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Initial-stage pulses in upward lightning: Leader/return stroke versus M-component mode of charge transfer to ground

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[1] We analyzed high-speed video images and corresponding current records for eight upward lightning flashes initiated by the Peissenberg tower (160 m) in Germany. These flashes contained a total of 33 measurable initial stage (IS) current pulses, which are superimposed on steady IS currents. Seven IS pulses had relatively short (<8 μs) 10-to-90% risetimes and 26 IS pulses had relatively long (>8 μs) risetimes. Six (86%) of seven IS current pulses with shorter risetimes each developed in a newly-illuminated branch, and 25 (96%) of 26 IS pulses with longer risetimes occurred in already luminous (current-carrying) channels. These results support the hypothesis that longer risetimes are indicative of the M-component mode of charge transfer to ground, while shorter risetimes are associated with the leader/return stroke mode. Similar results were obtained for M-component pulses that are superimposed on continuing currents following return-stroke pulses. **Citation:** Flache, D., V. A. Rakov, F. Heidler, W. Zischank, and R. Thottappillil (2008), Initial-stage pulses in upward lightning: Leader/return stroke versus M-component mode of charge transfer to ground, *Geophys. Res. Lett.*, *35*, L13812, doi:10.1029/2008GL034148.

1. Introduction

[2] Lightning initiated by tall structures (upward lightning) has been studied for over six decades. McEachron was the first to measure the current of an upward leader at the Empire State Building in New York City, USA [*McEachron*, 1939]. He also obtained time-resolved photographic images of upward lightning. Berger and co-workers acquired detailed current and optical data for upward lightning in their long-term study at the Mount San Salvatore in Switzerland [e.g., *Berger and Vogelsanger*, 1969]. Similar studies, mostly at instrumented towers, were conducted in several other countries, including Austria, Canada, Germany, Japan, and Russia (see *Rakov and Uman* [2003, chap. 6] for a recent review).

[3] Current records of upward lightning include the initial stage (IS), which is characterized by a slowly-varying current with typical duration of some hundreds of milliseconds and amplitude of some tens to some thousands of amperes. In most cases, the IS contains current pulses superimposed on the slowly-varying current. These pulses are referred to as initial continuous current (ICC) pulses or IS pulses. It is expected that most of IS pulses are due to processes developing in current-carrying channels. Therefore, they should be similar to M-components [*Rakov et al.*, 2001], as opposed to leader/return stroke sequences, which occur along essentially non-conducting paths.

[4] IS pulses in natural upward and rocket-triggered lightning were studied in detail by *Miki et al.* [2005]. They used data for the Gaisberg tower (Austria), Peissenberg tower (Germany), Fukui chimney (Japan), and rocket-triggered lightning in Florida. *Miki et al.* [2005] found that an appreciable fraction of IS current pulses initiated by tall grounded objects exhibit peaks and risetimes that are comparable to those of return-stroke pulses. Their finding suggests that some IS pulses may be manifestations of the leader/return stroke mode of charge transfer to ground, rather than the M-component mode. According to *Rakov and Uman* [2003, chap. 6] and *Miki et al.* [2005], this is possible when a downward leader/return stroke sequence occurs in one branch, while another branch is carrying a steady current, the two branches originating from a common channel section attached to the strike object. Such a scenario (reported from other experiments, for example, by *Berger* [1967] and *Gorin et al.* [1975]) implies that the branch carrying the leader/return stroke sequence decayed to such a point that the M-component mode of charge transfer was not possible, and the leader process was required to transport charge along this essentially non-conducting path.

[5] *Miki et al.* [2006], who used high-speed video images of lightning initiated from the Fukui chimney and corresponding current records, reported some evidence that IS pulses with risetimes less than 2 μs indeed developed in branches that were not luminous (that is, did not carry an appreciable current) immediately prior to the IS pulse occurrence.

[6] In this paper, we use high-speed video images and corresponding current records of eight upward flashes, which were initiated by the 160-m high Peissenberg tower in Germany, to examine the relation between the 10-to-90% risetime of IS pulses and conditions along their corresponding channels (presence or absence of channel luminosity immediately prior to pulse occurrence in that channel). We assume that the absence of background luminosity (current) is indicative of the leader/return stroke mode of charge transfer to ground and its presence is indicative of the M-component mode [*Rakov et al.*, 2001]. Additionally, we performed a similar analysis for M-component current pulses.

2. Experiment and Data Overview

[7] The Peissenberg tower near Munich, Germany, is located at the top of a mountain (about 900 m above mean

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Table 1. Summary of Eight Flashes Analyzed in This Study

Flash ID	Date	Polarity	IS Pulses	Return Stroke Pulses	M-Component Pulses	Total Pulses
1	28 March 1997	+	3	none	none	3
2	28 March 1997	–	5	none	none	5
3	29 March 1997	–	5	none	none	5
4	06 January 1998	–	14	4	5	23
5	05 March 1998	–	3	none	none	3
6	08 March 1998	–	1	none	none	1
7	29 April 1998	+	none	1	4	5
8	17 February 1999	–	2	none	none	2
Total			33	5	9	47

sea level) called "Hoher Peissenberg". The height of the tower is about 160 m. The lightning currents were measured with a current transformer (Pearson CT: 0.15 Hz to 200 kHz) [*Fuchs et al.*, 1998] installed at the top of the tower. Current waveforms were recorded by a digitizing oscilloscope with a storage capacity of 1 million points. Sampling interval was 1 μs. Two current measuring channels with different sensitivities were used, (1) ±2 kA for measuring smaller current components and (2) ±20 kA to measure larger current components. The lower current measurement limit for (1) was 15.6 A and for (2) it was 156 A. The record length was 1 s for both (1) and (2), with a pretrigger time of 100 ms.

[8] A second digitizing oscilloscope was used to measure current waveforms in more detail. The storage capacity was 5000 points, and the sampling interval was 10 ns (sampling rate of 100 MHz). Currents were measured in the range from of −90 kA to +150 kA. The lower current measurement limit was 235 A, and the record length was 50 μs. It was possible to record up to 10 pulses in one flash.

[9] Optical images of lightning were obtained using a digital video camera Kodak EktaPro 1012 with a sampling rate of 1000 frames per second and a resolution of 239 × 192 pixels. The exposure time, which is the inverse of sampling rate, was 1 ms. The camera was placed about 200 m from the tower. At this distance, the field of view included the top portion of the tower and approximately 350 m above it. The current recording digitizers and the video system were triggered simultaneously. A GPS-clock was used to ensure time matching of video and current records.

[10] The eight flashes, which were used for this study, occurred in the months of January to April from 1997 to 1999. Table 1 gives a summary of these flashes. The flashes are numbered from 1 to 8. Six of eight flashes were negative (transported negative charge to ground), and two flashes were positive.

[11] We refer to a current pulse as an IS pulse when the pulse is superimposed on a slowly-varying initial-stage current of upward lightning. There is essentially no steady current to ground immediately prior to return-stroke pulses [e.g., *Fisher et al.*, 1993]. M-component current pulses are superimposed on a continuing current following a return-stroke pulse. The current pulse risetime here is the time interval between the 10% and 90% of pulse peak values at the wavefront of the pulse. The pulse peak is measured with respect to the preceding background current level, if any. A current pulse was included in this analysis if the pulse peak was at least twice the background noise, and the duration was at least 2 μs.

[12] The eight flashes contained a total of 33 IS pulses, 5 return-stroke pulses, and 9 M-component pulses. For all eight flashes, current records are indicative of upward (tower-initiated) lightning, with four flashes showing upward branching and the other four flashes showing no branching in video records.

[13] In eight flashes (flashes 1, 2, 5, 6 and 7 in Table 1 and three more flashes not considered here), upward stepped leaders produced pronounced current pulses in the first 25 ms of the flash. These pulses, having durations ranging from 1 to 5 μs and the interpulse time intervals ranging from 5 to 37 μs, are outside the scope of this study.

[14] Figure 1a shows, as an example, a low-current record of flash 4. The corresponding cumulative video image of this flash is shown in Figure 1b, where the four detectable branches are labeled A, B, C, and D. Flash 4 contained a total of 14 IS pulses, seven of which were saturated in the low-current record, and four return stroke pulses, which were all saturated in the low-current record. It also contained five M-component pulses superimposed on the continuing current following the fourth return stroke, three of which were saturated. The corresponding unsaturated pulse waveforms (not shown in this paper) were available from the high-current records.

[15] The four upward branches, labeled A, B, C, and D, appear to originate from a common section of the channel attached to the tower. Note that branches A and B have a common channel section, as apparently do branches C and D. Branch C is associated with the first 100 ms of the IS; no pulses developed in this branch. The first 3 of 14 IS pulses

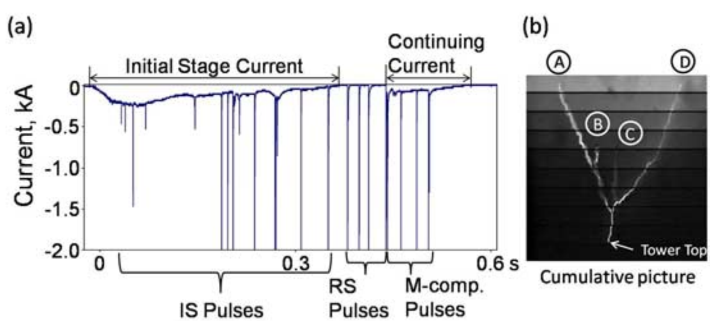

Figure 1. (a) Low-current record as a function of time of flash 4 showing initial-stage (IS) current with superimposed IS pulses and four return-stroke (RS) pulses. The fourth return-stroke pulse is followed by continuing current with five superimposed M-component pulses. (b) Cumulative video image of the same flash.

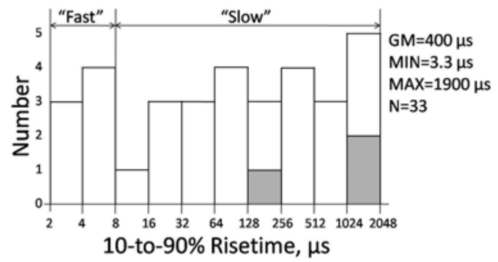

Figure 2. The 10-to-90% risetimes for IS current pulses. Data for positive lightning are shaded.

developed in branch A. The next ten IS pulses used branch B. The last IS pulse, the first three return-stroke pulses, and the first M-component pulse developed in branch D. The fourth return-stroke pulse, and all M-component pulses, except for the first one, occurred in branch A. The occurrence of different types of pulses in the four branches in tabular form and selected video frames are found in the auxiliary material for this paper.[1]

3. Analysis and Results

3.1. Current Analysis

[16] Analyzed here are a total of 33 IS pulses with peaks equal to or greater than 156 A, for which we could measure 10-to-90% risetimes in the eight upward flashes. 30 IS pulses occurred in six negative flashes and three IS pulses occurred in two positive flashes. Figure 2 shows a histogram of 10-to-90% risetimes for these pulses. The range of variation of risetimes was from 3.3 μs to 1900 μs, with the geometric mean (GM) being 400 μs. A similar distribution of risetimes for IS pulses for the Peissenberg tower flashes was reported by *Miki et al.* [2005]. The overall distribution in Figure 2 appears to be a superposition of two distributions with the ‘‘borderline’’ somewhere between 8 and 16 μs. We will refer to pulses with risetimes shorter than 8 μs as ‘‘fast’’ pulses and pulses with longer risetimes as ‘‘slow’’ pulses. Seven IS pulses belonged to the ‘‘fast’’ category and 26 to the ‘‘slow’’ category. All three IS pulses observed in positive flash 1 belonged to the ‘‘slow’’ category. The range of variation of peak current for ‘‘fast’’ pulses was from 3.6 kA to 13 kA with a GM of 6.5 kA. For pulses belonging to the ‘‘slow’’ category the peak current ranged from 156 A to 6.2 kA, with the GM being 1 kA. Thus, ‘‘fast’’ pulses are on average considerably larger than ‘‘slow’’ ones. We found a moderate correlation between the logarithms of IS pulse peak and 10-to-90% risetime (the shorter the risetime the larger the peak) with a determination coefficient (the square of correlation coefficient) of 0.6. There was a weak trend for the 10-to-90% risetime of IS pulses to increase with increasing background IS current.

[17] For nine M-component pulses (five from negative flash 4 and four from positive flash 7), 10-to-90% risetimes varied from 3 to 1775 μs, with the GM being 277 μs. Four M-component pulses (all from negative flash 4) belonged to the ‘‘fast’’ category (10-to-90% risetimes shorter than 8 μs) and five (one from negative flash 4 and four from positive flash 7) to the ‘‘slow’’ category (risetimes longer than 8 μs). Note that there were no M-component pulses with risetimes between 8 and 32 μs, and that all 4 risetimes longer than 64 μs were observed in positive flash 7. The peak current for the four M-component pulses belonging to the ‘‘fast’’ category ranged from 3 to 11 kA with a GM of 6.6 kA, while for ‘‘slow’’ M-component pulses the peak current ranged from 156 A to 1.2 kA with a GM of 480 A. This result is similar to the trend observed for IS pulses (see above).

3.2. Video Analysis

[18] We examined video records frame-by-frame to identify luminous channels before, during, and after the occurrence of each pulse. Whether the channel or branch illuminated by the pulse was luminous immediately prior to pulse occurrence was of particular interest. If there were multiple current pulses within a 1-ms interval, we assumed that the largest one was associated with luminosity enhancement in video record.

[19] *Diendorfer et al.* [2003] found a reasonably good correlation between the brightness of lightning channel and its corresponding IS current for most of their data. The determination coefficient for nine flashes ranged from 0.25 to 0.98 with a geometric mean of 0.66. For one of their flashes, the range of variation of IS current on the scatter plot was from about 15 to 240 A, which implies that the lowest optically detectable current was 15 A. In our data, for flashes 1 and 7 (both positive) and flash 5 (negative) the channel was discernible (after brightness inversion) in video record until the current fell below its lower measurement limit of 15.6 A. For flashes 3 and 4 the minimum optically detectable current was approximately 40 A, while for flashes 2, 6, and 8 it was about 100 to 200 A. The majority of IS pulses (25 of 33) and all M-component pulses analyzed here occurred in flashes for which the minimum optically detectable current was relatively low, 40 A or less. Based on the above observations, we used channel luminosity as a proxy for current in determining which channel or branch carried the current at a certain time. We had to invert brightness levels for some video frames in order to make luminous channels or branches black and easier detectable on the white background. If a channel or branch was not detectable in video records (even after brightness inversion) at a certain time, we assumed that it carried an insignificant current, if at all, at that time.

[20] We found from the video analysis that 7 (all of them from negative flashes 4 and 5) of the 33 IS pulses developed in branches that did not carry a steady current (as detected by its luminosity) immediately prior to the pulse occurrence. In all seven cases, the newly-illuminated branch was actually seen earlier in the flash, but decayed so that it could not be seen in at least five video frames (5 ms) immediately prior to the pulse, even with brightness inversion. For a given branch, the largest ‘‘no-current interval’’ prior to IS pulse occurrence was 30 frames (30 ms). There appears to be no correlation between the risetime and the ‘‘no-current interval,’’ although the sample size is rather small. In the other 26 cases (3 of them from positive flashes and 23 from negative flashes), the channel or branch, in which the pulse

[1]Auxiliary materials are available in the HTML. doi:10.1029/2008GL034148.

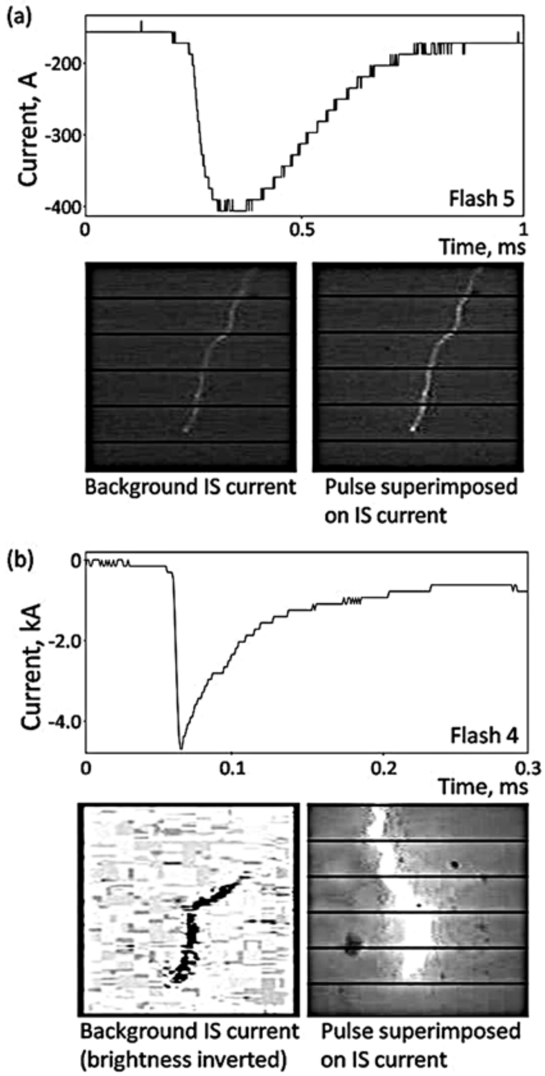

Figure 3. Example of "slow" and "fast" IS pulses. (a) Slow pulse: low-current record (lower current measurement limit 15.6 A), and corresponding consecutive video frames. The magnitude of background IS current is 156 A. (b) Fast pulse: high-current record (lower current measurement limit 156 A), and corresponding consecutive video frames. The magnitude of background IS current is 94 A, as estimated from the corresponding low-current record.

occurred, carried appreciable current immediately prior to the pulse.

[21] We also found that four out of nine M-component pulses occurred in newly-illuminated branches, as opposed to occurring in the branches carrying steady current immediately prior to pulse occurrence, and five M-component pulses enhanced the brightness of already luminous channels.

4. Discussion

[22] As noted in the Introduction, sharper IS pulses are expected to be produced by leader/return stroke sequences in one branch, while the steady IS current is carried by a different branch, both branches originating near the tower top. In this view, pulses with shorter risetimes ("fast" pulses) should occur in newly-illuminated branches and pulses with longer risetimes ("slow" pulses) in branches carrying appreciable steady currents.

[23] Six (86%) of the seven IS pulses that occurred in newly-illuminated branches were "fast" pulses. All six occurred in flash 4, for which the minimum optically detectable current was about 40 A; they had risetimes between 3.3 and 6.3 μs and peaks between 3.6 and 13 kA (geometric mean 6 kA). The exception was a "slow" IS pulse in flash 5 with a 10-to-90% risetime of 336 μs and a peak of 156 A. The branch in which the pulse occurred was not luminous and, by inference, did not carry any appreciable current for 14 ms prior to the pulse occurrence. The channel that carried the steady IS current was not illuminated by the pulse. Thus, the pulse appeared to follow an essentially new path, while exhibiting a long risetime which is expected for pulses retracing current-carrying channels. It is important to note, however, that the visibility in this case was rather poor, so that we cannot rule out that the branch did carry a current below 15.6 A, the minimum optically detectable current in flash 5, immediately prior to the pulse occurrence.

[24] The overwhelming majority (25 or 96% of 26) of IS pulses that occurred in luminous channels were "slow"; that is, they had 10-to-90% risetimes ranging from 9 μs to 1900 μs (peak currents varied from 156 A to 5.8 kA). The exception was an IS pulse in flash 8 with a risetime of 4.9 μs and a peak of 3.9 kA. Contrary to expectation, this pulse occurred in the channel that was carrying a steady IS current above 115 A, the minimum optically detectable current for flash 8. The exception could be caused by a newly-illuminated branch outside the field of view of the camera (more than 350 m above the tower top).

[25] Examples of "slow" and "fast" IS pulses are shown in Figure 3. Figure 3a shows a 1-ms current record of typical "slow" IS pulse and corresponding video frames. The 10-to-90% risetime of this IS pulse is 56 μs. The left video frame shows the channel carrying steady IS current immediately prior to pulse occurrence. No branches can be seen. The right frame shows the same channel at the time when the pulse took place. The luminosity of the channel has increased. In our interpretation, the event shown in Figure 3a represents the M-component mode of charge transfer to ground [*Rakov et al.*, 2001].

[26] Figure 3b shows a 0.3-ms current record of typical "fast" IS pulse and corresponding video frames. The 10-to-90% risetime for this pulse is 3.5 μs and pulse peak is 4.5 kA, as measured in the high-current record. The magnitude of background steady current is 94 A, as measured in the corresponding low-current record (lower current measurement limit 15.6 A). The shape of the lightning channel that carried the IS current immediately prior to the pulse occurrence is shown in the left frame. In the original video frame, the channel was very faint, therefore the brightness inversion was used to improve its detectability. In the right frame, a very bright branch, illuminated by the IS pulse, is seen. In our interpretation, the example shown in Figure 3b represents the leader/return stroke mode of charge transfer to ground [*Rakov et al.*, 2001].

[27] In addition to IS pulses, we analyzed nine M-component pulses (five from negative flash 4 and four from positive flash 7). Four M-components with short-

est 10-to-90% pulse risetimes in the range from 3 to 6 μs developed in branches that were not luminous immediately prior to pulse occurrence. In each case, the newly-illuminated branch joined the lower part of the previously luminous channel that was carrying continuing current. The other five M-components, with longer 10-to-90% pulse risetimes ranging from 49 to 1775 μs, developed in the channels which carried appreciable continuing current. Thus, the trend for M-components is similar to that for IS pulses.

5. Summary

[28] Pulses superimposed on steady initial-stage (IS) current of upward flashes initiated by tall grounded objects are thought to be manifestations of the M-component mode of charge transfer to ground, which requires the presence of a grounded, current-carrying channel. In this view IS pulses are expected to have relatively long risetimes. However, some IS current pulses were found to have shorter risetimes which are comparable to those of return-stroke pulses, so that some of the IS pulses could be actually associated with the leader/return stroke mode of charge transfer to ground.

[29] From our analysis of 33 IS current pulses and their correlated video images, we found that seven IS pulses had shorter (<8 μs) 10-to-90% risetimes, six (86%) of which developed in a branch, which carried an insignificant, if at all, current (as detected by its luminosity) immediately prior to the pulse occurrence. A similar trend was found for nine M-component pulses. Four M-component pulses with 10-to-90% risetimes in the range of 3 to 6 μs each developed in a newly-illuminated branch. Thus, both IS and M-component pulses with shorter (<8 μs) risetimes tended to use branches that did not carry appreciable current immediately prior to the pulse occurrence. In our interpretation, these events represent the leader/return stroke mode of charge transfer to ground.

[30] On the other hand, 25 (96%) of 26 IS and all five M-component pulses with longer (>8 μs) risetimes occurred in already luminous channels. These, in our interpretation, are manifestations of the M-component mode of charge transfer to ground.

[31] Although, there was one exception in each category, overall results do support the hypothesis that longer risetimes are indicative of the M-component mode of charge transfer to ground, while shorter risetimes are associated with the leader/return stroke mode.

[32] **Acknowledgments.** This work was supported in part by NSF grant ATM-0346164.

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