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Characterization of the initial stage in upward lightning at the Gaisberg Tower: 1. Current pulses

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ARTICLE INFO

Keywords: Lightning Upward lightning Initial stage Current measurements Current pulses Gaisberg Tower

ABSTRACT

We examined current waveforms for 58 upward flashes occurring in 2006–2014 initiated from the Gaisberg Tower located near Salzburg, Austria. The initial stage (IS) of these flashes comprised of relatively slowly varying "background" current, with faster, more impulsive current variations overlaid on this background current. In 46 of the 58 flashes (79%) the background continuing current was negative, and in the other 12 flashes (21%) it was bipolar. 1180 current pulses occurred during the IS of these 58 flashes, of which 708 (60%) were positive bipolar (positive initial polarity with a negative opposite polarity overshoot), 28 (2.4%) were positive unipolar (positive initial polarity with no opposite polarity overshoot), 440 (37%) were negative unipolar, and four (0.3%) were negative bipolar pulses. We found that bipolar current pulses only occurred in the IS at early times. We divided the IS current into two phases: (1) upward leader initiation and propagation phase (IPP) and (2) upward leader mature phase (MP). 901 or 76% (712 bipolar and 189 unipolar) pulses occurred during the IPP, and 279 or 21% (unipolar) pulses occurred during the MP. The median background-to-peak current was 134 A for IPP pulses and 687 A for MP pulses.

1. Introduction

Upward lightning from tall objects on ground involves an upward leader initiated from the top of a tall structure which bridges the gap between the tower-top and an overhead cloud charge region. An initial continuous current (ICC) flows along this channel, typically for many tens to several hundred milliseconds. There often exist current pulses, referred to as ICC pulses, superimposed on the slowly-varying ICC. The upward leader and the ICC compose the initial stage (IS) of upward lightning. In roughly 30% of flashes (e.g., [12]) the IS is followed by one or more downward-leader/return-stroke sequences, the return strokes being similar to subsequent strokes in downward lightning. The IS in upward lightning from tall, grounded objects is similar to the initial stage of rocket-triggered lightning (e.g., [8], Ch. 7). The IS pulses (which includes ICC pulses) in upward and rocket-triggered lightning have been examined in various studies (e.g., [2,3,6,11,15]). IS current pulses in upward lightning have been associated with a leader/return-stroke mode and an M-component mode of charge transfer to ground. The leader/return-stroke mode of charge transfer can occur when a downward leader/return-stroke sequence occurs in one (previously decayed or new) branch, while another branch is carrying a steady current, the two branches originating from a common channel section attached to the strike object (e.g., [6,15]). The junction point of the two branches is expected to be relatively close to the tower top. This mode of charge transfer has also been referred to as a "mixed mode of charge transfer to ground" (e.g., [16]). The M-component mode of charge transfer is expected to typically occur along a single channel below the cloud base, which carries both a steady current as well as an impulsive component, the latter being likely injected via an in-cloud branch attaching to the main channel high above the tower top. Generally, longer current risetimes in IS pulses are indicative of the M-component mode of charge transfer to ground, while shorter risetimes are associated with the leader/return-stroke mode [2,3].

In this study, we characterize in detail 1180 IS current pulses occurring during the IS of 58 upward flashes initiated from the Gaisberg Tower in 2006–2014. We categorize pulses based upon their initial

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polarity, waveshape, and their occurrence context in the IS. We also examine the current waveform parameters of the IS pulses. The electric field pulses that occurred during the IS in these flashes are analyzed in part 2 of this study ([13], this issue).

2. Instrumentation and data

A current measuring shunt was located at the base of a 1.5 m high air terminal on top of the 100 m tall Gaisberg Tower. The shunt had an impedance of 0.25 m Ω and a bandwidth from DC to 3.2 MHz. Two separate fiber-optic links (Nicolet ISOBE 3000, with bandwidth from DC to 15 MHz) with vertical-scale limits of ± 2 kA and ± 40 kA were used to transmit signals from the shunt to the 8-bit (12-bit after May 16, 2012) digital acquisition system located at a nearby housing facility. The current sampling rate was 20 MHz, and the total record length was 800 ms with a 15-ms pre-trigger time. The trigger threshold of the system was set at ± 200 A. Prior to analysis, the current waveforms were filtered using a second order Butterworth low pass filter with a -3 dB at 250 kHz to remove high frequency noise and resampled at 5 MHz.

In this paper, we analyzed 58 upward flashes that occurred at the Gaisberg Tower from 2006 to 2014, for which both current and electric field records were available. Note that the results of the analysis of electric field pulses occurring during the IS of these 58 flashes are shown in part 2 of this study ([13], this issue). Of these 58 flashes, 46 (79%) were negative and 12 (21%) were bipolar. The bipolar flashes can be further classified as Type 1S (single background-current polarity reversal during the IS) and Type 1M (multiple current polarity reversals during the IS), as defined by Watanabe et al. [12] who expanded the traditional classification [9,10] of bipolar flashes to include five categories. Five of the 12 bipolar flashes were of Type 1S and the other seven were of Type 1M. All Type 1M flashes had negative polarity current at the beginning of the flash. All five Type 1S flashes had positive polarity current at the beginning. Note that, in our data, the polarity of current indicates the polarity of charge transferred to ground. The percentage of bipolar flashes in this dataset is somewhat larger than that (17%) reported by Watanabe et al. [12] for 823 upward flashes at the Gaisberg Tower. This discrepancy is likely due to our selection criteria of including only those flashes from among Watanabe et al.'s 823 flashes for which both current and electric field data were available. The IS durations for these 58 flashes ranged from 74 to 691 ms.

We define an IS current "pulse" as a faster variation in current relative to the slower (typically on the order of many tens to hundreds of milliseconds) "background" continuing current. The -3 dB upper-limit of frequency-bandwidth of the current waveform measurements of 250 kHz translates to full-cycle time domain signals of 4 μs . This means that risetimes shorter than 4 \times 0.33 = 1.32 μs for current pulses in our data would be overestimates, and hence the arithmetic and geometric means as well as median values for risetimes in this study should be treated as being overestimates of the actual IS current pulse risetimes. For low-amplitude IS pulses (peak current < 2 kA), the digitizer channel with a vertical scale limit of ± 2 kA was used. Only pulses with background-to-peak current-magnitudes equal to or greater than 20 A were included, in order to account for the measurement limit of the 8-bit digitizer. For pulses with peak currents greater than 2 kA, the digitizer channel with a vertical-scale limit of ± 40 kA was used.

3. Analysis and results

3.1. Occurrence characteristics of IS current pulses

Based on the polarity of initial peak and overall waveshape, we categorized IS current pulses into the following four types: positive unipolar and bipolar, and negative unipolar and bipolar. Unipolar pulses are defined as those having no measurable opposite "polarity" overshoot with respect to the IS background current while bipolar pulses are ones that have an initial peak as well as an opposite "polarity" overshoot with

respect to the background current. Note that, for the purpose of defining pulse-polarity we used the local background current-level as the reference rather than the zero current-level. This is different than our definition of the overall current-polarity which is with respect to the zero current-level and is used to determine flash polarity (that is indicative of the polarity of charge effectively transferred to ground). Fig. 1 shows examples of each pulse type. We examined 1180 pulses that occurred during the IS of 58 flashes; 28 (2.4%) were positive unipolar occurring in 8 negative and 15 bipolar flashes, 708 (60%) were positive bipolar occurring in 29 negative and 13 bipolar flashes, 440 (37.3%) were negative unipolar occurring in 41 negative and 11 bipolar flashes, and 4 (0.3%) were negative bipolar occurring in 2 negative flashes.

We examined the occurrence context of unipolar and bipolar current pulses in the IS of each flash. In order to do so, we normalized the starttime of each pulse with respect to the IS current duration by finding the ratio of the pulse-start-time (measured from the start of the IS) and the IS current duration. Fig. 2 shows the histograms of normalized pulse-starttime for the 58 flashes in our dataset. We found that bipolar current pulses only occurred in the IS at early times. In fact, all bipolar pulses occurred within the first 15% of the IS duration in all flashes, and all bipolar pulses except one pulse occurred within the first 10% of the IS duration. The first 15% of IS duration in our 58 flashes corresponded to time-intervals of 11 - 104 ms from the start of IS current, with the median being 43 ms. For upward flashes, this early part of the IS current is expected to be associated with the inception of corona streamers from the tower-top and formation of one or more upward leaders, followed by the propagation of these upward leaders toward the cloud charge region. The later part of the IS current is expected to be associated with transfer of charge to ground from cloud charge regions (which could be various pockets of charge in different parts of the thundercloud) via the channel established by the upward leader and various in-cloud channels and branches. With the above considerations in mind, we divided the IS current into two phases: (1) upward leader initiation and propagation phase (IPP) and (2) upward leader mature phase (MP). As shown in Fig. 3a, we defined the first phase as the time-interval between the IS start-time and 15% of its total duration; the second phase lasts from this 15%-time to the IS current end-time. In the 58 flashes in our dataset, the MP-durations ranged from 63 to 587 ms, with the median being 241 ms. (The IPP-durations were already noted above). Fig. 2a and b show the histograms of the normalized pulse start-time for the IPP and MP, respectively, in the 58 flashes in our dataset. 901 (712 bipolar and 189 unipolar) of 1180 (i.e., 76%) pulses occurred during the IPP and 279 (all unipolar) of 1180 (i.e., 24%) pulses occurred during the MP. Fig. 3b and c show, respectively, example of a bipolar pulse occurring during the IPP and a unipolar pulse occurring during the MP. Additionally, during the IPP, a large majority of pulses (829 of 901 or 92%) occurred within the first 5% of the IS duration. On the other hand, pulse-counts were moreor-less evenly distributed during the MP with them diminishing in the last 5% of the IS duration (see Fig. 2b).

3.2. Characterization of IPP pulses

For the 1180 current pulses in our dataset, we examined the background-to-peak and 10–90% risetimes, total duration, full-width at half-maximum (FWHM), background-to-peak current, and maximum pulse-current. These parameters are defined in Fig. 3b and c. We defined the total duration of a unipolar IS pulse as the time-interval between the initial deflection from the background current-level to the point where the falling edge of the pulse reaches 10% of its peak current. For a bipolar pulse, it was defined as the time interval between the initial deflection from the background current-level to the point where the opposite polarity overshoot returned to the background current-level. The FWHM is the width of the current pulse (or the first part of the pulse with the initial peak for bipolar pulses, prior to the opposite "polarity" overshoot with respect to the background current, see Fig. 3b) at 50% of its background-to-peak current value. The maximum pulse-

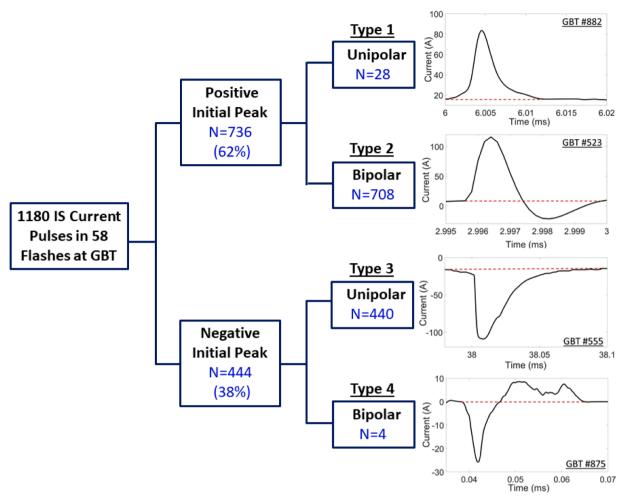


Fig. 1. Categorization of IS current pulses based on the polarity of their initial peak and overall waveshape with respect to the local background current-level. We analyzed 1180 current pulses that occurred during the IS of 58 flashes recorded at the GBT in 2006–2014. Typical current waveforms of each pulse-type are shown in the rightmost panel. The red dashed line indicates the background IS current-level at the start of each pulse.

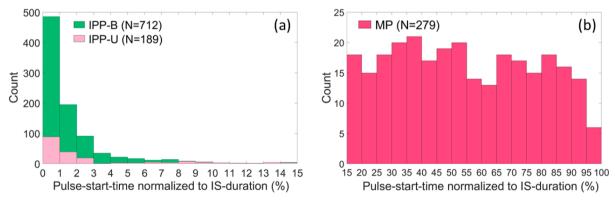


Fig. 2. Histogram of pulse-start-time normalized with respect to IS-duration for pulses occurring during (a) the IPP, color-coded in green and pink for bipolar (IPP-B) and unipolar (IPP-U) pulses, respectively, and (b) the MP of the IS in the 58 upward flashes in our dataset. Only unipolar pulses occurred during the MP.

current is the maximum magnitude of current that occurs during a pulse with respect to the zero-current level. Note that, depending upon the IS background current-level and pulse-type, this maximum current magnitude can occur at the start, initial peak, or (in the case of bipolar pulses) the opposite "polarity" peak of a pulse. We discuss these characteristics for pulses occurring during the IPP below in this section and during the MP in Section 3.3. In the following text as well as in part 2 of this study ([13], this issue), we refer to bipolar and unipolar pulses

occurring during the IPP as IPP-B and IPP-U pulses, respectively.

Fig. 4a–f shows histograms of background-to-peak risetime, 10–90% risetime, total duration, FWHM, background-to-peak current, and maximum pulse-current for 901 (712 IPP-B, shown in green, and 189 IPP-U, shown in pink) pulses that occurred during the IPP of 56 flashes in our dataset (there were no IPP pulses in 2 of our 58 flashes). Also shown are the statistics associated with each histogram. The background-to-peak risetimes (Fig. 4a) ranged from 0.41 to 513 μ s, with

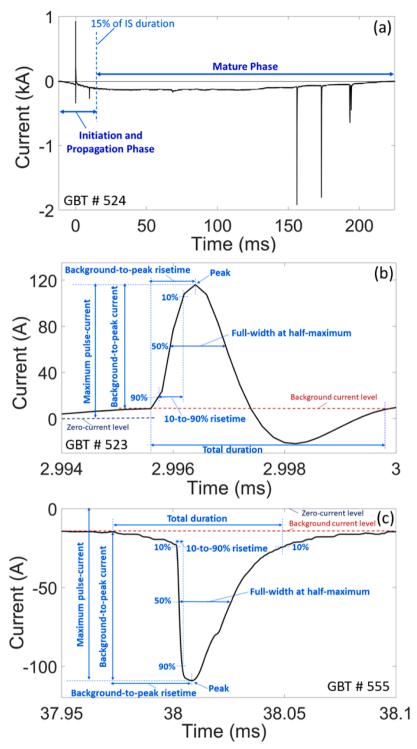


Fig. 3. (a) Current waveform of the IS in upward flash GBT #524 showing the upward-leader initiation and propagation phase (IPP) and mature phase (MP). We defined the former as the time-interval between the IS start-time and 15% of its duration and the latter as that between this 15%-time and the IS current end-time. See text for further details. Polarity of current (positive or negative with respect to the zero-level) indicates the polarity of charge transferred to ground. Current waveforms of (b) a bipolar and (c) a unipolar pulse showing the various parameters examined in this study. Bipolar pulses occurred during the IPP only and we refer to them as IPP-B pulses. Unipolar pulses occurred during both the IPP and MP; we refer to them as IPP-U and MP pulses, respectively.

median being 1.1 μs . For IPP-B and IPP-U pulses, the median risetimes were 1 and 5.6 μs , respectively. The 10–90% risetimes (Fig. 4b) for all IPP pulses ranged from 0.16 to 122 μs , with median being 0.58 μs . The median for IPP-B and IPP-U pulses were 0.55 and 3.0 μs , respectively. The median background-to-peak and 10–90% risetimes were, respectively, 5.6 and 5.5 times longer for IPP-U than IPP-B pulses. The total durations (Fig. 4c) and FWHM (Fig. 4d) for all IPP pulses ranged from 2.2 μs to 1.4 ms and 0.39 to 489 μs , respectively, with the medians being 6.3 and 1.5 μs , respectively. The median duration and FWHM were, respectively, 2.6 and 4.4 times longer for IPP-U than IPP-B pulses. The magnitudes of the background-to-peak currents (Fig. 4e) and maximum

pulse-currents (Fig. 4f) for all IPP pulses ranged from 21 A to 20 kA and 16 A to 21 kA, respectively, with the medians being 134 and 172 A, respectively. The median currents were, respectively, 2.1 and 2.2 times larger for IPP-B than IPP-U pulses. Note that the 16-A minimum value of the maximum pulse-current is less than the 20-A background-to-peak current-magnitude lower-limit in Section 2. This is because, as stated earlier, depending upon the background current-level at the start-time of a pulse, the magnitude of the maximum pulse-current may not necessarily occur at the peak of the pulse.

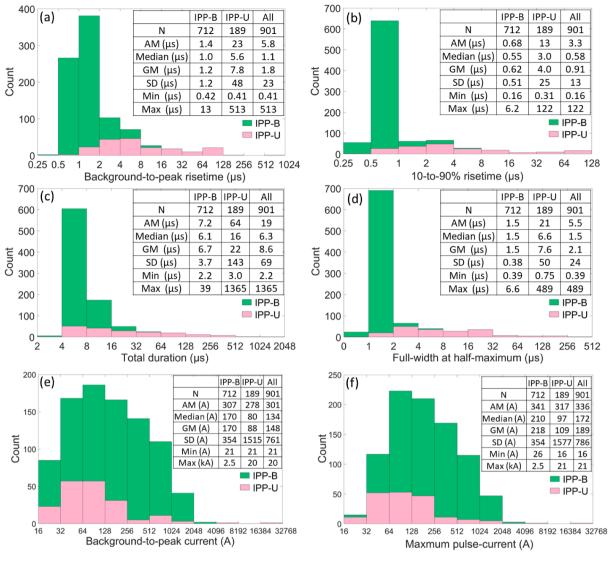


Fig. 4. Histogram of (a) background-to-peak risetime, (b) 10–90% risetime, (c) total duration, (d) FWHM, (e) background-to-peak current, and (f) maximum pulse-current, color-coded in green and pink for IPP-B and IPP-U pulses, respectively, for 901 pulses occurring during the IPP of 56 flashes in our dataset. Arithmetic mean (AM), median, geometric mean (GM), standard deviation (SD), minimum (Min), and maximum (Max) values for bipolar, unipolar, and all pulses are shown in each histogram.

3.3. Characterization of MP pulses

Fig. 5a-f shows histograms of background-to-peak risetime, 10–90% risetime, total duration, FWHM, background-to-peak current, and maximum pulse-current for 279 unipolar pulses that occurred during the MP of 41 flashes in our dataset (there were no MP pulses in 17 of our 58 flashes). The background-to-peak risetimes (Fig. 5a) ranged from 2.0 μ s to 19 ms, with the median being 107 μ s. The 10–90% risetimes (Fig. 5b) ranged from 0.57 μ s to 6.6 ms, with a median of 43 μ s. The total durations (Fig. 5c) and FWHM (Fig. 5d) ranged from 20 μ s to 29 ms and 8.9 μ s to 8.9 ms, respectively, with the medians being 441 μ s and 134 μ s, respectively. Finally, the magnitudes of the background-to-peak currents (Fig. 5e) and maximum pulse-currents (Fig. 5f) ranged from 21 A to 10 kA and 33 A to 10 kA, respectively, with the medians being 687 and 893 A, respectively.

4. Discussion

As discussed in Section 3.1, we defined the IPP as the first 15% of the IS duration which corresponded to a median time-interval of 43 ms in our dataset. Assuming that an upward leader propagates with an

average speed of 10^5 m/s, the upward-leader channel length in this timeinterval would be 4.3 km. Of course, in object-initiated lightning, relatively-low-altitude upward branching is common, so the leaderchannels that developed during the IPP would include both vertical and quasi-horizontal sections. Interestingly, in the current waveforms of most (60%) of the flashes in our dataset, we noted that the IS background current generally increased during the IPP and reached a peak by the end of this phase or soon after (during the MP, within 10 ms of the IPP end-time as seen in Fig. 3a). For the other 40% of flashes, the ISbackground current reached a maximum value during the MP, more than 10 ms after the end of the IPP. Observations of upward lightning using current measurements, high-speed video cameras, and VHF mapping systems are needed in order to determine the duration of the IPP on a flash-by-flash basis, rather than the 15%-IS-duration approach adopted in this study. These observations would allow the identification of the point in time in an upward flash by which the initial extension of the upward leader toward the cloud charge region has occurred, which would mark the end of the IPP.

The bipolar (IPP-B) current pulses that occurred at early times during the IPP, especially those occurring within the first several milliseconds of flash (or IS) start, (see Figs. 3b and 6) can be compared to precursor

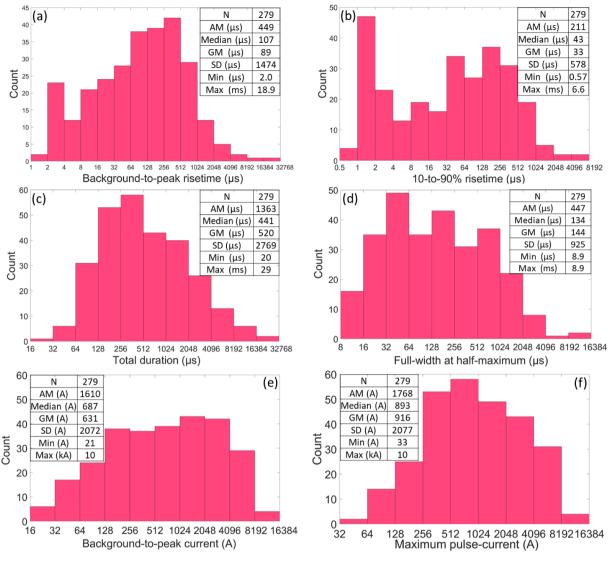


Fig. 5. Histogram of (a) background-to-peak risetime, (b) 10–90% risetime, (c) total duration, (d) FWHM, (e) background-to-peak current, and (f) maximum pulse-current, for 279 unipolar pulses occurring during the MP of 41 flashes in our dataset. Statistics are shown in each histogram.

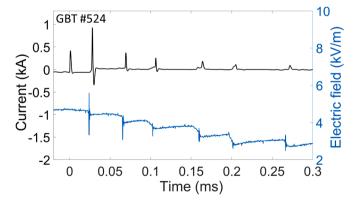


Fig. 6. Upper (in black) and lower (in blue) waveforms show, respectively, the bipolar current pulses (scale shown on the left vertical axis) that occurred at early times during the IPP and the associated electric field changes (scale shown on the right vertical axis) measured at 170 m from the GBT in flash GBT #524. See also Fig. 2a in part 2 of this study ([13], this issue).

pulses in rocket-triggered lightning (e.g., [1,5,14]), which are brief current pulses from the tip of the wire that do not initiate stable leader propagation. As seen in Fig. 4, our IPP-B pulses had median background-to-peak risetime and total duration of 1 and 6.1 µs, respectively, and median background-to-peak current of 170 A. Willett et al. [14] examined precursor pulses (see for example their Figure 9 [14] which can be compared to Fig. 6 in this study) in positive leaders initiating rocket-triggered lightning in Florida. Their pulse risetimes and durations (ignoring the oscillations at the end of each pulse) appear to be similar to those for our IPP-B pulses and their peak amplitudes of 10-20 A are roughly an order of magnitude smaller than our median amplitude of 170 A. Willett et al. assumed that such precursor impulses were caused by the sudden development of an extensive corona "fan" of positive streamers preceding the development of short leader segments at the time of positive leader inception. Their pulses had the same initial polarity as that of the background current, both indicating negative charge transfer to ground, consistent with an upward positive leader. Our IPP-B pulses occurred in 32 negative and 12 bipolar flashes of the 58 flashes we examined. Seven and five bipolar flashes had negative and positive polarity background current, respectively, at the beginning of the IS. As noted earlier, in our data the polarity of current indicates the polarity of charge transferred to ground. Also, almost all (708 of 712 or

99%) of our IPP-B pulses had positive initial polarity; in negative flashes these pulses were overlaid on negative IS background current, and in bipolar flashes they were overlaid on either negative or positive background current. The four negative initial-polarity pulses were overlaid on negative background current. For 95% (671 of 708) of the positive initial-polarity IPP-B pulses, their initial polarity was opposite to the polarity (negative) of the background current, which is different than the observations of Willett et al. [14], as discussed above. The exact reason for this discrepancy is currently unknown. One possible reason could be that the top of the GBT is usually engulfed by cloud at the time of upward leader initiation and therefore in a vastly different space-charge environment than that at the tip of rockets at about 400 m above ground for rocket-triggered lightning in Florida. Also, the waveshapes of our IPP-B pulses do not display the somewhat pronounced oscillatory behavior after the initial bipolar pulse that was observed by Willett et al. [14]. This oscillatory waveshape is consistent with those of precursor pulses reported in other rocket-triggered lightning studies, e. g., Lalande et al. [4] at Camp Blanding, Florida. This could suggest that the IPP-B pulses occurring at the beginning of the IS in upward flashes involve a different mechanism than the precursor pulses observed in rocket-triggered lightning. Another difference between rocket-triggered lightning and the GBT current measurements is the location of the current measuring shunt; for triggered lightning the shunt is located few hundred meters below the rocket-and-wire from the tip of which the upward leader emerges, while at the GBT the shunt is located at the tower-top, just a few meters below the Franklin rod from which the upward leader is initiated. More detailed measurements of these early bipolar pulses in upward lightning are needed to determine the mechanism of their occurrence.

Paul and Heidler [7] reported 12 bipolar current pulses during the IS of negative upward flashes initiated from the Peissenberg Tower; all of them had negative initial polarity. The exact occurrence context of these pulses during the IS is unclear. The geometric mean (GM) 10–90% risetime, FWHM, and peak current for their bipolar pulses were 6.6 μ s, 34.2 μ s, and 1.2 kA, respectively. In our study, for the 712 IS bipolar pulses the GM 10–90% risetime, FWHM, and peak current were 0.62 μ s, 1.5 μ s, and 170 A, respectively, which are all significantly smaller than those reported by Paul and Heidler [7].

The GM values of various waveform parameters for "classical" IS pulses reported by Miki et al. [6] for upward lightning from tall objects (Gaisberg and Peissenberg Towers, and Fukui Chimney) as well as rocket-triggered lightning are shown in Table 1. Also shown are the GM values from this study for the IPP, MP, and the entire IS. The GM

background-to-peak current, total duration, 10-90% risetime, and FWHM in previous studies ranged from 113 - 781 A, 514 - 2590 µs, 44.2 $-464 \mu s$, and $141 - 943 \mu s$, respectively. In this study, these GM values for pulses during the IPP were 148 A, 8.6 µs, 0.91 µs, and 2.1 µs, respectively, and during the MP were 631 A, 520 µs, 33 µs, and 144 µs, respectively. Clearly, the pulses during the MP had characteristics similar to those of the "classical" IS pulses reported in previous studies. The IPP pulses had GM background-to-peak current within the range of those reported in previous studies but had significantly shorter GM total duration, risetime, and FWHM. This is likely because the pulses during the IPP are associated with impulses in relatively short channel-sections and branches as the upward leader initiates and progresses toward the cloud charge region from the tower. On the other hand, during the MP the impulses occur in the relatively long upward leader channel and associated branches that bridge the gap between the tower top and cloud charge sources.

Flache et al. [2] analyzed high-speed video images and corresponding current records for 33 IS current pulses in eight upward lightning flashes initiated from the Peissenberg Tower in Germany. They found that six (86%) of seven IS current pulses with shorter (<8 µs) 10–90% risetimes each developed in a newly illuminated branch, and 25 (96%) of 26 IS pulses with longer (>8 µs) risetimes occurred in already luminous (current-carrying) channels. These results supported 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. He et al. [3] examined current and electric field records of 9 return-stroke pulses, 70 mixed-mode (leader/return stroke type) IS pulses, 11 classical M-component pulses, and 19 M-component-type IS pulses (a total of 109 pulses) in upward flashes initiated from the Santis Tower in Switzerland. They classified the charge-transfer mode of IS pulses as M-component and leader/return stroke types based on the (risetime versus fall-time) symmetry of their current waveforms. For 70 leader/return stroke type IS pulses the median background-to-peak current, 10-90% risetime, and FWHM were 4.0 kA, $4.4 \mu s$, and $49.2 \mu s$, respectively. They found that such IS pulses can have risetimes as long as 28 μ s. For the 19 M-component type IS pulses, the median background-to-peak current, 10-90% risetime, and FWHM were 1.5 kA, 83.1 μ s, and 109 μ s, respectively. In our dataset of 1180 IS pulses, 937 (79%) had 10-90% risetimes less than or equal to 8 μs. For these pulses, the median background-to-peak current, 10-90% risetime, and FWHM were 163 A, 0.6 µs, and 1.5 µs, respectively. For 522 of these pulses the background current at the start of each pulse was reliably measurable (equal to or greater than 20 A). The median

Table 1
IS current-pulse parameters in natural upward and rocket-triggered lightning. For this study, the IS-pulse characteristics are provided for the IPP, MP, as well as the entire IS.

Study	Object of initiation	Number and polarity of flashes	Number of IS pulses	GM background-to-peak current (minimum - maximum), A	GM total duration (minimum - maximum), μs	GM 10-to-90% risetime (minimum - maximum), μs	GM full-width at half- maximum (minimum - maximum), μs
Miki et al.	Gaisberg Tower, Austria	74 negative flashes	348 – 377	> 377 (31 – 16,904, <i>N</i> = 351)	1190 (32 – 35,180, N = 377)	< 110 (0.035 –8433, N = 344)	276 (3.55 – 13,590, <i>N</i> = 348)
[6]	Peissenberg Tower, Germany	21 negative flashes	124	512 (36 – 13,450)	833 (30 – 21,710)	60.9 (1 – 6771)	153 (6 – 6136)
	Fukui Chimney, Japan	36 negative flashes	231	781 (81 – 22,934)	514 (22 – 31,350)	44.2 (0.3 – 7756)	141 (7.9 – 13,202)
	Rocket triggered lightning, Camp Blanding, FL, USA	45 negative flashes	247 – 296	113 (18 – 2179, <i>N</i> = 296)	2590 (300 – 26,240, N = 254)	464 (52 – 8380, <i>N</i> = 267)	943 (100 – 13,554, <i>N</i> = 247)
This study	Gaisberg Tower, Austria	56 (44 negative and 12 bipolar flashes)	901 during IPP	148 (21 – 20,235)	8.6 (2.2 – 1365)	0.91 (0.16– 122)	2.1 (0.39 – 489)
		41 (31 negative and 10 bipolar flashes)	279 during MP	631 (21 – 10,034)	520 (20 – 29,030)	33 (0.57 – 6610)	144 (8.9 – 8850)
		58 (46 negative and 12 bipolar flashes	1180 during IS	208 (21 – 20,235)	23 (2.2 – 29,030)	2.1 (0.16 – 6610)	5.7 (0.39 – 8850)

background current was 47 A for these pulses. For the 243 IS pulses with risetimes greater than 8 µs, the median background-to-peak current, 10-90% risetime, and FWHM were 243 A, 79.2 µs, and 84 µs, respectively. Out of these pulses, 205 had a measurable background current at the start of each pulse; the median background current was 118 A. Therefore, the median background current at the start of IS pulses with shorter risetimes (which can be assumed to be associated with leader/return stroke mode of charge transfer) was 2.5 times smaller than that for IS pulses with longer risetimes (assumed to be associated with M-component mode of charge transfer). Additionally, using He et al. [3]'s definition of the so-called asymmetrical waveform coefficient $(AsWC = \frac{FWHM - t_{50\%-100\%}}{FWHM}$, where $t_{50\%-100\%}$ is the 50–100% risetime of a pulse), we calculated the AsWC for the 1180 IS pulses in our dataset as well as for 869 return strokes in 195 negative flashes occurring at the GBT. Note that these return strokes are not analyzed in this study except for their AsWC, which we compare against those for our IS pulses. Fig. 7a and b show the histograms of the AsWC for IS pulses and return strokes, respectively; larger values of AsWC indicate more asymmetric pulses.

For the IS pulses, the AsWC ranged from 0.3 to 0.99, with the median being 0.64. Note that all except two of our IPP-B pulses had AsWC less than 0.7. For return strokes at the GBT, the AsWC ranged from 0.49 to 0.98, with the median being 0.92 (which is significantly greater than that for IS pulses). In fact, the large majority of return strokes (656 of 869 or 75%) had AsWC greater than 0.87. For comparison, He et al. [3] reported AsWC values for nine return strokes ranging from 0.95 to 0.99 with the geometric mean being 0.98. Finally, He et al. defined IS pulses with AsWC values greater than 0.8 as being of the mixed mode (or leader/return stroke) type and those with values less than 0.8 to be of the M-component type. This definition was based, in part, on all 11 of their M-component pulses having AsWC values less than 0.8. Using this definition (and setting aside IPP-B pulses, which only occur at early times during the IS, see Fig. 2), 71% (332 of 468) of our IPP-U and MP IS pulses were of the M-component type while 29% (136 of 468) were of the mixed-mode type.

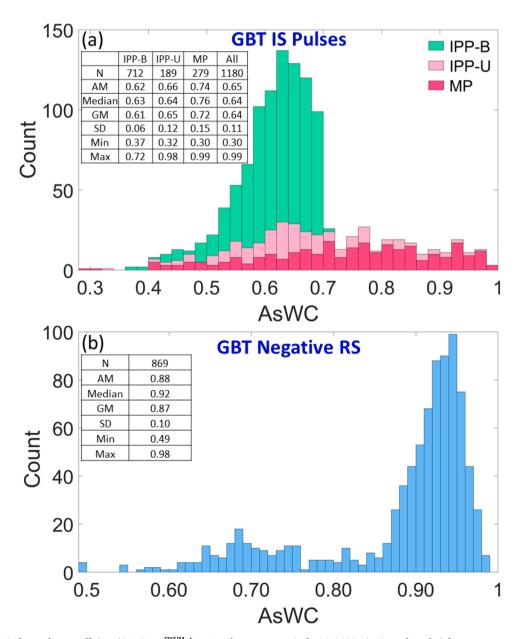


Fig. 7. The asymmetrical waveform coefficient ($AsWC = \frac{FWHM - t_{50\%-100\%}}{FWHM}$), where $t_{50\%-100\%}$ is the 50–100% risetime of a pulse) for current waveforms of (a) IS pulses and (b) return strokes measured at the GBT. Larger values of AsWC indicate more asymmetric (faster risetime, slower fall-time) pulses.

5. Summary

In this paper, we analyzed 58 upward flashes that occurred at the Gaisberg Tower from 2006 to 2014. Of these 58 flashes, 46 (79%) were negative and 12 (21%) were bipolar. Five of the 12 bipolar flashes were of Type 1S (single background current polarity reversal during the IS as defined by [12]), and the other seven were of Type 1M (multiple current polarity reversals during the IS). Based on the polarity of initial peak and overall waveshape, we categorized IS current pulses into the following four types: positive unipolar and bipolar, and negative unipolar and bipolar. We examined 1180 pulses that occurred during the IS of 58 flashes; 28 (2.4%) were positive unipolar occurring in 8 negative and 15 bipolar flashes, 708 (60%) were positive bipolar occurring in 29 negative and 13 bipolar flashes, 440 (37.3%) were negative unipolar occurring in 41 negative and 11 bipolar flashes, and 4 (0.3%) were negative bipolar occurring in 2 negative flashes.

We examined the occurrence context of unipolar and bipolar current pulses in the IS of each flash. We found that bipolar current pulses only occurred in the IS at early times; all such pulses occurred within the first 15% of the IS duration in all flashes. These bipolar current pulses (which we referred to as IPP-B pulses) can be compared to precursor pulses in rocket-triggered lightning, which are brief current pulses from the tip of the wire that do not initiate stable leader propagation. We divided the IS current into the upward leader initiation and propagation phase (or IPP) and mature phase (or MP). The first phase was defined as the timeinterval between the IS start-time and 15% of its duration and the second phase lasts from this 15%-time to the IS current end-time. In our dataset of 58 flashes, the median IPP and MP durations were 43 ms and 241 ms, respectively. Assuming that an upward leader propagates with an average speed of 10⁵ m/s, this corresponds to an upward-leader channel length of 4.3 km. Of course, in object-initiated lightning, relatively-low-altitude upward branching is common, so the leaderchannels developed during the IPP would include both vertical and quasi-horizontal sections. Observations of upward lightning using current measurements, high-speed video cameras, and VHF mapping systems are needed in order to determine the duration of the IPP on a flashby-flash basis, rather than the 15%-IS-duration approach adopted in this study. For IPP pulses, the median background-to-peak risetime, 10-90% risetime, total duration, and FWHM were 1.1, 0.58, 6.3, and 1.5 µs, respectively. The median background-to-peak current and maximum pulse-current during the IPP were 134 and 172 A, respectively. For MP pulses, the median background-to-peak risetime, 10–90% risetime, total duration, and FWHM were 107, 43, 441, and 134 us, respectively. The median background-to-peak current, and maximum pulse-current during the MP were 687 and 893 A, respectively. The MP IS-pulse parameters are comparable to those of the "classical" IS pulses reported in previous studies.

IS pulses with shorter ($<8~\mu s$) risetimes are thought to be associated with leader/return stroke mode (or mixed mode) of charge transfer (e.g., [2]). The median background current at the start of such IS pulses in our dataset was 2.5 times smaller than that for IS pulses with longer risetimes (which are assumed to be associated with M-component mode of charge transfer).

CRediT authorship contribution statement

Naomi Watanabe: Methodology, Formal analysis, Writing – original draft, Visualization. Amitabh Nag: Conceptualization, Methodology, Writing – original draft, Visualization, Supervision, Funding acquisition. Gerhard Diendorfer: Writing – review & editing, Data curation, Funding acquisition. Hannes Pichler: Writing – review & editing, Data curation. Wolfgang Schulz: Writing – review & editing, Data curation. Hamid K. Rassoul: Writing – review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

Acknowledgements

This study was supported in part by funding from U.S. IARPA grant 2019–19022700011, the U.S. National Science Foundation Award 1934066, and Austrian Power Grid (APG) contract 4500294593/2016. Data from the Gaisberg Tower used in this study can be obtained by contacting W. Schulz (w.schulz@ove.at).

References

- L. Barret, Campagne Foudre RTLP 86 (in French), Note Technique STT/ASP 86-12/
 LB-mA, Laboratoire D'Applications Speciales de la Physique, 1986, 85 X., 38041
 Grenoble Cedex, France, 1 December.
- [2] D. Flache, V.A. Rakov, F. Heidler, W. Zischank, R. Thottappillil, Initial-stage pulses in upward lightning: leader/return stroke versus M-component mode of charge transfer to ground, Geophys. Res. Letters. 35 (2008) L13812, https://doi.org/ 10.1029/2008GL034148.
- [3] L. He, M. Azadifar, F. Rachidi, M. Rubinstein, An analysis of current and electric field pulses associated with upward negative lightning flashes initiated from the Santis tower, J. Geophys. Res. Atmos. 123 (2018) 4045–4059, https://doi.org/ 10.1029/2018.102895.
- [4] P. Lalande, A. Bondiou-Clergerie, P. Laroche, A. Eybert-Berard, J.P. Berlandis, B. Bador, A. Bonamy, M.A. Uman, V.A. Rakov, Leader properties determined with triggered lightning techniques, J. Geophys. Res. 103 (D12) (1998), https://doi.org/ 10.1029/97JD02492, 14,109–14,115.
- [5] P. Laroche, A. Eybert-Berard, L. Barret, J.P. Berlandis, Observations of preliminary discharges initiating flashes triggered by the rocket and wire technique, in: 8th International Conference on Atmospheric Electricity (ICAE), Uppsala, 1988.
- [6] M. Miki, V.A. Rakov, T. Shindo, G. Diendorfer, M. Mair, F. Heidler, W. Zischank, M. A. Uman, R. Thottappillil, D. Wang, Initial stage in lightning initiated from tall objects and in rocket-triggered lightning, J. Geophys. Res. 110 (D02109) (2005), https://doi.org/10.1029/2003.JD004474.
- [7] C. Paul, F.H. Heidler, Electric field characteristics of subsequent return strokes, M-components, and ICC pulses from negative upward lightning measured at the Peissenberg tower, IEEE Trans. EMC. 61 (4) (2019) 1490–1497, https://doi.org/10.1109/TEMC.2018.2845686.
- [8] V.A. Rakov, M.A. Uman, Lightning: Physics and Effects, Cambridge Univ. Press, Cambridge, U.K., 2003.
- [9] V.A. Rakov, A review of positive and bipolar lightning discharges, Bull. Amer. Meteorol. Soc. 84 (2003) 767–776, https://doi.org/10.1175/BAMS-84-6-767.
- [10] V.A. Rakov, Lightning flashes transporting both negative and positive charges to ground, in: C. Pontikis (Ed.), Recent Progress in Lightning Physics, Res. Signpost, Trivandrum, Kerala, India, 2005, pp. 9–21.
- [11] D. Wang, V.A. Rakov, M.A. Uman, M.I. Fernandez, K.J. Rambo, G.H. Schnetzer, R. J. Fisher, Characterization of the initial stage of negative rocket triggered lightning, J. Geophys. Res. 104 (D4) (1999) 4213–4222, https://doi.org/10.1029/1998JD200087.
- [12] N. Watanabe, A. Nag, G. Diendorfer, H. Pichler, W. Schulz, Characteristics of current in upward lightning flashes initiated from the Gaisberg tower, IEEE Trans. EMC. 61 (3) (2019) 705–718, https://doi.org/10.1109/TEMC.2019.2916047.
- [13] N. Watanabe, A. Nag, G. Diendorfer, H. Pichler, W. Schulz, H.K. Rassoul, Characterization of the initial stage in upward lightning at the Gaisberg tower: 2. Electric field pulses, Electric Power Syst. Res. (2022) this issue.
- [14] J.C. Willett, D.A. Davis, P. Laroche, An experimental study of positive leaders initiating rocket-triggered lightning, Atmos. Res. 51 (1999) 189–219, https://doi. org/10.1016/S0169-8095(99)00008-3.
- [15] H. Zhou, V.A. Rakov, G. Diendorfer, R. Thottappillil, H. Pichler, M. Mair, A study of different modes of charge transfer to ground in upward lightning, J. Atmos. Solar-Terrestrial Phys. 125-126 (2015) 38–49, https://doi.org/10.1016/j. iastb.2015.02.008.
- [16] H. Zhou, G. Diendorfer, R. Thottappillil, H. Pichler, M. Mair, Mixed mode of charge transfer to ground for initial continuous current pulses in upward lightning, in: Proceeding of the 7th Asia-Pacific International Conference on Lightning, Chengdu, China, 2011, https://doi.org/10.1109/apl.2011.6110212.