with those of upward lightning initiated from man-made objects [1]. He stated that triggered lightning "largely surpasses" natural upward lightning in term of the "maximum intensity" (peak current) and the electric charge transferred by the flash. M. A. Uman also compared rocket-triggered lightning with upward lightning from tall objects [2] and found no apparent differences in terms of the flash duration and flash charge. It is worth noting that Hubert [1] apparently lumped data for flashes containing and not containing return strokes. As a result, the relatively low values of "maximum intensity" (0.25 kA) and flash charge (10 C) quoted in [1] with reference to Berger are largely determined by upward flashes without return strokes. In our view, upward flashes with and without return strokes should be examined separately, particularly when the peak current is concerned. Uman [2] apparently did not consider natural upward flashes without return strokes, which explains the discrepancy between his results and those of Hubert [1]. Additionally, at least in the case of rocket-triggered flashes, neither Hubert [1] nor Uman [2] distinguished between current pulses due to downward leader/upward return stroke sequences and current pulses occurring during the initial stage. These two types of pulses may involve different mechanisms leading to the observed differences in their characteristics (Rakov et al. [3]).

Wang et al. [4], have studied the characteristics of the current pulses in the initial stage (IS) of the rocket-triggered lightning. In most cases, the IS contained current pulses (initial continuous current (ICC) pulses) superimposed on the slowly varying continuous current. A statistical comparison between these pulses and the M-component pulses superimposed on continuing currents following return strokes in triggered lightning indicates that both types of pulses are due to similar physical processes. Thus, the ICC pulses in natural upward lightning are also expected to be similar to the M component-type pulses. However, no quantitative confirmation of this inference is available at this time.

In this international collaborative study, we compare the characteristics of the IS in rocket-triggered lightning in Florida with their counterparts in natural upward lightning as observed on (1) the Gaisberg tower (100 m Austria), (2) the Peissenberg tower (160 m, Germany), and (3) the Fukui chimney (200 m, Japan). In the comparison of IS, the duration, charge, average current, and action integral of IS were compared. The magnitude, duration, risetime, and half-peak width were used in characterizing ICC pulses.

2. Data

The Gaisberg tower is located at the top of the mountain (1270 m) near Salzburg, Austria. The height of the tower is 100 m. The current was measured at the tower top, at the base of the air terminal, by a 0.25 mohm current viewing resistor (shunt) having a bandwidth of 0 Hz to 3.2 MHz [5]. The shunt output signal was recorded by an 8 bit digitizing board (Bandwidth: 15 MHz, Memory: 16 MB) installed in a personal computer. The lower current measurement limit was 17 A.

The Peissenberg tower is located about 60 km southwest of Munich, Germany on a ridge (about 950 m above sea level) called "Hoher Peissenberg". The height of the Peissenberg tower is about 160 m. The lightning current was measured with a current transformer (Pearson CT: 0.15 Hz – 200 kHz) [6]. The signal was recorded by a digitizing oscilloscope with a storage capability of 1 million points using a sample interval of 1μs. The lower current measurement limit was 15 A.

The Fukui chimney is located in the Fukui thermal plant on the coast of the Sea of Japan. The height of the chimney is 200 m. The current was measured by two shunts (2 mohm and 10 mohm) [7]. The 2 mohm shunt was used for measuring large currents (8 - 150 kA) and the 10 mohm shunt for measuring small currents (0.2 - 12 kA). The shunt outputs were recorded by a 10-bit digital recorder (2M words, 100M sample/s). The lower current measurement limit was about 200 A.

The rocket-triggered lightning experiments were conducted at the International Center for Lightning Research and Testing (ICLRT) at Camp Blanding, Florida. Rocket launchers were located on flat ground, 20-30 m above sea level. The current was measured with a 1 mohm current viewing resistor [4]. The signal was recorded by a tape recorder with a bandwidth from dc to 400 kHz and a noise level of approximately 20 A.

All measurement systems employed fiber optic links from the shunt (or CT) to the digital recorder. All current records in Japan and some of the current records in Germany and Austria were obtained in winter, whereas all triggered-lightning data were obtained in summer. In this paper, we used data only for negative flashes.

3. Results and Discussion

3.1. Initial stage

Table 1 shows the geometric means (GM) values of the overall characteristics of the IS, duration, charge, average current, and action integral.

The overall characteristics of IS for rocket-triggered lightning are similar to their counterparts for Gaisberg tower flashes and Peissenberg tower flashes, while the Fukui chimney flashes are characterized by a somewhat shorter GM initial stage duration, a larger average current

Table 1 Overall characteristics (geometric mean values) of the initial stage in upward-initiated lightning

Data Set	Sample Size	Duration [ms]	Charge [C]	Current [A]	Action Integral [A^2s]
Fukui chimney (Japan)	36 1996-1999	> 77.05	> 38.89	504.8	46440
Peissenberg tower (Germany)	21 1996-1999	289.9	38.50	132.9	3540
Gaisberg tower (Austria)	76 2000	234.6	29.55	126.0	--
Rocket-triggered lightning (USA)	45 1996-2000	305.3	30.39	99.55	8505 (N=8)

and action integral. The GM initial stage charge for Fukui chimney is 38.9 C. The latter value is not so different from the other charge values in Table 1. The difference in the IS duration is probably related to the differences in the lower current measurement limits, as further discussed in the next paragraph.

The overall characteristics of the IS for Japan, Germany, Austria, and Florida are shown in Figures 1, 2, 3, and 4, respectively. The shapes of the histograms for Peissenberg tower flashes, Gaisberg tower flashes, and Florida rocket-triggered flashes are similar, suggesting that the IS of the rocket-triggered lightning is similar to that of the natural upward lightning. However, the shapes of the histograms for Fukui chimney flashes are somewhat different from the others. In particular, Fukui chimney sample contains many flashes of short duration that are less than some milliseconds. One of the possible reasons of the relatively short IS duration is the underestimation of the duration due to the low current limit. Further, the action integral for Fukui chimney flashes (see Table 1) is considerably larger than for Peissenberg-tower and Florida rocket-triggered flashes. Note that the GM values of charge and action integral for Fukui-chimney flashes are probably underestimated due to the relatively high lower current limit. Thus, the IS in Fukui-chimney flashes is characterized by considerably larger energy than for other data sets considered here.

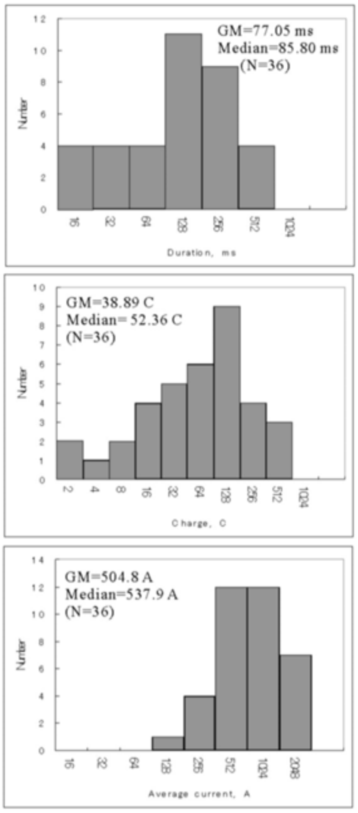

Fig. 1 Initial stage of object initiated lightning (Fukui chimney, Japan)

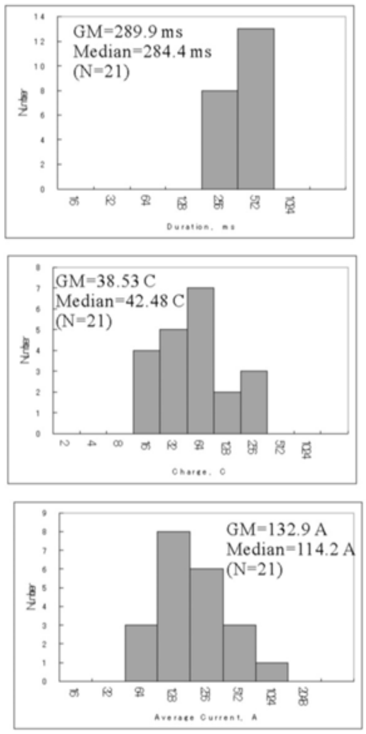

Fig. 2 Initial Stage of object-initiated lightning (Peissenberg, Germany)

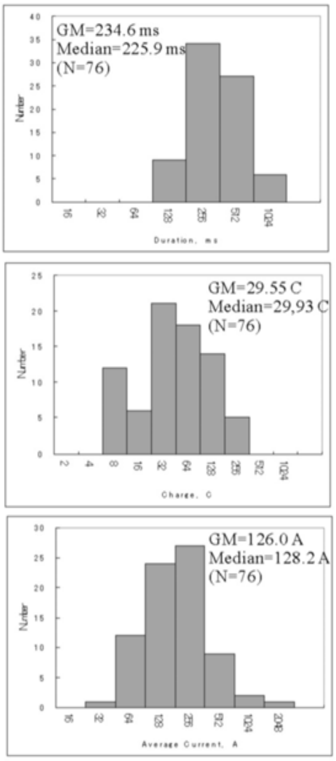

Fig. 3 Initial Stage of object-initiated lightning (Gaisberg, Austria)

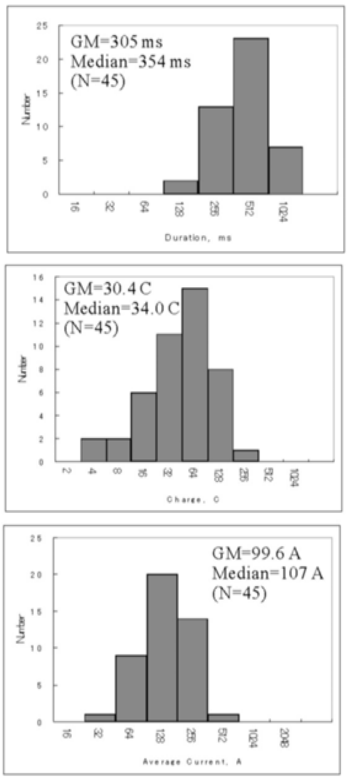

Fig. 4 Initial Stage of Rocket-triggered lightning (Florida, USA)

Table 2. Parameters (geometric mean values) of ICC pulses in upward-initiated lightning

Data Set	Sample Size	Magnitude [A]	Duration [ms]	Risetime [us]	Half Peak Width [us]
Fukui chimney (Japan)	231	781.1	0.5140	44.2	140.7
Peissenberg tower (Germany)	124	512.3	0.8329	60.87	153.3
Gaisberg tower (Austria)	348 ~ 377	> 376.9 N=351	1.199 N=377	< 109.7 N=344	275.5 N=348
Rocket-triggered Lightning (USA)	247 ~ 296	112.6 N=296	2.590 N=254	463.6 N=267	943.1 N=247
M-components (USA) Ref. [8]	124 ~ 113	117	2.1 N=114	422	800 N=113

3.2. ICC pulses

Table 2 shows the GM values of the parameters of ICC pulses, magnitude, duration, risetime, and half-peak width. The characteristics of the ICC pulses in the natural upward lightning (Peissenberg, Gaisberg, and Fukui) are similar within a factor of two to three, but differ more significantly from their counterparts in rocket-triggered lightning. Specifically, the ICC pulses in natural upward lightning exhibit larger peaks and shorter half-peak widths and durations than do the ICC pulses in rocket-triggered lightning. In Table 2, the magnitude and risetime for Gaisberg tower are underestimates, because in Gaisberg-tower flashes, the waveforms of 26 ICC pulses that are larger than 2 kA and have less than 10 µs risetime are distorted due to a problem with the measurement system.

The characteristics of the ICC pulses in rocket-triggered lightning are similar to those of M-component pulses superimposed on continuing currents following return strokes in rocket-triggered lightning [3, 4, 8]. This result suggests that the mechanisms of ICC pulses are similar to those of M-components.

Figures 5, 6 and 7 show the histograms of half-peak width, magnitude, and risetime, respectively of the ICC pulses in rocket-triggered lightning and in natural upward lightning. These figures suggest that the ICC pulses in rocket-triggered lightning do not exhibit short half-peak widths (< 64 µs), large magnitudes (> 4096 A) and short risetimes (<32 µs). This result may be interpreted as

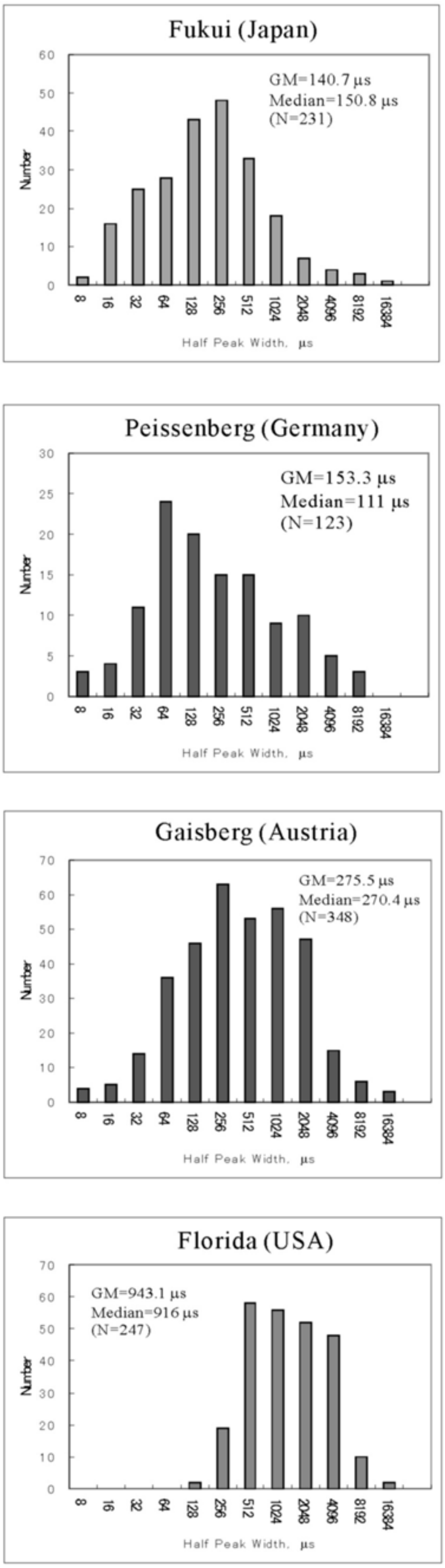

Fig. 5 Half Peak Width of ICC pulses

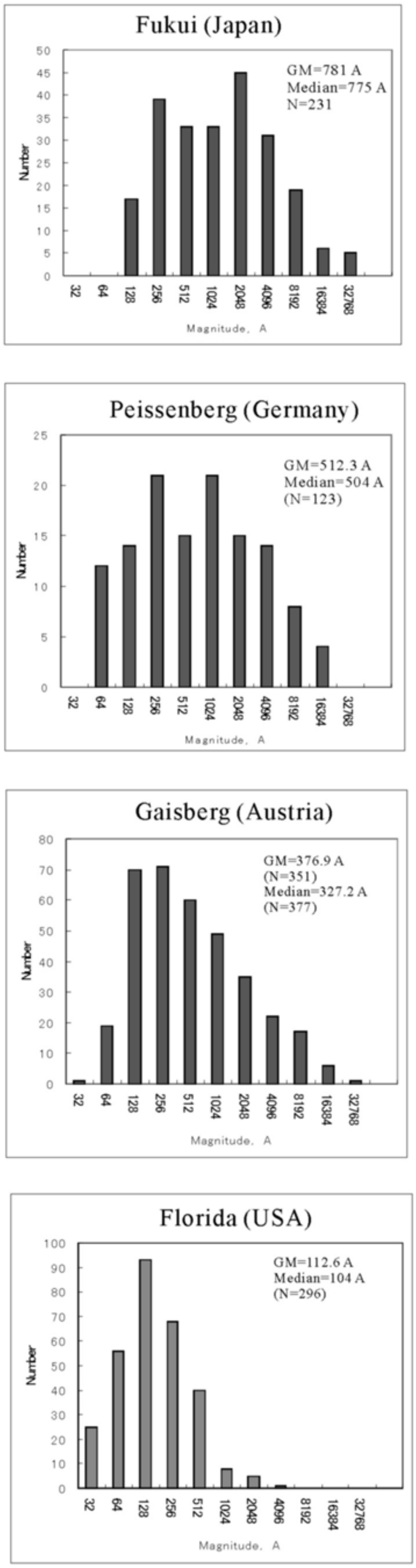

Fig. 6 Magnitude of ICC pulses

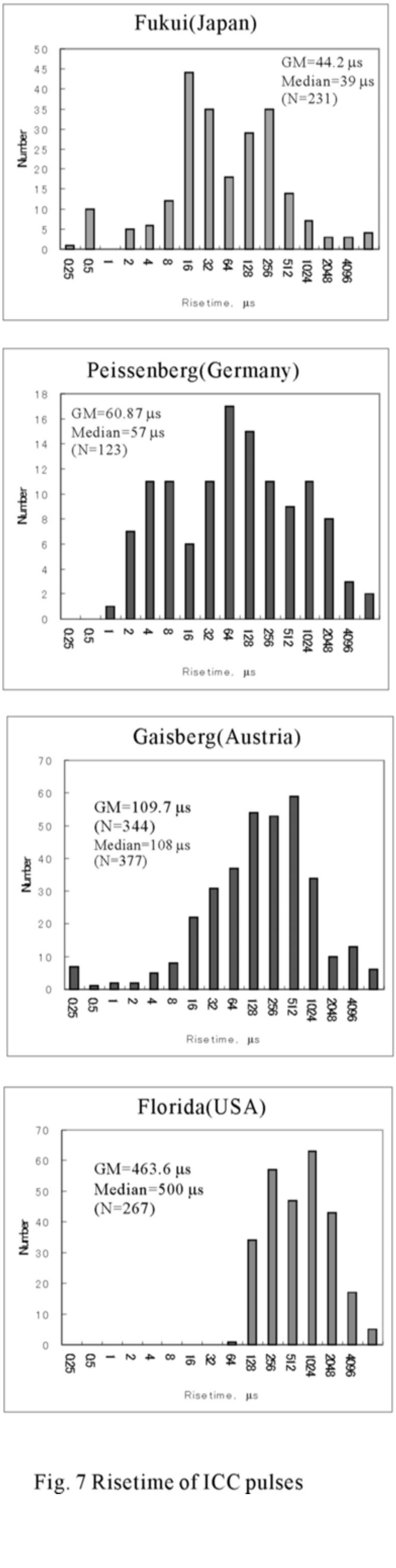

Fig. 7 Risetime of ICC pulses

indicative of the fact that ICC pulses in natural upward lightning are different from ICC pulses in rocket-triggered lightning. Since ICC pulses in natural upward lightning for the Gaisberg tower, the Peissenberg tower, and the Fukui chimney are similar, we conclude that the parameters of the ICC pulses of the natural upward lightning are independent of geographical location.

4. Concluding Remarks

We compared the overall characteristics of the IS and the parameters of ICC pulses in rocket-triggered lightning and in natural upward lightning in three different geographical locations. The initial stage of rocket-triggered lightning appears to be similar to that of natural upward lightning. However, the overall characteristics of the IS for the Fukui chimney are somewhat different from those for Gaisberg tower flashes, Peissenberg tower flashes, and Florida rocket-triggered flashes. One of the reasons is the relatively-high lower current measurement limit at the Fukui chimney. Another reason is that the Fukui chimney flashes are characterized by considerably larger action integral than upward-initiated flashes in other data sets considered here.

Parameters of ICC pulses of rocket-triggered lightning are different from those of natural upward lightning. The ICC pulses of natural upward lightnings appear to be similar in different geographical locations.

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