GROUND2020/21

&

9th LPE

International Conference on Grounding
&
Lightning Physics and Effects

Belo Horizonte, Brazil - June, 2021

CHARACTERIZATION OF INITIAL STAGE CURRENT PULSES IN UPWARD LIGHTNING INITIATED FROM THE GAISBERG TOWER

Naomi Watanabe[1], Amitabh Nag[1], Gerhard Diendorfer[2], Hannes Pichler[2], Wolfgang Schulz[2], Hamid K. Rassoul[1]
1. Aerospace, Physics and Space Sciences, Florida Institute of Technology, 2. Austrian Lightning Detection and Information System, OVE Service GmbH

Abstract - We examine current and electric field waveforms for 58 negative upward flashes occurring in 2006-2014 initiated from the Gaisberg Tower located in Salzburg, Austria. Current was measured at the top of the tower using a 0.25 mΩ shunt. The initial stage (IS) of these flashes comprised of relatively slowly varying "background" current (having durations ranging from 74 to 691 ms), with faster, more impulsive current variations (pulses having durations ranging from 2.2 μs to 29 ms) 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; all bipolar pulses occurred within the first 15% of the IS duration in all flashes. We divided the IS current into two phases: (1) upward leader initiation and propagation phase (IPP) and (2) upward leader mature phase (MP). 901 (712 bipolar and 189 unipolar) pulses occurred during the IPP, and 279 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 the 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., Watanabe et al., 2019 [1]) the IS is followed by one or more downward-leader-return-stroke sequences, the latter being similar to subsequent return 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., Rakov and Uman, 2003, Ch. 7 [2]). The IS pulses in upward and rocket-triggered lightning have been examined in various studies (e.g., Miki et al., 2005; Flache et al. 2008; Zhou et al. 2015; and He et al., 2018 [3, 4, 5, 6]). IS current pulses in upward lightning has 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., Miki et al., 2005; Zhou et al., 2015 [3, 5]). The junction point of the two branches is expected to be relatively close to the tower top. This mode of charge transfer has been referred to as a "mixed mode of charge transfer to ground" (e.g., Zhou et al., 2011 [7]). 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 (Flache et al. 2008; He at al., 2018 [5, 6]).

In this study, we characterize in detail 1180 IS current pulses occurring during IS of 58 upward flashes initiated from the Gaisberg Tower in 2006-2014. We categorize pulses based upon their initial polarity, waveshape, and their occurrence context in the IS. We also examine the current waveform parameters of the IS pulses.

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 Gaisberg Tower. The shunt had an impedance of 0.25 mΩ 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 is 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 not shown in this paper. 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 Watanabe et al., 2019 [1]), and the other seven were of Type 1M (multiple current polarity reversals during the IS). 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. (2019) [1] 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 measurement system of 250 kHz translates to full cycle time domain signals of 4 μs. This means that risetimes shorter than 4 x 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 peak-current absolute values 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.

3.1 – 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. Figure 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 start-time 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. Figure 2 shows the histograms of normalized pulse-start-time 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 to 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 Figure 3a, we defined the first phase as the time-interval between the IS start-time and 15% of its 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. Figure 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 (76%) pulses occurred during the IPP and 279 (all unipolar) of 1180 (24%) pulses occurred during the MP. Figure 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 more or less evenly distributed during the MP with them diminishing in the last 5% of the IS duration (see Figure 2b).

3.2 – CHARACTERIZATION OF IPP PULSES

For the 1180 current pulses in our dataset, we examined the background-to-peak and 10-to-90% risetimes, total duration, full-width at half-maximum (FWHM), background-to-peak current, and maximum pulse-current. These parameters are defined in Figure 3c 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 the peak value. 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, prior to the opposite "polarity" overshoot with respect to the background current for bipolar pulses, see Figure 3b) at 50% of its background-to-peak current value. The maximum pulse-current is the maximum value of the current that occurs during a pulse with respect to the zero-current level. Note that, depending upon the IS current-level and pulse-type, this maximum current 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 of pulses occurring during the IPP below in this section and during the MP in section 3.3.

Figure 4a-f shows histograms of background-to-peak risetime, 10-to-90% risetime, total duration, FWHM, background-to-peak current, and maximum pulse-current

for 901 (712 bipolar shown in green and 189 unipolar shown in pink) pulses that occurred during the IPP of the 58 flashes in our dataset. The background-to-peak risetimes (Figure 4a) ranged from 0.41 to 513 μs, with median being 1.1 μs. For bipolar and unipolar pulses, the median risetimes were 1 and 5.6 μs, respectively. The 10-to-90% risetimes (Figure 4b) ranged from 0.16 to 122 μs, with median being 0.58 μs. The median for bipolar and unipolar pulses were 0.55 and 3.0 μs, respectively. The median background-to-peak and 10-to-90% risetimes were, respectively, 5.6 and 5.5 times longer for unipolar than bipolar pulses. The total durations (Figure 4c) and FWHM (Figure 4d) 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 unipolar than bipolar pulses. The magnitudes of the background-to-peak currents (Figure 4e) and maximum pulse-currents (Figure 4f) 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 bipolar than unipolar pulses.

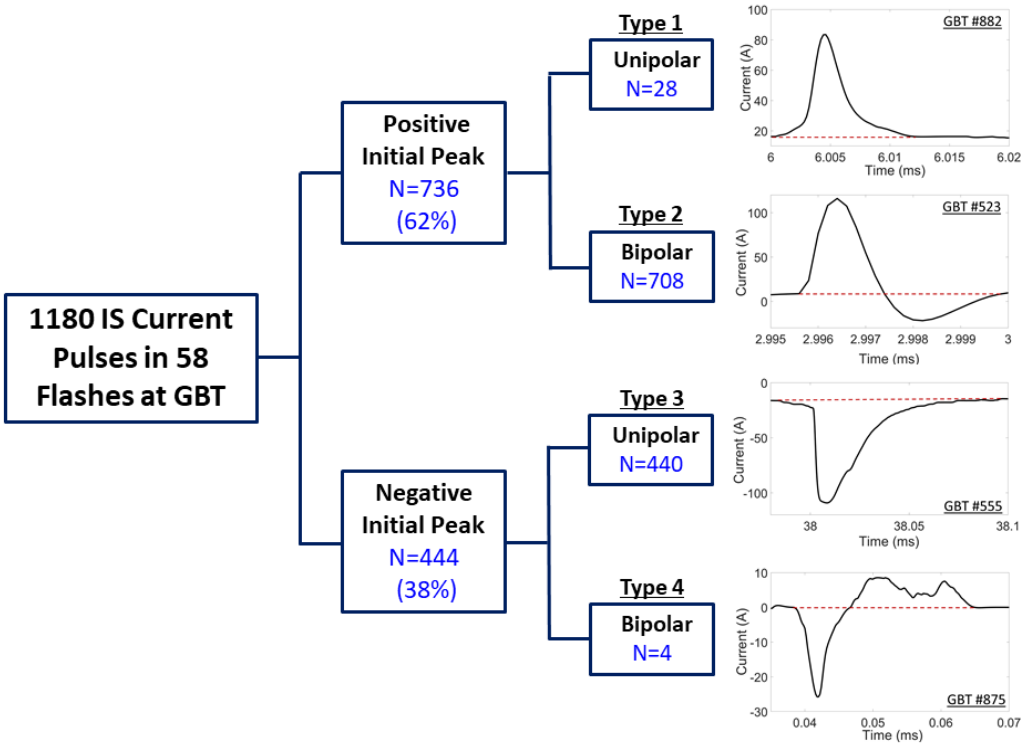


Figure 1 - Categorization of IS current pulses based on the polarity of initial peak and overall waveshape with respect to the background current. We analyzed 1180 current pulses that occurred during the IS of 58 flashes recorded at the GBT in 2006-2014. Typical current waveforms of each pulse type are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

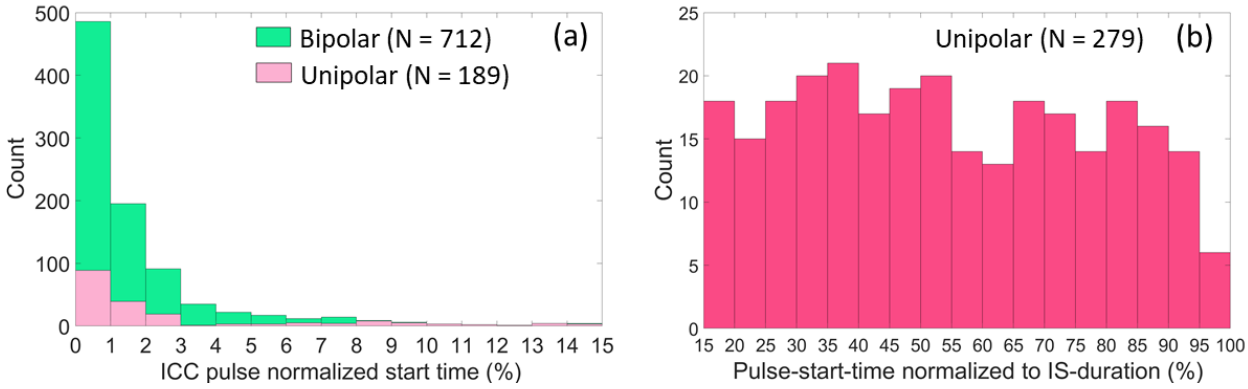


Figure 2 - Histogram of the normalized pulse-start-time for pulses occurring during (a) the IPP, color-coded in green and pink for bipolar and unipolar pulses, respectively, and (b) the MP of the IS in the 58 upward flashes in our dataset. Only unipolar pulses occur during the MP.

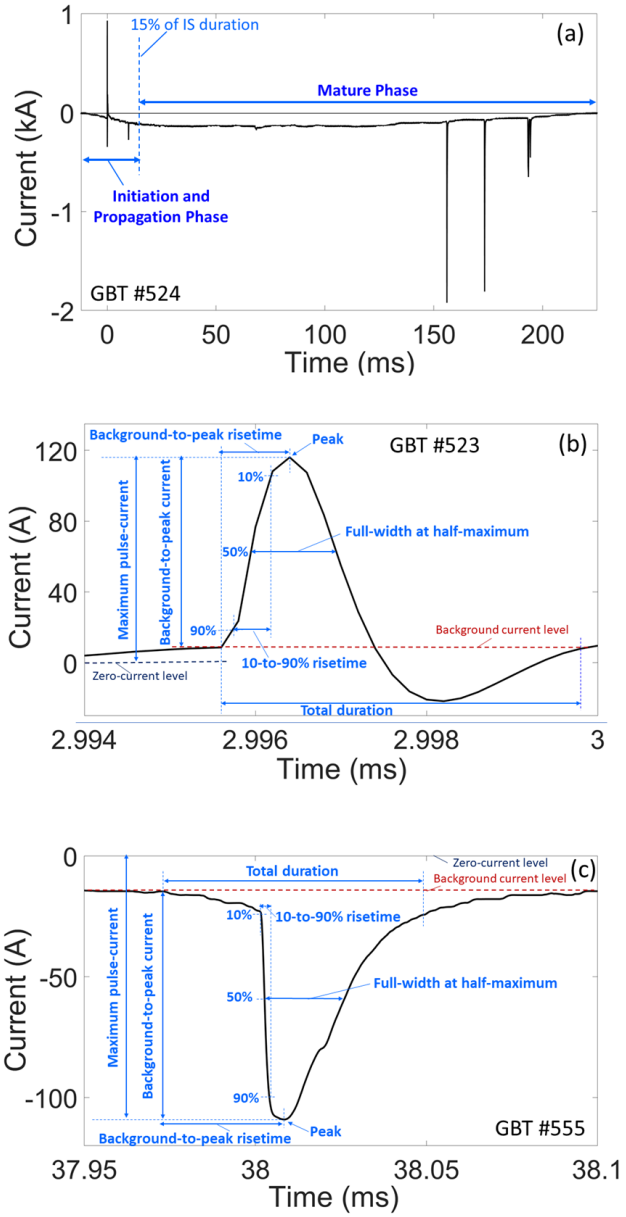


Figure 3 - (a) Current waveform of the IS of upward flash GBT #524 showing the upward-leader initiation and propagation phase (IPP) and mature phase (MP). We defined the former as the time-interval between the IS start-time and 15% of its duration and the latter as that between this 15%-time to the IS current end-time. See text for further details. Polarity of current 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.

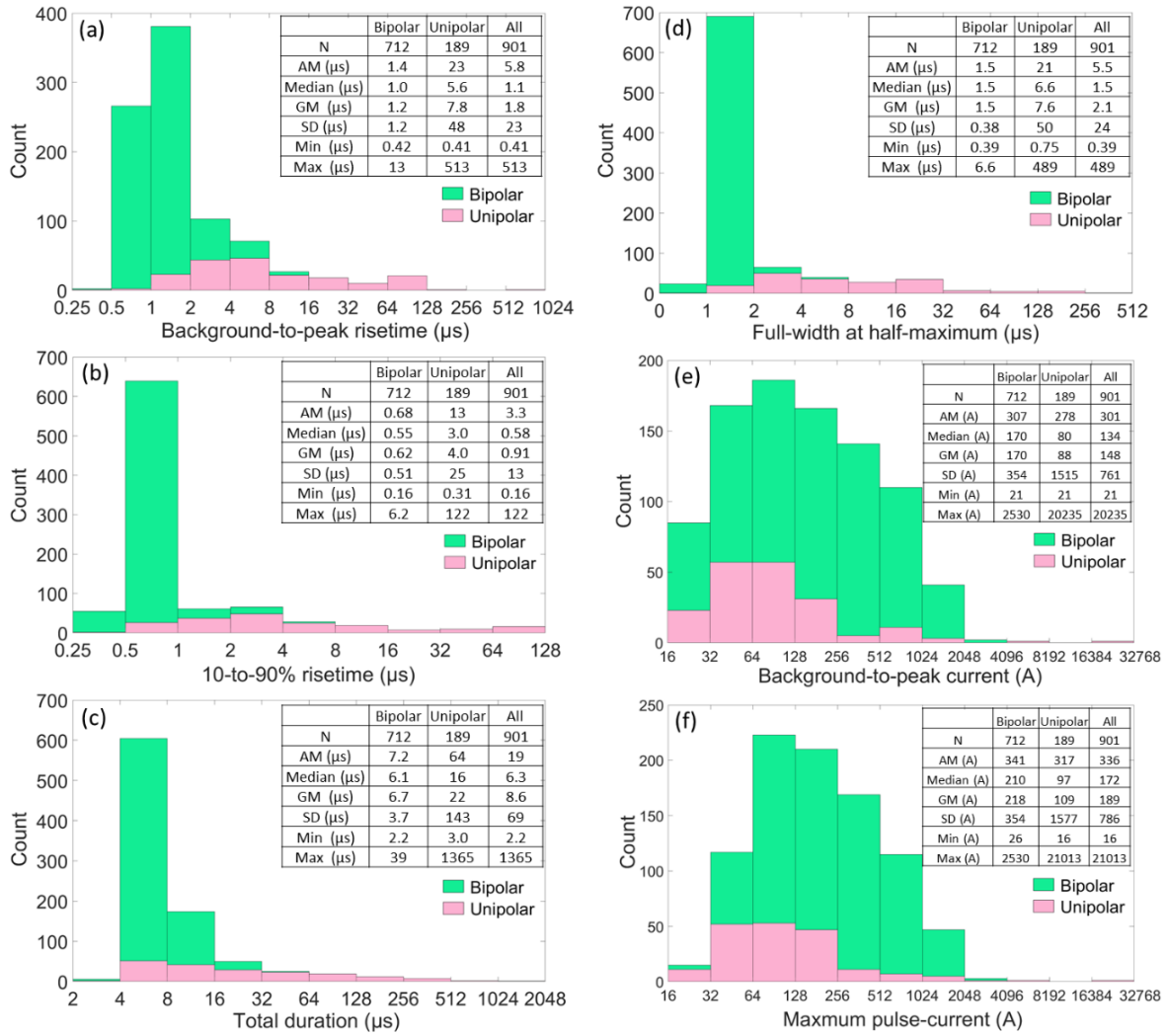
3.3 – CHARACTERIZATION OF MP PULSES

Figure 5a-f shows histograms of background-to-peak risetime, 10-to-90% risetime, total duration, full-width at half-maximum, background-to-peak current, and maximum pulse current for 279 unipolar pulses that occurred during the MP of the 58 flashes in our dataset. The background-to-peak risetimes (Figure 5a) ranged from 2.0 µs to 19 ms, with the median being 107 µs. The 10-to-90% risetimes (Figure 5b) ranged from 0.57 µs to 6.6 ms, with a median of 43 µs. The total durations (Figure 5c) and FWHM (Figure 5d) ranged from 20 µs to 29 ms and 8.9 µs to 8.9 ms, respectively, with the medians being 441 µs and 134 µs, respectively. Finally, the magnitudes of the background-to-peak currents (Figure 5e) and maximum pulse-currents (Figure 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 AND 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 Watanabe et al., 2019 [1]), 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 occurring at early times during the IPP 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 (e.g., Barret, 1986; Laroche et al., 1988, Willett et al., 1999 [8, 9, 10]).

We divided the IS current into the upward leader initiation and propagation phase and mature phase. The first phase was defined as the time-interval 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 leader-channels 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 flash-by-flash basis, rather than the 15%-IS-duration approach adopted in this study. The median background-to-peak risetime, 10-to-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. The median background-to-peak risetime, 10-to-90% risetime, total duration, and FWHM were 107, 43, 441, and 134 µs, respectively. The median background-to-peak current, and maximum pulse-current during the IPP were 687 and 893 A, respectively. The MP IS-pulse parameters are comparable to those of the “classical” IS pulses reported in previous studies.



	Bipolar	Unipolar	All
N	712	189	901
AM (μs)	1.4	23	5.8
Median (μs)	1.0	5.6	1.1
GM (μs)	1.2	7.8	1.8
SD (μs)	1.2	48	23
Min (μs)	0.42	0.41	0.41
Max (μs)	13	513	513

	Bipolar	Unipolar	All
N	712	189	901
AM (μs)	0.68	13	3.3
Median (μs)	0.55	3.0	0.58
GM (μs)	0.62	4.0	0.91
SD (μs)	0.51	25	13
Min (μs)	0.16	0.31	0.16
Max (μs)	6.2	122	122

	Bipolar	Unipolar	All
N	712	189	901
AM (μs)	7.2	64	19
Median (μs)	6.1	16	6.3
GM (μs)	6.7	22	8.6
SD (μs)	3.7	143	69
Min (μs)	2.2	3.0	2.2
Max (μs)	39	1365	1365

	Bipolar	Unipolar	All
N	712	189	901
AM (μs)	1.5	21	5.5
Median (μs)	1.5	6.6	1.5
GM (μs)	1.5	7.6	2.1
SD (μs)	0.38	50	24
Min (μs)	0.39	0.75	0.39
Max (μs)	6.6	489	489

	Bipolar	Unipolar	All
N	712	189	901
AM (A)	307	278	301
Median (A)	170	80	134
GM (A)	170	88	148
SD (A)	354	1515	761
Min (A)	21	21	21
Max (A)	2530	20235	20235

	Bipolar	Unipolar	All
N	712	189	901
AM (A)	341	317	336
Median (A)	210	97	172
GM (A)	218	109	189
SD (A)	354	1577	786
Min (A)	26	16	16
Max (A)	2530	21013	21013

Figure 4 - Histogram of (a) background-to-peak risetime, (b) 10-to-90% risetime, (c) total duration, (d) FWHM, (e) background-to-peak current, and (f) maximum pulse-current, color-coded in green and pink for bipolar pulses and unipolar pulses, respectively, occurring during the IPP in the 58 flashes in our dataset. Arithmetic mean (AM), geometric mean (GM), maximum (Max), and minimum (Min) values for bipolar, unipolar, and all pulses are shown in each histogram.

5 – REFERENCES

[1] Watanabe, N., A. Nag, G. Diendorfer, H. Pichler, & W. Schulz. (2019). Characteristics of current in upward lightning flashes initiated from the Gaisberg Tower. IEEE Trans. Electromagn. Compat., Vol (61), no. 3, pp. 705–718. doi.org/10.1109/TEMC.2019.2916047.

[2] Rakov, V. A., & M. A. Uman (2003). Lightning: Physics and Effects. Cambridge, U.K.: Cambridge Univ. Press.

[3] Miki, M., V. A. Rakov, T. Shindo, G. Diendorfer, M. Mair, F. Heidler, W. Zischank, M. A. Uman, R. Thottappillil, & D. Wang, (2005). Initial stage in lightning initiated from tall objects and in rocket-triggered lightning. J. Geophys. Res., Vol (110), 2005, Art. no. D02109. doi.org/10.1029/2003JD004474.

[4] Flache, D., Rakov, V., Heidler, F., Zischank, W., & Thottappillil, R. (2008). Initial-stage pulses in upward lightning: Leader/return stroke versus M-component mode of charge transfer to ground. Geophys. Res Letters, Vol (35), L13812. doi.org/10.1029/2008GL034148.

[5] Zhou, H., V. A. Rakov, G. Diendorfer, R. Thottappillil, H. Pichler, & M. Mair. (2015). A study of different modes of charge transfer to ground in upward lightning. J. Atmos. Solar-Terrestrial Phys., Vol (125-126), pp. 38–49. doi.org/10.1016/j.jastp.2015.02.008.

[6] He, L., M. Azadifar, F. Rachidi, & M. Rubinstein. (2018). An analysis of current and electric field pulses associated with upward negative lightning flashes initiated from the Santis tower. J. Geophys. Res., Atmospheres, Vol (123), pp. 4045–4059. doi.org/10.1029/2018JD028295.

[7] Zhou, H., Diendorfer, G., Thottappillil, R., Pichler, H., & Mair, M. (2011). Mixed mode of charge transfer to ground for initial continuous current pulses in upward lightning, paper presented at 2011 7th Asia-Pacific International Conference on Lightning, Cheng du, China, 1-4 Nov. 2011. https://doi.org/10.1109/apl.2011.6110212.

[8] Barret, L. (1986). Campagne Foudre RTLP 86 (in French), Note Technique STT/ASP 86-12/LB-mA, Laboratoire D'Applications Speciales de la Physique, 85 X., 38041 Grenoble Cedex, France, 1 December.

[9] Laroche, P., A. Eybert-Berard, L. Barret, J. P. Berlandis (1988). Observations of preliminary discharges initiating flashes triggered by the rocket and wire technique. 8th International Conference on Atmospheric Electricity, Uppsala.

[10] Willett, J.C., D.A. Davis, & P. Laroche. (1999). An experimental study of positive leaders initiating rocket-triggered lightning. Atmos. Res., Vol (51), pp. 189–219. doi.org/10.1016/S0169-8095(99)00008-3.

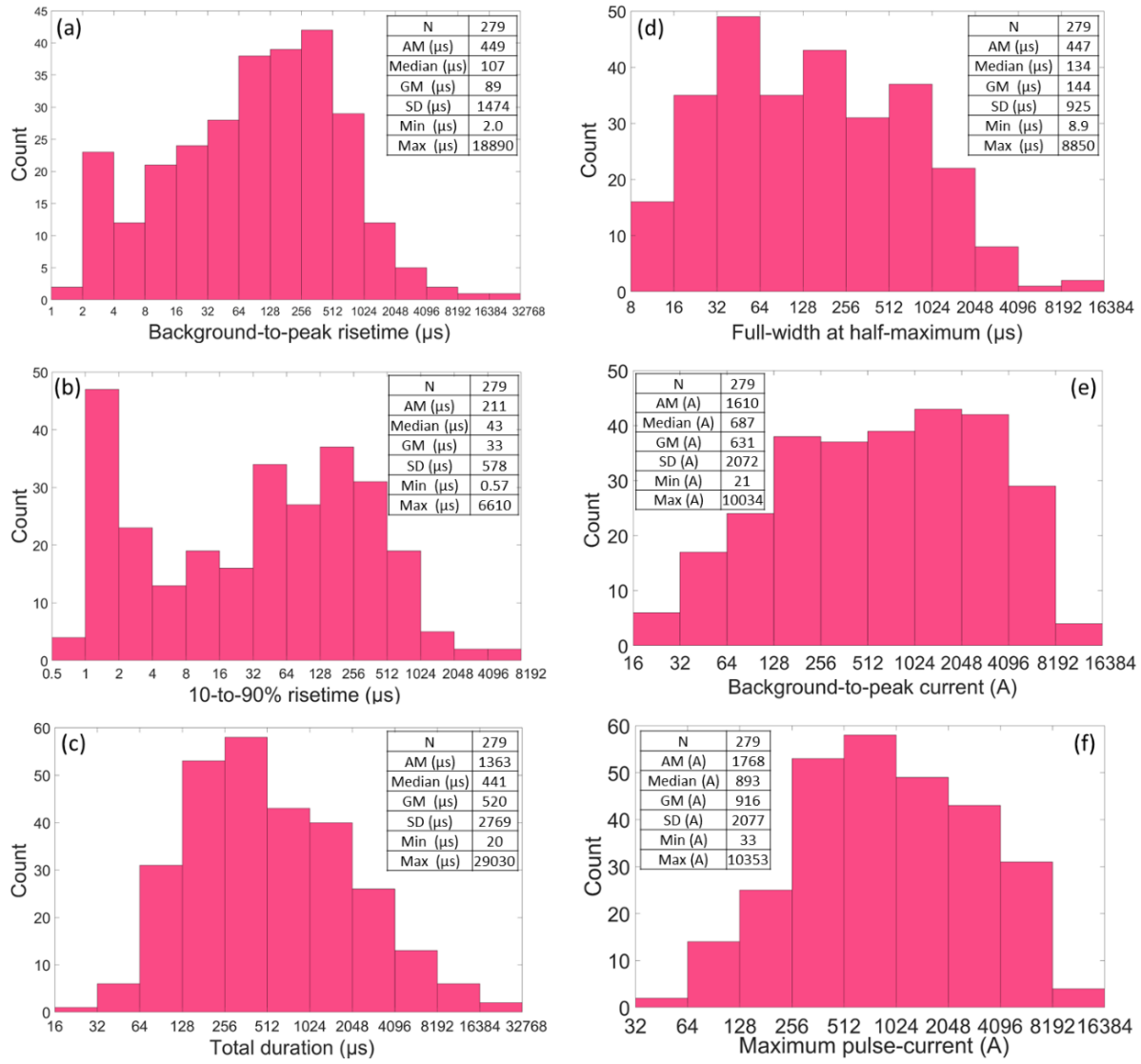


Figure 5 - Histogram of (a) background-to-peak risetime, (b) 10-to-90% risetime, (c) total duration, (d) FWHM, (e) background-to-peak current, and (f) maximum pulse-current, for unipolar pulses occurring during the MP in the 58 flashes in our dataset. Statistics are shown in each histogram.