Characteristics of Currents in Upward Lightning Flashes Initiated From the Gaisberg Tower

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***Abstract*—We examined the occurrence characteristics of the lightning observed at the Gaisberg Tower (GBT) in the years 2000 to 2018 and analyzed current waveforms (measured using a 0.25-mΩ shunt) of upward flashes initiated from the tower. During this period, 865 flashes were recorded at the GBT, of which 823 (95%) were upward and 4 (0.5%) were downward. For 18 flashes, the current waveforms were ambiguous and for 20 flashes they were unsuitable for analysis. Of the 823 upward flashes, 651 (79%) were negative, 35 (4.3%) were positive, and 137 (17%) were bipolar. The median initial stage (IS)-current durations in upward negative, positive, and bipolar flashes were 275, 96, and 282 ms, respectively. The median IS-current peaks in these flashes were 1.4, 3.2, and 1.8 kA, respectively. We expanded the traditional classification of bipolar flashes to include five categories. Of the 137 bipolar flashes, 45% were of Type 1S (single reversal of current polarity during IS), 47% of Type 1M (multiple reversals of current polarity during IS), 5.1% of Type 2 [different polarities of current during IS and return stroke (RS)], 1.5% of Type 3 (RSs of different polarities), and 0.73% (one flash) of Type 4 (different polarities of RS and the following continuing current).**

***Index Terms*—Bipolar lightning, current polarity, Gaisberg Tower (GBT), occurrence characteristics, upward lightning.**

I. Introduction

UPWARD lightning from tall objects on ground can be an important aspect of winter lightning activity (e.g., in Japan). A majority of lightning attaching to wind turbines along the west coast of Japan during the winter season is of this type (Ishii *et al.* [1]; NEDO report [2]; Saito and Ishii [3]; Saito and Ishii [4]; Vogel *et al.* [5]). Additionally, there has been a rapid deployment of large wind farms in lightning-prone regions such as the central United States, where wind turbines are also often affected by upward lightning. As a result, upward lightning has attracted a lot of interest in recent years (e.g., Saito *et al.* [6]; Ishii *et al.* [7]; Smorgonskiy *et al.* [8]), and a CIGRE Working Group (C4.36) [9] has been assembled to examine the characteristics of upward (and other winter-type) lightning discharges. In the context of lightning attachment to tall objects, upward lightning can be defined as lightning in which the initial upward leader from the object is the dominant leader (that is, the upward leader is initiated first and has longer vertical extent than that of the descending or otherwise approaching leader); it is often the only leader seen below the cloud base (e.g., Miki *et al.* [10]; Wang *et al.* [11]; Diendorfer *et al.* [12]; Warner *et al.* [13]). The upward-leader channel may terminate in clear air, attach to a descending leader branch in clear air (below the cloud base), or enter the cloud; in the latter case, it generally becomes difficult or impossible to determine whether it is dominant or not (see, for example, Berger's positive flashes discussed in [14, Ch. 5]). Such lightning is often associated with large (several tens to hundreds of coulombs) amounts of charge transfer. The initial upward leader can be either positive or negative, facilitating either negative or positive charge transfer to ground, respectively. Some upward flashes transfer both negative and positive charge to ground. Such bipolar flashes are reviewed by Rakov [15]. Usually, 25% or so of upward flashes contain leader-return stroke sequences, with the remaining 75% being composed of the so-called initial stage (IS) (CIGRE TB 549, [16, p. 67]), which is characterized by a slowly varying current with or without superimposed pulses. In the New Energy and Industrial Technology Development Organization (NEDO) project, only 11% of upward flashes contained return strokes (RSs) (Saito and Ishii [4]). A dominant upward leader can be self-initiated or induced by another flash occurring nearby. The conditions that determine the likelihood of the production of a dominant upward leader are 1) a small effective gap between the cloud charge region and the tall object tip; and/or 2) a rapid change in electric field due to fast neutralization or rearrangement of charge within the cloud due to a preceding CG or IC flash (e.g., Miki *et al.* [10]; Wang *et al.* [11]; Diendorfer *et al.* [12]; Warner *et al.* [13]; Zhou *et al.* [17]; Saba *et al.* [18]). Either of these conditions can lead to the intensification of the electric field at the tall object tip needed for the initiation of the upward leader.

The characteristics of the currents associated with upward lightning initiated from tall towers have been examined in detail in many previous studies (e.g., Saba *et al.* [18], Miki *et al.* [19],

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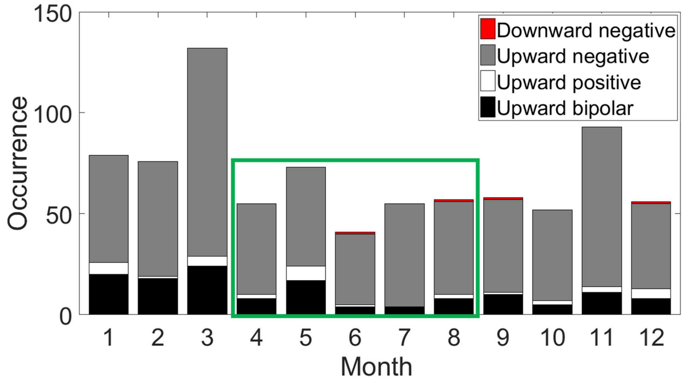
Azadifar *et al.* [20], Zhou *et al.* [21], Zhou *et al.* [22], and Zhou *et al.* [23]). The current waveforms of upward lightning flashes necessarily includes the IS part, which typically lasts for many tens to several hundreds of milliseconds. The initial part of the IS current is due to the initial upward leader and is followed by a relatively slowly varying "background" current known as the initial continuous current (ICC). Faster and more impulsive current variations (pulses with durations ranging from a few microseconds to a few tens of milliseconds) are overlaid on the ICC and are referred to as ICC pulses (e.g., Diendorfer *et al.* [24]). Watanabe *et al.* [25] reported that in addition to the "classical" ICC pulses, which typically last for many tens to hundreds of microseconds, faster current pulses with durations of few microseconds overlaid on the ICC are also observed. After the IS, following an interval of a few to few-hundred milliseconds, during which there is essentially no current (above 0.1 A, McCann [26]), one or more RSs may occur. These RSs are similar to the subsequent strokes in natural downward lightning. Zhou *et al.* [21] examined the current records for upward flashes initiated from the Gaisberg Tower (GBT), which is a 100-m high radio tower on the 1287-m tall (above the mean sea level) Gaisberg mountain near the City of Salzburg in Austria. For the flashes occurring between the years 2000 and 2009, they found that 3.2% (21 of 652) of the flashes were bipolar. In this study, we examine the occurrence characteristics of the lightning observed at the GBT in the years 2000 to 2018. Additionally, we analyze in detail the current waveforms of 865 upward lightning discharges initiated from the GBT during this period and classify them into various categories on the basis of their current-polarity characteristics.

II. Instrumentation and Data

A current measuring shunt is located at the base of a 1.5-m high air-terminal on top of the GBT. The shunt has an impedance (essentially resistance) of 0.25 mΩ and a bandwidth from dc to 3.2 MHz. Two separate Nicolet ISOBE 3000 fiber optic links, each with bandwidth from dc to 15 MHz, were used to transmit signals from the shunt to an 8-bit (12-bit after May 16, 2012) digital acquisition system located at a nearby building. The vertical-scale upper limits of the two current-measuring channels were $\pm$2 and $\pm$40 kA. The 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 to $\pm$200 A. Prior to the analysis, the current waveforms were filtered using a second-order Butterworth low-pass filter (with the –3 dB frequency being 250 kHz) to remove high-frequency noise and were then resampled at 5 MHz. All the current records are GPS time-stamped. When determining the polarity of the current in upward flashes, we ignored the microsecond-scale pulses that often occurred toward the very beginning of these flashes. These pulses appeared in 63% (516 of 823) of our upward-flash current waveforms and are similar to "precursor" pulses in rocket-triggered lightning associated with attempted upward-leader inceptions (e.g., Lalande *et al.* [27]). Of the 516 upward flashes with precursor pulses, 79.6%, 1.7%, and 18.8% were negative, positive, and bipolar flashes, respectively. The polarity of the current was determined only when its absolute value was equal to or greater than 20 A, which is greater than the 16-A lower-measurement-limit of the $\pm$2-kA current-measuring channel with an 8-bit digitizer. For the portions of the flashes during which currents exceeded $\pm$2 kA, the waveforms recorded by the $\pm$40-kA channel were used. For 58 flashes, the $\pm$2-kA channel was not available, and current polarity was determined for these flashes using the $\pm$40-kA channel, which had a 313-A vertical-scale lower-limit with an 8-bit digitizer. The same current lower-limit restrictions were applied when determining the start- and end-times of no-current intervals and of flashes. In the flashes with RSs, the impulsive return-stroke currents occurred after no-current intervals and were recognized by their microsecond-scale rise times. The time at which the impulsive component of the return-stroke current decayed to less than 10% of its peak value was defined as the start-time of the post return-stroke continuing current (CC).

Between the years 2000 and 2018, 865 flashes were recorded at the GBT, of which 823 (95%) were upward and 4 (0.5%) were downward (all negative) flashes. The current waveforms were ambiguous for 18 flashes, and for 20 flashes they were unsuitable for analysis (because of poor signal-to-noise ratio). Fig. 1(a) shows the histogram of the occurrence of the downward negative ($N = 4$), upward negative ($N = 651$), upward positive ($N = 35$), and upward bipolar ($N = 137$) flashes occurring in each month between the years 2000 and 2018. Note that no current measurements were made at the GBT between October, 2015 and May, 2017. As seen from the tables in Figs. 1(b) and (c), of the 827 (823 upward and 4 downward) flashes at the GBT, 546 (66%) occurred during the seven months (September–March) of the non-convective season in Austria (Diendorfer *et al.* [24]). Also, 544 (66%) of the 823 upward flashes and 425 (65%) of the 651 upward negative flashes occurred during this season. Note that, 94.8% of the cloud-to-ground flashes in Austria reported by the Austrian Lightning Detection and Information System in 2000–2017 occurred during the convective season (April–August) versus 5.2% during the non-convective season. Clearly, the proportion of the upward lightning at the GBT relative to all cloud-to-ground flashes in Austria during the non-convective season is much higher than that in the convective season. The upward negative flashes comprised 67%–87% of the monthly flash counts during the non-convective season, with the median being 78% and 67%–93% of the monthly flash counts during the convective season, with the median being 82%. The upward bipolar flashes comprised 9.6%–25% of the monthly flash counts during the non-convective season (median of 17%) and 7.3%–23% of the monthly flash counts during the convective season (median of 14%). So, even though the majority, 96 (70%) of 137 bipolar flashes, occurred during the non-convective season, they are only slightly more likely to occur during the months of the non-convective versus during those of the convective season. Also, while the majority, (23 of 35; that is, 66%) of the upward positive flashes at the GBT occurred during the non-convective season, they comprised 1.3%–8.9% of the monthly flash counts in this season, with the median being 3.8%, which is similar to their monthly occurrence frequency in the convective season during which they comprise 0%–9.6% of the monthly flash counts, with



(a)

(b) Monthly percentages

Month	Downward negative (% of monthly flash count)	Upward negative (% of monthly flash count)	Upward positive (% of monthly flash count)	Upward bipolar (% of monthly flash count)	Annual count (% of total flash count)
Jan	0 (0.0%)	53 (67%)	6 (7.6%)	20 (25%)	79 (9.6%)
Feb	0 (0.0%)	57 (75%)	1 (1.3%)	18 (24%)	76 (9.2 %)
Mar	0 (0.0%)	103 (78%)	5 (3.8%)	24 (18%)	132 (16%)
Apr	0 (0.0%)	45 (82%)	2 (3.6%)	8 (15%)	55 (6.7%)
May	0 (0.0%)	49 (67%)	7 (9.6%)	17 (23%)	73 (8.8%)
Jun	1 (2.4%)	35 (85%)	1 (2.4%)	4 (9.8%)	41 (5.0%)
Jul	0 (0.0%)	51 (93%)	0 (0.0%)	4 (7.3 %)	55 (6.7%)
Aug	1 (1.8%)	46 (81%)	2 (3.5%)	8 (14%)	57 (6.9%)
Sep	1 (1.7%)	46 (79%)	1 (1.7%)	10 (17%)	58 (7.0%)
Oct	0 (0.0%)	45 (87%)	2 (3.8%)	5 (10%)	52 (6.3%)
Nov	0 (0.0%)	79 (85%)	3 (3.2%)	11 (12%)	93 (11%)
Dec	1 (1.8 %)	42 (75%)	5 (8.9%)	8 (14%)	56 (6.8%)

(c) Summary

2000 – 2018 (% of all flashes)	Downward negative = 4 (0.5%)	Upward negative = 651 (79%)	Upward positive = 35 (4.2%)	Upward bipolar = 137 (17%)	Total flash count = 827 (100%)

Fig. 1. (a) Histogram, (b) monthly percentages, and (c) summary of the occurrence of downward negative, upward negative, upward positive, and upward bipolar flashes in each month between the years 2000 and 2018 at the GBT. Note that no current measurements were made at the GBT between October, 2015 and May, 2017. The green boxes in (a) and (b) indicate the convective season (April–August) in Austria. The non-convective season extends from September to March.

the median being 3.5%. Of the four downward negative flashes, two occurred during the non-convective season and two during the convective season. Most (16%) flashes occurred at the GBT in the month of March, while the least (5.0%) occurred in the month of June.

III. Analysis of Upward Flashes

We now examine in detail the characteristics of the current in the upward discharges at the GBT. As shown in Fig. 2, of the 823 upward flashes, 651 (79.1%) transferred only negative charge to ground, 35 (4.3%) transferred only positive charge to ground, and 137 (16.6%) were bipolar (i.e., both polarities of charge were transferred to ground during each flash). Also, in 262 (32%) of the 823 upward flashes, the IS was followed by one or more RSs, while 561 (68%) flashes were composed of the IS only. Fig. 3(a) and (b) show, respectively, the histograms of the current durations during entire flashes (or at least during the cloud-to-ground component of the flashes within the 800-ms current record length) and during the IS of the flashes. In this study, we refer to these current-durations as “flash-current” and “IS-current” durations, respectively. Note that in the current records of 56 flashes, there was non-zero current either at the beginning or at the end of the record. Also, we found the flash-current durations in two flashes to be longer than 800 ms, and in three additional flashes, both the IS- and flash-current durations were longer than 800 ms. Because of this record-length limitation, our median current durations should be viewed as underestimates. Also, note that upward flashes can have in-cloud components lasting for significant periods of time prior to the initiation and after the cessation of charge transfer to ground, which are not captured in their current records. The flash- and IS-current durations for the upward flashes both ranged from 2.3 to 800 ms, with the median durations being 311 and 269 ms, respectively.

A. *Upward Unipolar Flashes*

Of the 686 unipolar flashes, 651 (94.9%) flashes transferred negative charge to ground and 35 (5.1%) flashes transferred positive charge to ground. As seen from Fig. 3(a), the duration of the flash-current measured at the GBT for negative flashes ranged from 6.4 to 800 ms, with the median value being 322 ms, and for positive flashes it ranged from 2.3 to 789 ms, with the median duration being 96 ms. The median flash-current duration for the positive flashes was 3.4 times shorter than that for the negative flashes. The duration of the IS-current for negative and positive flashes ranged from 6.4 to 800 ms and 2.3 to 789 ms, respectively, with the median durations being 275 and 96 ms, respectively, as shown in Fig. 3(b). The median IS-current duration was 2.9 times shorter for the positive flashes than for the negative flashes. Note that 33 of the 35 positive flashes did not contain RSs and, hence, their flash-current duration was equal to the IS-current duration; this is why the ranges and medians of those two parameters for the positive flashes are the same.

Fig. 4 shows the histograms of flash-current durations for flashes with and without RSs. In 210 (32%) of the 651 upward negative flashes, the IS was followed by one or more RSs, with the median flash-current durations for flashes with and without RSs being 443 and 271 ms, respectively, as shown in Fig. 4(a). Note that for the flashes without RSs, the flash-current and IS-current durations are identical. The median IS-current duration for the negative flashes with RSs (not shown in Fig. 4) was 281 ms, which is comparable to the flash- or IS-current duration in the flashes without RSs. In only two (5.7%) of 35 upward positive flashes, the IS was followed by RSs. The flash-current durations [see Fig. 4(b)] for these two positive flashes were 155 and 721 ms, and the IS-current durations (not shown in Fig. 4) were 104 and 180 ms, respectively. The median flash- or IS-current duration for 33 positive flashes without RSs was 85 ms, which is 3.2 times shorter than that for upward negative flashes without RSs.

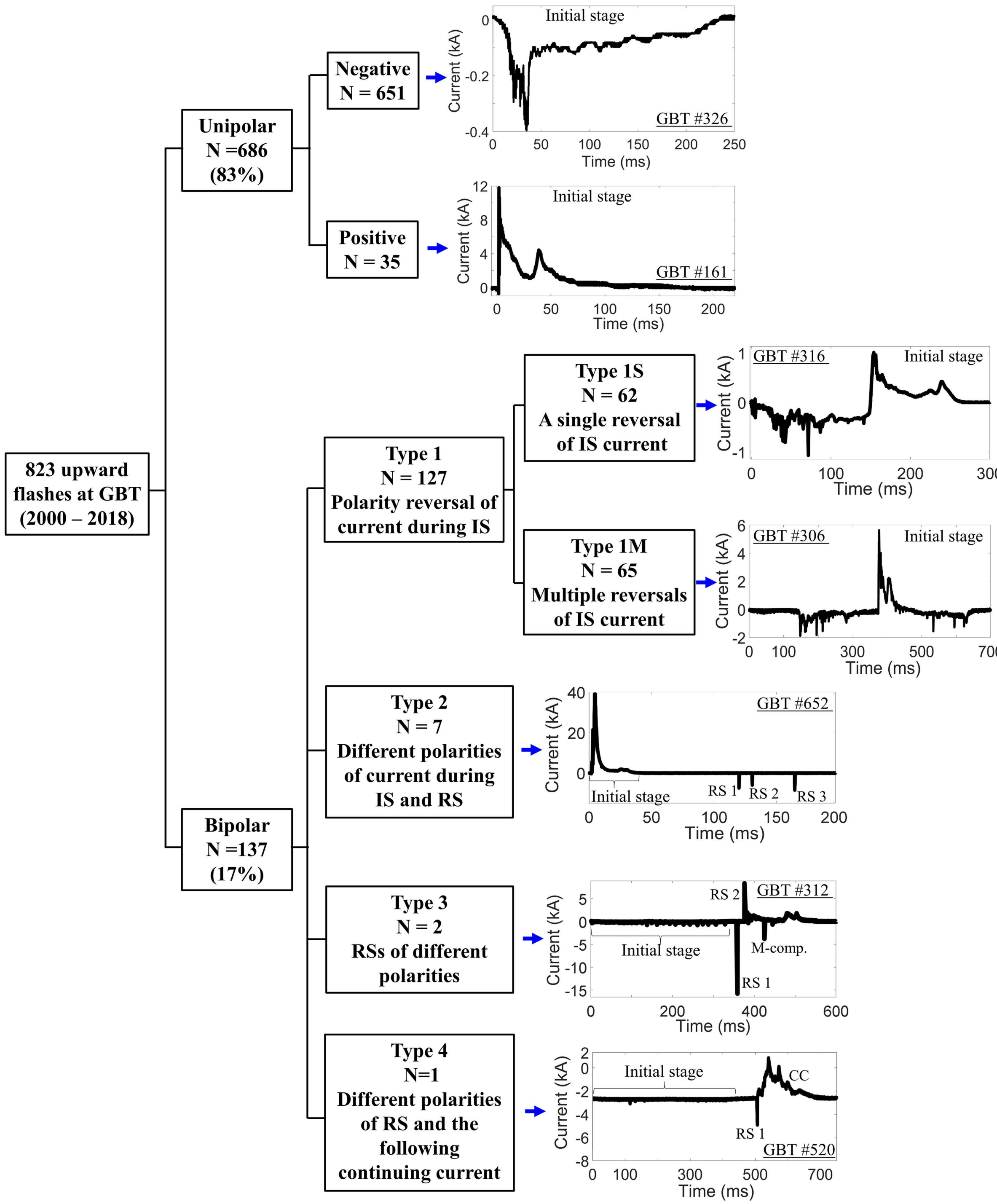
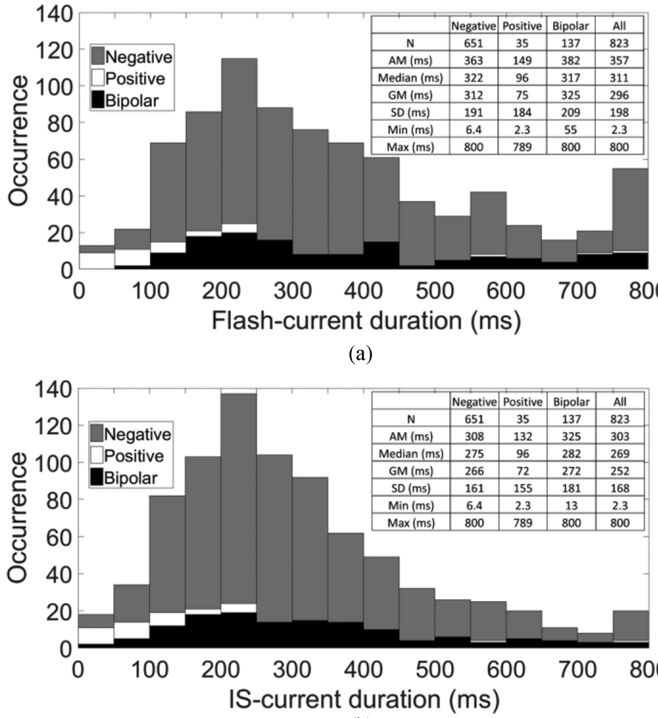


Fig. 2. Classification of upward flashes initiated from the GBT between the years 2000 and 2018. Typical current waveforms of flashes of each type are shown on the right side. IS = Initial stage, RS = return stroke, M-comp. = M-component, and CC = continuing current. The polarity of the current corresponds to the polarity of the charge transferred to ground.

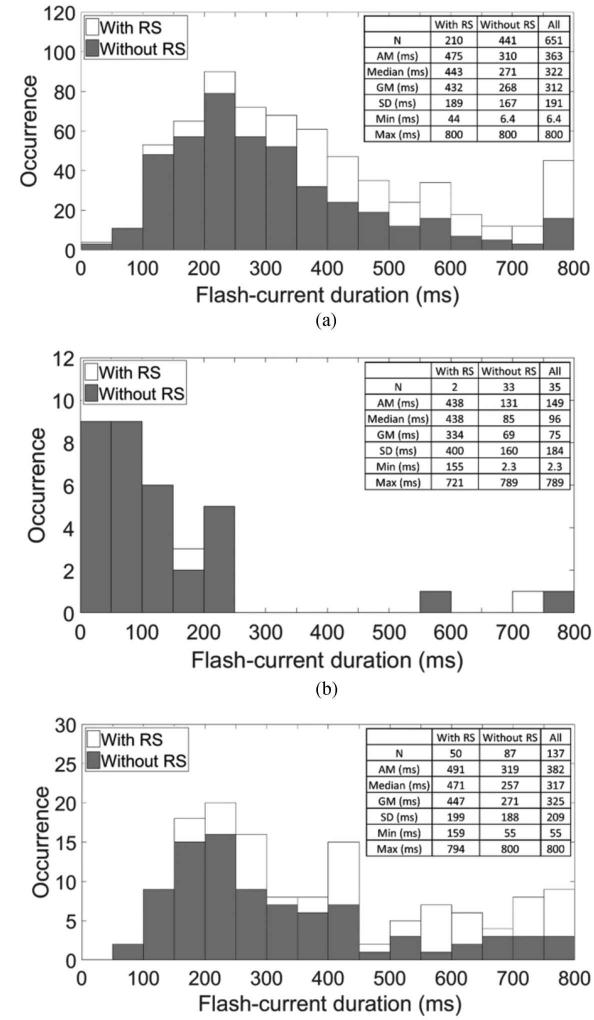
Fig. 5 shows the histogram of the peak currents during the IS of flashes. The peak IS-current is defined as the highest absolute value of either the slowly varying or the impulsive current component during the IS. The peak IS-current for 642 upward negative flashes ranged from 0.03 to 22 kA, with the median being 1.4 kA. For nine flashes, the ±40-kA channel was not available, the current records of the ±2-kA channel were saturated, and these flashes were not included in the histogram. The peak IS-current for the 33 upward positive flashes ranged from 0.04 to 39 kA, with the median being 3.2 kA. For two flashes, the current records of the ±40-kA channel were saturated, and these flashes were not included in the histogram. The median peak IS-current for the positive flashes was 2.3 times higher than that for the negative flashes. The IS-current



(a)

(b)

Fig. 3. Histograms of the (a) flash-current and (b) IS-current duration for upward flashes at the GBT color-coded by negative, positive, and bipolar flashes. Additionally given are the flash count (*N*) and the arithmetic mean (AM), median, geometric mean (GM), standard deviation (SD), minimum (Min), and maximum (Max) durations.



(a)

(b)

(c)

Fig. 4. Histograms of the flash-current duration for (a) upward negative, (b) upward positive, and (c) upward bipolar flashes at the GBT, color-coded by flashes with and without RSs. Additionally given are the flash count (*N*) and the arithmetic mean (AM), median, geometric mean (GM), standard deviation (SD), minimum (Min), and maximum (Max) durations.

durations and peak currents were essentially uncorrelated, with the coefficients of determination (R^2) being 0.14 and 0.01 for the negative and positive upward flashes, respectively.

B. Upward Bipolar Flashes

We expanded the traditional classification of bipolar flashes, introduced by Rakov [15], [28] and later used by others (e.g., Azadifar *et al.* [20]; Zhou *et al.* [21]), from three to five categories by adding one new category (Type 4) and splitting the Type 1 category into two sub-categories (Types 1S and 1M). Fig. 2 shows the definitions of these types of bipolar flashes along with a typical current waveform for each flash type. Type 1 bipolar flashes exhibit current-polarity reversal during the IS; Type 2 flashes have different polarities of current during the IS and RS; Type 3 flashes have RSs that are of different polarities; Type 4 flashes have different polarities of RS and the following continuing current. We categorized Type 1 flashes into Types 1S and 1M, depending on whether there were single or multiple polarity reversals of the IS-current, respectively. Of the 137 upward bipolar flashes in our dataset, 127 (93%) were of Type 1. Furthermore, 62 (48.8%) of the 127 Type 1 flashes were categorized as Type 1S and 65 (51.2%) of the 127 Type 1 flashes as Type 1M. Types 1S and 1M flashes comprised 45% and 47% of all the bipolar flashes, respectively. Of the 137 bipolar flashes,

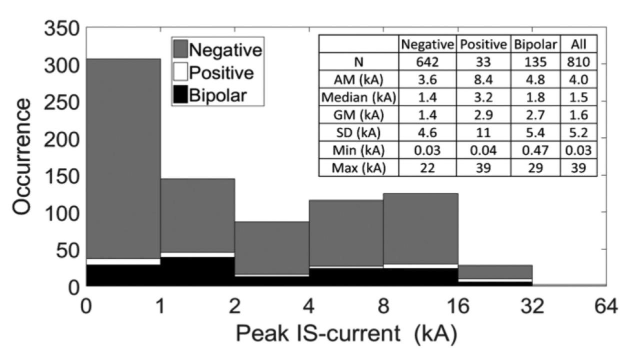


Fig. 5. Histograms of the absolute value of peak IS-current for 810 flashes color-coded by negative, positive, and bipolar flashes. For nine negative, two positive, and two bipolar flashes, the current records were saturated and these flashes were not included in the histogram. Additionally given are the flash count (*N*) and the arithmetic mean (AM), median, geometric mean (GM), standard deviation (SD), minimum (Min), and maximum (Max) peak IS-currents.

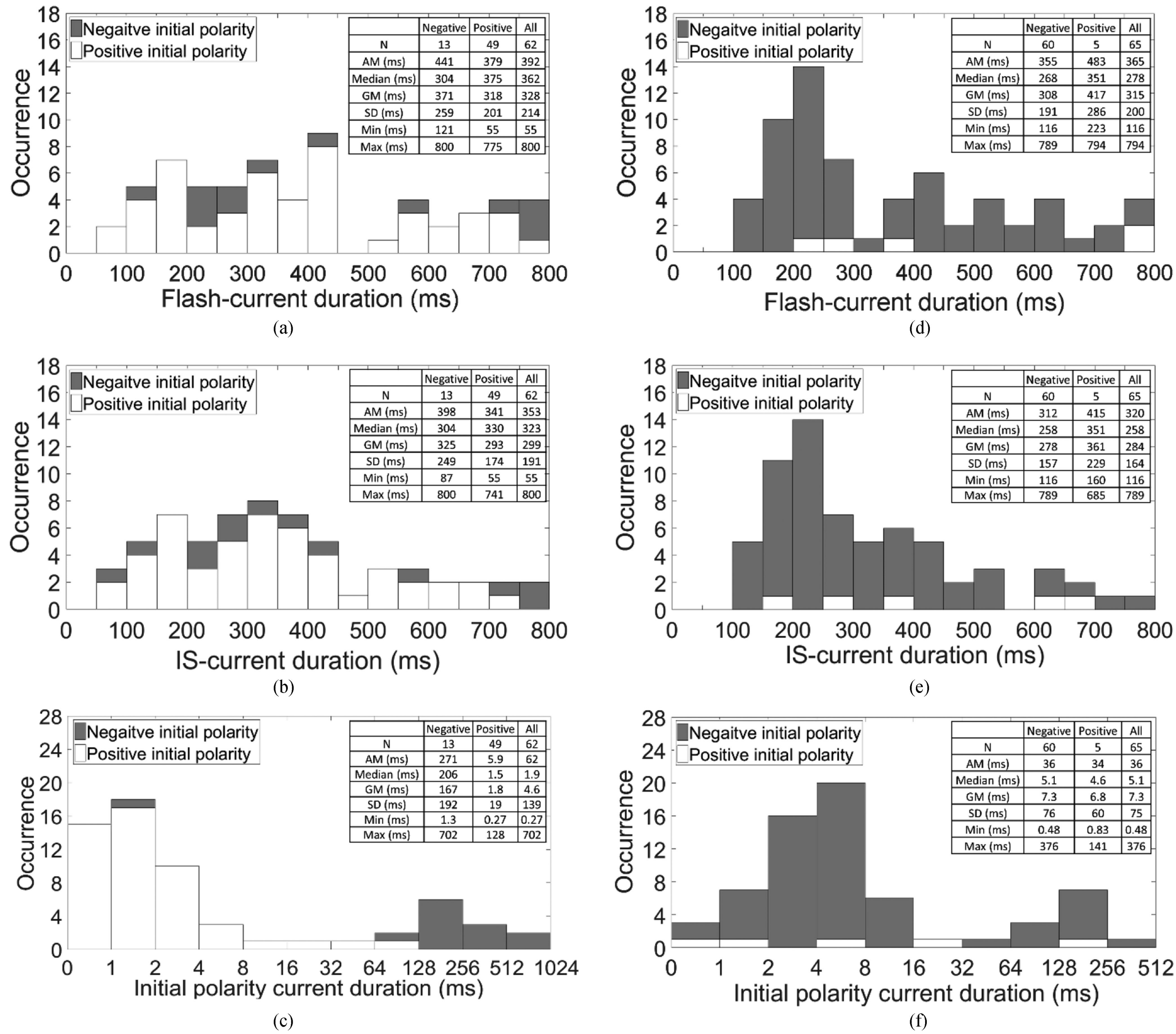


Fig. 6. Left panel shows histograms of the (a) flash-current, (b) IS-current, and (c) initial-polarity current durations for Type 1S flashes, color-coded in gray and white for negative and positive initial-polarity, respectively, of the IS-current. Right panel shows histograms of the (d) flash-current, (e) IS-current, and (f) initial-polarity current durations for Type 1M flashes, color-coded in gray and white for negative and positive initial-polarity, respectively, of the IS-current. Also shown are the flash count (*N*) and the arithmetic mean (AM), median, geometric mean (GM), standard deviation (SD), minimum (Min), and maximum (Max) durations.

7 (5.1%) were of Type 2, 2 (1.5%) of Type 3, and 1 (0.73%) of Type 4.

The flash-current durations for the upward bipolar flashes ranged from 55 to 800 ms, with the median duration being 317 ms, as shown in Fig. 3(a). The IS-current durations ranged from 13 to 800 ms, with the median duration being 282 ms, as shown in Fig. 3(b). In 50 (36%) of the 137 upward bipolar flashes, the IS was followed by one or more RSs. Fig. 4(c) shows the histograms of the flash-current durations for the upward bipolar flashes with and without RSs. The median durations were 471 and 257 ms, respectively. The median IS-current duration for bipolar flashes with RSs (not shown in Fig. 4) was 340 ms.

The peak IS-current for 135 upward bipolar flashes ranged from 0.47 to 29 kA, with the median being 1.8 kA, as seen in Fig. 5. For two flashes, the current records of the $\pm$40-kA channel were saturated, and these flashes were not included in the histogram. The IS-current durations and peak currents were essentially uncorrelated ($R^2 = 0.02$).

Next, we examine the characteristics of the currents for each type of upward bipolar flash.

1) Type 1 Bipolar Flashes: Of the 127 Type 1 bipolar flashes, the initial polarity of the IS current was negative in 73 (57%) flashes and positive in 54 (43%) flashes. Note that the polarity of the current in this study corresponds to the polarity of the charge transferred to ground. The histograms of the durations of flash-current, IS-current, and the initial-polarity of the IS-current for Types 1S and 1M flashes are shown in Fig. 6. The left [see Fig. 6(a), (b), and (c)] and right [see Fig. 6(d), (e), and (f)] panels

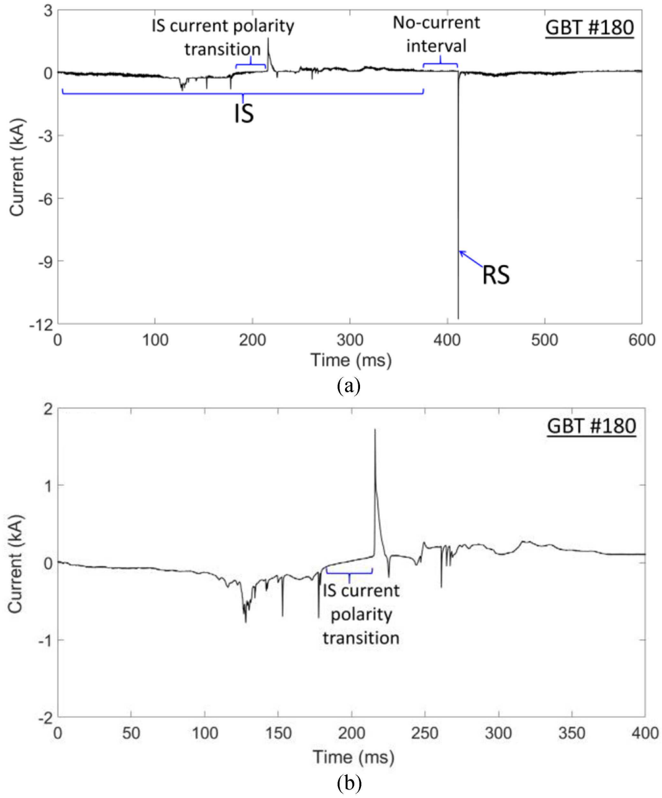


Fig. 7. (a) Current waveform measured using the ±40-kA channel of a Type 1S bipolar flash in which the IS current exhibited negative to positive polarity reversal followed by a no-current interval, and then one negative RS. This flash, therefore, exhibits polarity reversal between the IS current immediately preceding the no-current interval and the following RS, similar to Type 2 bipolar flashes. (b) The IS current of the flash measured using the ±2-kA channel is shown on a 400-ms timescale. The period over which the IS current transitions from negative to positive polarity is marked. The polarity of the current corresponds to the polarity of the charge transferred to ground.

show, respectively, these durations for Types 1S and 1M flashes. Note that, the horizontal axis in Fig. 6(c) and (f) is non-linear (logarithmic), while it is linear for all other parts of Fig. 6. The histogram bars are color-coded by the initial polarity (negative or positive) of the IS-current. For the majority (49 of 62 or 79%) of Type 1S flashes, the initial polarity of the IS-current was positive. On the other hand, the majority (60 of 65 or 92%) of Type 1M flashes had IS-current with negative initial polarity. The median durations of flash-current, IS-current, and initial-polarity current for Type 1S flashes with negative initial polarity were 304, 304, and 206 ms, respectively, while for Type 1S flashes with positive initial polarity they were 375, 330, and 1.5 ms, respectively. The median duration of the positive initial-polarity current in the IS was more than two orders of magnitude smaller than that of the negative initial-polarity current in Type 1S flashes. The duration of the positive initial-polarity current was less than 8 ms in 45 (92%) of 49 flashes, as can be seen from Fig. 6(c). In only 1 (7.7%) of 13 Type 1S flashes with negative initial polarity, the duration of the initial-polarity current was less than 8 ms. For Type 1M flashes with negative initial polarity, the median durations of flash-current, IS-current, and initial-polarity current were 268, 258, and 5.1 ms, respectively, while for Type 1M flashes with positive initial polarity they were 351, 351, and 4.6 ms, respectively.

In 18 (29%) of the 62 Type 1S flashes and 22 (34%) of the 65 Type 1M flashes, the IS was followed by one or more RSs. In three Type 1S flashes, the IS current exhibited negative to positive polarity reversal and was followed by a no-current interval and then by one or more negative RSs (see, for example, Fig. 7). Therefore, these three flashes also exhibited polarity reversal between the IS current immediately, preceding the no-current interval and the following RSs, similar to Type 2 bipolar flashes. Fifty four Type 1M flashes with negative initial polarity exhibited two polarity reversals (negative–positive–negative) of the IS current. Additionally, six flashes with negative initial polarity exhibited three or four polarity reversals. Finally, the five flashes with positive initial polarity exhibited three, four, or five polarity reversals.

The peak IS-current for 61 Type 1S flashes ranged from 0.58 to 20 kA, with the median being 1.6 kA. For one flash, the current record of the ±40-kA channel was saturated. The peak IS-current for the 65 Type 1M flashes ranged from 0.47 to 19 kA, with the median being 1.8 kA.

2) Type 2 Bipolar Flashes: Table I summarizes the characteristics of the seven Type 2 bipolar flashes in our dataset. An example of the current waveform of a Type 2 flash is shown in Fig. 2. The flash-current durations ranged from 174 to 786 ms, and the median was 270 ms. The IS-current durations ranged from 13 to 339 ms, with the median being 57 ms. The absolute value of the IS-peak currents ranged from 1.4 kA to just greater than 39 kA. Note that the 39-kA peak of the IS was slightly saturated in the ±40 kA channel. Five of the Type 2 flashes were composed of positive IS current, followed by two or more negative RSs. Two flashes had negative IS current, which, in one of these flashes, was followed by one positive RS. In the other flash (GBT #799), the negative IS current was followed by a no-current interval of 27 ms and then by a positive RS with peak current of +17 kA. After this, there was one negative M-component pulse (overlaid on the positive CC of the positive stroke) with a peak current of –11 kA. Finally, following the positive stroke and CC, nine negative RSs with peak currents ranging from –7.7 to –17 kA occurred in this flash. Therefore, in addition to exhibiting the polarity reversal between the IS current and the (immediately) following RS, this flash contained RSs of different polarities, as occurs in Type 3 bipolar flashes.

3) Type 3 Bipolar Flashes: There were two Type 3 bipolar flashes in our dataset, each with one negative RS followed by a positive one. One of the Type 3 flashes (GBT #312, see Type 3 current waveform in Fig. 2, occurring on July 6, 2002) was composed of a negative IS current followed by a negative and then a positive RS. The IS current lasted for 343 ms and had a peak (maximum value) of –0.8 kA. This was followed by a no-current interval of 16 ms. The negative and positive RSs had peak currents of –16 and 8.3 kA, respectively, and they were separated by a no-current interval of 17 ms. The positive stroke was followed by a positive CC that lasted for 168 ms. There were three M-component pulses with negative current-peaks superimposed on the positive CC. The flash-current duration was

TABLE I
SUMMARY OF THE CHARACTERISTICS OF THE SEVEN TYPE 2 BIPOLAR FLASHES THAT OCCURRED AT THE GBT IN THE YEARS 2000 TO 2018

Flash ID	**Flash description**[a]	**Flash-current duration (ms)**	**IS-current duration (ms)**	**Absolute peak IS-current (kA)**
GBT#192	Negative IS current followed by one positive RS	270	57	1.4
GBT#402	Positive IS current followed by eight negative RSs	293	33	15
GBT#646	Positive IS current followed by five negative RSs	237	108	23
GBT#652	Positive IS current followed by three negative RSs	174	55	39[b]
GBT#653	Positive IS current followed by two negative RSs	282	115	29
GBT#793	Positive IS current followed by two negative RSs	263	13	6.8
GBT#799	Negative IS current followed by one positive and nine negative RSs	786	339	4.0
Arithmetic Mean		329	103	17
Median		270	57	15
Geometric Mean		294	66	11
Standard Deviation		205	111	14
Minimum		174	13	1.4
Maximum		786	339	39

[a]The polarity of the current or RS in the flash description corresponds to the polarity of the charge transferred to ground.
[b]The 39-kA peak of the IS in GBT#652 was slightly saturated in the ±40 kA channel, but this is not expected to affect the peak current statistics in this table in any significant way.
An example of a Type 2 bipolar flash (GBT #652) is shown in Fig. 2.

568 ms. The second flash (Flash GBT #887, occurring on August 3, 2013, see Fig. 8) had negative IS current with a peak of 407 A and a duration of 360 ms, followed by a no-current interval of 7.8 ms. After that, a negative RS and then a positive RS with positive CC occurred. The negative- and positive-stroke peak currents were –1.6 and 3.4 kA, respectively, and they were separated by a no-current interval of 46 ms. The positive CC following the positive stroke had a peak of 2.2 kA and a duration of 301 ms with nine M-component pulses with negative current-peaks superimposed on the positive CC. The flash-current duration was 718 ms. Therefore, in addition to containing RSs of opposite polarity, these two Type 3 flashes each contained a RS and following M-components of opposite polarity (see Figs. 2 and 8).

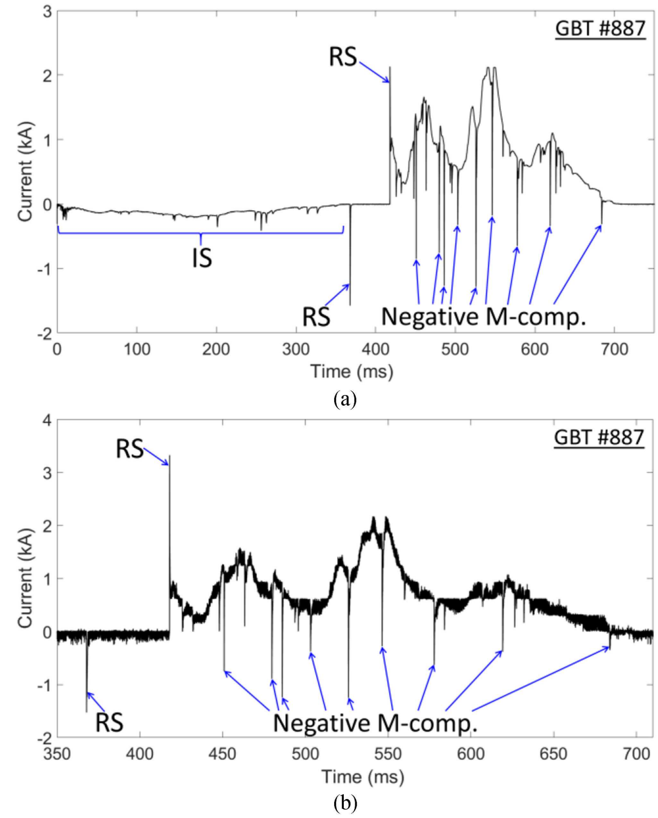


Fig. 8. (a) Current waveform measured using the ±2-kA channel of a Type 3 bipolar flash in which one negative RS was followed by a positive one. The positive CC following the positive stroke had nine M-component pulses with negative current-peaks superimposed on the positive continuing current. Note that this current record is saturated at times when the current magnitude exceeded 2 kA. (b) The post-IS portion of the flash measured using the ±40-kA channel is shown on a 360-ms timescale. The polarity of the current corresponds to the polarity of the charge transferred to ground.

4) Type 4 Bipolar Flashes: There was only one Type 4 bipolar flash in our dataset in which there was a negative RS that was followed by positive CC. In this flash, the negative IS current had a peak of 700 A and a duration of 489 ms. This was followed by a no-current interval of 12 ms, after which a negative RS having peak current of –3.4 kA occurred. The positive CC immediately following the RS had a peak of 5.3 kA, with its duration being 223 ms. The flash-current duration was 728 ms.

This flash (GBT #520, occurring on February 9, 2007; see Fig. 9) was previously reported by Zhou *et al.* [21], who left this flash in the "unassigned" category of bipolar lightning. To the best of our knowledge, no other flash of this type has been reported in recent studies. However, in our opinion, the altitude-triggered flash shown in [29, Fig. 4] (their flash 7813) was a Type 4 flash.

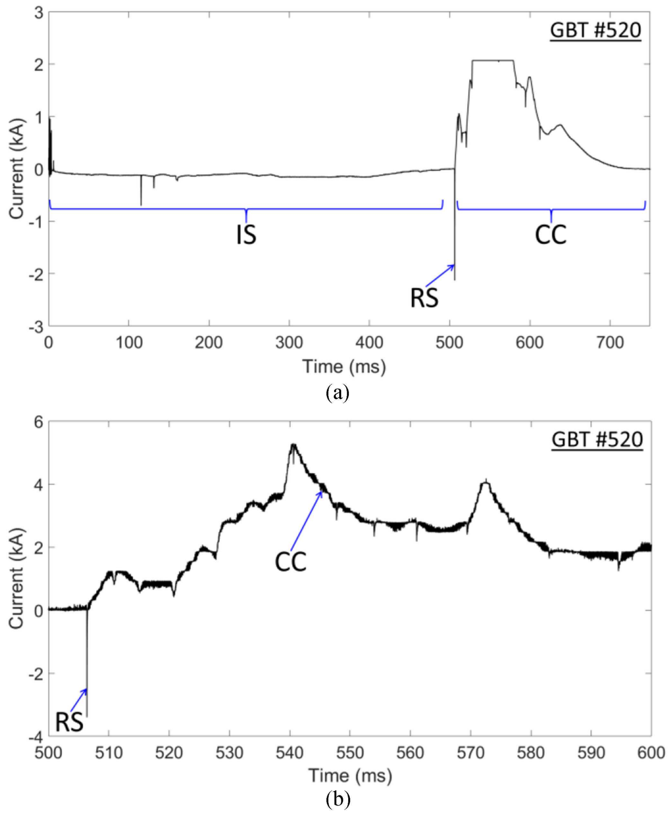


Fig. 9. (a) Current waveform measured using the ±2-kA channel of the Type 4 bipolar flash in which there was a negative RS that was followed by positive CC. Note that this current record is saturated at times when the current magnitude exceeded 2 kA. (b) The post-IS portion of the flash measured using the ±40-kA channel is shown on a 100-ms timescale. The polarity of the current corresponds to the polarity of the charge transferred to ground.

IV. Discussion

Table II summarizes the characteristics of the upward lightning observed in various parts of the world, along with the results obtained in this study. Of the 651 upward negative flashes in our dataset, in 210 (32%) flashes the IS was followed by one or more RSs. This percentage is comparable to but slightly larger than 24% and 26% reported from high-speed video camera observations by Saba *et al.* [18], for upward negative flashes initiated from a tower in Sao Paulo, Brazil and from towers in South Dakota, USA, respectively. Similarly, Yuan *et al.* [49], who analyzed electric field and high-speed video records of 19 upward negative flashes initiated from a meteorology tower in Beijing, China, reported that 32% of these flashes contained RSs. Gorin and Shkilev [33] reported that 27% of the negative flashes observed at the Ostankino TV tower, Moscow, Russia, contained RSs. As seen from Table II, the percentage of the upward negative flashes with RSs in various studies ranged from 11% to 50%. On the other hand, only two (5.7%) of the 35 upward positive flashes in our dataset had RSs. This is consistent with the previous reports in the scientific literature (e.g., Miki *et al.* [44]; Mazur and Ruhnke [50]), according to which positive upward flashes in which the IS is followed by RSs are very rare.

We found that for the upward positive flashes in our dataset, the median flash-current and IS-current durations were 3.4 and 2.9 times shorter, respectively, than those for the upward negative flashes. Also, as discussed above, a much smaller percentage of the positive flashes contained RSs. Therefore, in general, a typical upward positive flash was composed of a shorter duration IS-current, which was not followed by RSs, leading to a significantly shorter median flash-current duration. For the negative upward flashes, the median flash-current duration was 322 ms, which is comparable to but shorter than the median flash durations of 430 and 363 ms reported by Saba *et al.* [18] for the negative upward flashes observed in Sao Paulo and South Dakota, respectively. The median flash-current duration for the positive flashes in our dataset was 96 ms. This is comparable to the median durations of 72 ms reported by Berger [31] for the 138 positive flashes observed at the Monte San Salvatore, Switzerland, 80 ms reported by Romero *et al.* [47] for the 30 positive flashes observed at the Säntis Tower, Switzerland, and 82 ms reported by Zhou *et al.* [45] for the 26 positive flashes observed at the GBT from 2005 to 2009. Our median duration is about two times larger than the median duration of 40 ms reported by Miki *et al.* [44] for upward positive flashes initiated from the wind turbines at the Nikaho Kougen Wind Farm, Japan. The median IS-current duration for the negative flashes was 275 ms in this study, which is within the 195–336 ms range of the median or geometric mean durations reported in other studies (see Table II). For the positive flashes, our median IS-current duration of 96 ms was roughly three times larger than that reported by Heidler *et al.* [40].

Of the 823 upward flashes in our dataset for which we were able to examine the polarity of current, 79% were negative and 4.3% were positive. These percentages are similar to those reported by Miki *et al.* [44], who found that 76% and 6% of the 278 flashes observed at the Nikaho Kougen Wind Farm were negative and positive, respectively. Azadifar *et al.* [20] found that 356 (83%) of the 427 flashes at the Säntis Tower, Switzerland, were negative, which is similar to the percentage of the negative flashes in our dataset. However, 14% of their flashes were positive, which is more than three times larger than that in our dataset. As seen from Table II, the percentage of the upward negative and positive flashes reported in studies in different parts of the world ranged from 60% to 98% and 0% to 33%, respectively.

We found that 137 (17%) of the 823 upward flashes were bipolar. This is significantly larger than the bipolar flash occurrence of 3% reported by Zhou *et al.* [21] for the 652 flashes at the GBT from 2000 to 2009. This discrepancy is due to Zhou *et al.* [21] ignoring the ±2 kA current measurement channel and using the ±40-kA channel to determine current polarity. In this study, we used the ±2-kA channel to determine current polarity for all the flashes except 58 flashes for which this measurement channel was not available. The resolution of the vertical (current) axis is 20 times better for this channel than for the ±40-kA channel, and so we expect the bipolar flash occurrence of 17% reported in this study to be more accurate. Note that, if the ±2-kA channel is used to determine the current polarity for the 652 flashes in the dataset of Zhou *et al.* [21], 106 (16%) flashes can be classified as bipolar. Thus, the detectability of the bipolar flashes in current records depends on the vertical (amplitude) resolution of these records.

TABLE II
SUMMARY OF UPWARD LIGHTNING CHARACTERISTICS REPORTED IN STUDIES PERFORMED IN DIFFERENT PARTS OF THE WORLD

Study	Country	Object of initiation	Observation period	Total number of flashes	Number (percentage) of negative	Number (percentage) of positive flashes	Number (percentage) of bipolar flashes	Percentage of negative flashes with return strokes	Median/GM IS-current duration (ms)	Median/GM flash-current duration (ms)
Hagenguth and Anderson (1952) [30]	USA	Empire State Building	1935 – 1949	80	69 (86%)	0 (0%)	11 (14%)	50%	-	270 (median for UNF)
Berger (1978) [31]	Switzerland	Mount San Salvatore	1963 – 1973	1057	851 (81%)	138 (13%)	68 (6.4%)	20-25%	-	338 (median for 212 UNF with RS) 163 (median for 639 UNF without RS) 72 (median for UPF)
Nakahori et al. (1982) [32]	Japan	Fukui Chimney	1980 – 1981	21	15 (71%)	2 (9.5%)	4 (19%)	-	-	-
Gorin and Shkilev (1984) [33]	Russia	Ostankino Tower	2 years between 1968 and 1984	90	75 (83%)	9 (10%)	6 (6.7%)	27%	-	
Narita et al. (1989) [34]	Japan	Tower in Maki	1982 – 1987	40[a]	24 (60%)	7 (16%)	9 (20%)	-	-	-
Miyake et al. (1992) [35]	Japan	Kashiwazaki weather observation tower and Fukui Chimney	1978 – 1986	125	78 (62%)	41 (33%)	6 (4.8%)	-	-	-
Goto and Narita (1995) [36]	Japan	Maki meteorological tower	1982 – 1993	145	91 (63%)	25 (17%)	29 (20%)		-	-
Wada et al. (1996 a, b) [37, 38]	Japan	Fukui Chimney	1989 – 1994	45	36 (80%)	4 (8.9%)	5 (11%)	-	-	-
Nagai et al. (1996) [39]	Japan	Genden Tsuruga transmission line tower	1986 – 1992	24	15 (63%)	1 (4.2%)	8 (33%)	-	-	-
Heidler et al. (2000) [40]	Germany	Peissenberg Tower	1992 – 1998	145	109 (75%)	6 (4.1%)	2 (1.4%)	25%	307 (GM for UNF) About 30 (GM for UPF)	-
Miki et al. (2004) [41]	Japan	Fukui Chimney	1989 – 2002	213	148 (76%)	18 (8.5%)	43 (22%)	-	-	-
Wang and Takagi (2008) [42]	Japan	Windmill and lightning protection tower	2005 – 2007	11	-	-	3 (27%)	-	-	-
Hussein (2009) [43]	Canada	Canadian National Tower	1992 – 2001	160	156 (98%)	2 (1.3%)	2 (1.3%)	-	-	140-150 (median for UNF) 50 and 640 (for two UBF)
Miki et al. (2010) [44]	Japan	Wind turbines	2005 – 2008	278	212 (76%)	16 (6.0%)	50 (18%)	27%	-	167 (median for 135 UNF) 40 (median for 16 UPF) 194 (median for 40 UBF)
Zhou et al. (2011), Zhou et al. (2012) [21, 44]	Austria	Gaisberg Tower	2000 – 2009	651	604 (93%)	26 (4.0%)	21 (3.2%)	-	-	82 (median for UPF) 320 (GM for UBF)
Ishii et al. (2013), NEDO report (2015), Saito and Ishii (2018a, b) [46, 2, 3, 4]	Japan	Wind turbines	2008 – 2013	674	464 (69%)	92 (14%)	118 (17%)	11%	-	-
Romero et al (2013), Azadifar et al. (2016) [47, 20]	Switzerland	Santis Tower	2010 – 2015	427	356 (83%)	58 (14%)	13 (3.0%)	-	-	80 (median for 30 UPF)
Saba et al. (2016) [18][b]	Brazil	Towers in Sao Paulo	2011 – 2014	72	72	-	-	24%	336 (median for UNF)	430 (median for UNF)
Saba et al. (2016) [18][b]	USA	Towers in Rapid City	2011 – 2014	28	28	-	-	26%	195 (median for UNF)	363 (median for UNF)
Miki et al. (2017) [48]	Japan	Tokyo Sky Tree	2012 – 2016	35[c]	27 (77%)	1 (2.9%)	7 (20%)	44%	-	259 (GM for UNF)
Yuan et al (2017) [49][d]	China	Meteorology Tower	2012 – 2016	19	19	-	-	32%	316 (median for UNF)	383 (median for UNF)
This study	Austria	Gaisberg Tower	2000 – 2018	823	651 (79%)	35 (4.3%)	137 (17%)	32%	275 (median for UNF) 96 (median for UPF) 282 (median for UBF)	322 (median for UNF) 96 (median for UPF) 317 (median for UBF)

[a] Of 45 flashes, 40 were classified as upward flashes and five flashes were of unknown type.
[b] Flash polarity and durations were determined using high-speed video camera records and lightning locating system data.
[c] 37 upward flashes were observed, and currents were measured for 35 flashes.
[d] Flash polarity was likely determined using electric field records, and durations were measured using high-speed video camera records.
The median or geometric mean (GM) values of the IS-Current and flash-current durations are provided when available. UNF = upward negative flash, UPF = upward positive flash, UBF = upward bipolar flash, and RS = return stroke.

The occurrence of upward bipolar flashes reported in studies in different parts of the world ranges from 1.3% to 33%, as seen from Table II. Miki *et al.* [44] reported that 18% of the 278 flashes observed at Nikaho Kougen Wind Farm were bipolar. According to Miki *et al.* [41], of the 213 flashes at the Fukui Chimney, Japan, 43 (20%) were bipolar. In the NEDO project (Ishii *et al.* [46]; NEDO report [2]; Saito and Ishii [3]; Saito and Ishii [4]), 17% of the 674 upward flashes were bipolar. Berger *et al.* [31] reported that 72 (6%) of the 1196 flashes observed at the Mount San Salvatone were bipolar flashes. Azadifar *et al.* [20], who used a ±120-kA full-scale Rogowski-coil current measurement system with 12-bit resolution (see Romero *et al.* [47]), found that 13 (3%) of the 427 flashes at the Säntis Tower were bipolar. Interestingly, the current measurement system at the Säntis Tower was triggered using *dI/dt* (time derivative of current) versus current at the GBT, which could perhaps result in not

TABLE III
SUMMARY OF THE OCCURRENCE OF BIPOLAR FLASHES REPORTED IN ROCKET-TRIGGERED LIGHTNING STUDIES

Study	Country	Observation period	Number total flashes	Number of bipolar flashes
Hubert and Mouget (1981) [29]	France	1978	2	1
Akiyama et al. (1985) [51]	Japan	1977 – 1982	45	2
Mata (2000) [52]	USA	1999	-	1
Jerauld et al. (2004), Jerauld et al. (2005) [53, 54]	USA	2001 – 2003	37	1
Yoshida et al. (2012), Hill et al. (2013) [55, 56]	USA	2008 – 2012	77	2

recording flashes that comprise of an IS with slowly varying CC only and no transients (ICC pulses with relatively high values of *dI/dt*). In Table III, we list the rocket-triggered lightning studies in which bipolar flashes were reported. Hubert and Mouget [29] and Akiyama *et al.* [51] reported one bipolar flash in France and two bipolar flashes in Japan, respectively. For rocket-triggered lightning at Camp Blanding, FL, USA, four bipolar flashes have been reported over the period from 1999 to 2012 (Mata [52, Fig. 6.8]; Jerauld *et al.* [53]; Yoshida *et al.* [55]; Hill *et al.* [56]).

The vast majority (92.7%) of our bipolar flashes were of Type 1, with only 5.1%, 1.5%, and 0.72% being of Types 2, 3, and 4, respectively. Azadifar *et al.* [20] reported that 10 of their 13 (77%) bipolar flashes were of Type 1, 2 were of Type 2, and 1 was of Type 3. The majority (79%) of our Type 1S flashes had positive initial polarity; that is, they were initiated by upward negative leaders transporting positive charge to ground. On the other hand, the majority (92%) of Type 1M flashes had negative initial polarity, which means that they were initiated by upward positive leaders transporting negative charge to ground. Overall, 73 (57%) of the 127 Type 1 flashes had negative initial polarity (negative charge transferred to ground). Previous observations (e.g., Berger [31]; Gorin and Shkilev [33]) also suggest that negative initial polarity is more common in upward bipolar flashes.

The median duration of the positive initial-polarity current in Type 1S flashes (which were the majority) was 1.5 ms. In such flashes, assuming an average vertical velocity of 1×10^5 m/s of the negative upward leader (see [14, Ch. 6.2]) at the time of current-polarity reversal, the upper end of the upward leader is expected to be at a distance of 150 m from the top of the tower. This could indicate that Type 1S flashes with positive initial polarity were probably initiated in response to a relatively low-altitude lower positive charge region. Once the charge in this region was neutralized by the upward negative leader and the leader channel extended to a negative charge region just above or adjacent to this lower positive charge region, the current polarity measured at the tower changed. On the other hand, the median duration of the negative initial-polarity current in Type 1S flashes was 206 ms. The upward positive leaders in such flashes were probably initiated in response to the main negative charge region or to in-cloud lightning activity in this region. In either case, the upward positive leader would extend vertically over a few kilometers to bridge the gap between the tower-top and the charge region or the in-cloud channel. The main negative charge region is expected to have a relatively large spatial extent in a typical thundercloud, and this is consistent with the relatively long median duration of the negative initial-polarity current observed by us. When the negative charge in the vicinity of the positive leader is neutralized and this leader connects with an in-cloud leader in a positive charge region just above or adjacent to the negative charge region, the polarity of the measured current would change. Interestingly, most upward flashes initiated in response to in-cloud or cloud-to-ground lightning in the vicinity of a tall object are negative (initiated by upward positive leaders) (e.g., Saba *et al.* [18]).

Azadifar *et al.* [20] classified Type 1 (they use the term Category I) bipolar flashes into two sub-types, which they referred to as Category Ia and Category Ib. The flashes in which the IS-current polarity reversal was presumably associated with in-cloud processes were assigned to Category Ia, and the flashes in which it occurred because of the sequential initiation of two opposite-polarity leaders from the tower were assigned to Category Ib (see [20, Fig. 10]). The key to identifying a Category 1b flash using only its current waveform, it seems, was identifying stepping in current (presumably associated with a negative upward leader) and slowly changing current with ICC pulses (presumably associated with an upward positive leader and ICC) separated by an "inactive interval" at the time of polarity reversal of IS current. Of the 10 Category I bipolar flashes in Azadifar *et al.* [20], two were in Category Ib. So, some Type 1 bipolar flashes can perhaps be viewed as upward lightning in which two (or more) leaders sequentially extend from the tower-top into the nearby cloud charge regions of opposite polarity. The current measurement at the tower-top, in such a case, is effectively a sequential superposition of the currents from an upward positive flash and an upward negative flash. In addition to current measurements, high-speed video camera records of bipolar flashes initiated from towers are needed to confirm whether such flashes are indeed associated with two opposite-polarity leaders sequentially developing from towers, as speculated by Azadifar *et al.* [20].

The exact reasons for multiple current-polarity reversals during the IS of upward flashes remain unknown. One reason for their occurrence could be a more complicated "lumpy" cloud charge structure (e.g., Imyanitov *et al.* [57]; Rakov [15]) with pockets of negative and positive charge formed in the vicinity of each other at any given height inside the cloud. A leader extending upward and producing extensive predominantly horizontal branching could successively encounter charge pockets of opposite polarity, resulting in multiple reversals in the polarity of the measured current. Such extensive quasi-horizontal branching in bipolar flashes has been observed by Narita *et al.* [34] and Yoshida *et al.* [55], using interferometry, and by Hill *et al.* [56] using a time-of-arrival lightning mapping array (LMA). It remains to be seen if at least some of our Type 1M flashes occurred because of the speculative scenario described above; more current measurements of bipolar flashes in conjunction with LMA and/or interferometer observations are needed to examine this.

Finally, we did not find clear dependence of the characteristics of Types 1S and 1M flashes on the season, apart from the fact that a larger percentage (74% and 69%, respectively) of them occur during the seven months of the non-convective season, which is consistent with the occurrence of the bipolar (70%) and all upward (66%) flashes in our dataset during this season. The detailed observations of the cloud charge structure associated with bipolar flashes are required to better understand the conditions conducive to their occurrence.

V. Summary

In this study, we examined the current waveforms of upward flashes initiated from the GBT in the years 2000 to 2018. Of the 823 upward flashes for which current waveforms were analyzed, 651 (79%) were negative, 35 (4.3%) positive, and 137 (17%) bipolar. The majority (66%) of the upward flashes occurred during the non-convective season (September–March) in Austria. In 210 (32%) of the 651 upward negative flashes in our dataset, the IS was followed by one or more RSs. The median flash-current durations in upward negative, positive, and bipolar flashes were 322, 96, and 317 ms, respectively. The median IS-current durations for these flashes were 275, 96, and 282 ms, respectively. We found that for the upward positive flashes in our dataset, the median flash-current and IS-current durations were 3.4 and 2.9 times shorter, respectively, than those for the upward negative flashes. Of the 35 positive flashes, 2 (5.7%) contained RSs. The median IS-current peaks in the upward negative, positive, and bipolar flashes were 1.4, 3.2, and 1.8 kA, respectively. We expanded the traditional classification of bipolar flashes to include five categories by adding one new category (Type 4) and splitting the Type 1 category into two sub-categories (Types 1S and 1M). Of the 137 bipolar flashes, 62 (45%) were of Type 1S, 65 (47%) of Type 1M, 7 (5.1%) of Type 2, 2 (1.5%) of Type 3, and 1 (0.73%) of Type 4.

On the basis of the duration of the initial polarity of the IS-current, we speculate that Type 1S flashes with positive initial polarity were probably initiated in response to a relatively low-altitude lower positive charge region. Once the charge in this region was neutralized by the upward negative leader and the leader channel extended to a negative charge region just above or adjacent to this lower positive charge region, the current polarity measured at the tower changed. On the other hand, Type 1S flashes with negative initial polarity were probably initiated in response to the main negative charge region or to in-cloud lightning activity in this region. In either case, the upward positive leader would extend vertically over a few kilometers to bridge the gap between the tower-top and the charge region or the in-cloud channel. When the negative charge in the vicinity of the positive leader is neutralized and this leader connects with an in-cloud leader in a positive charge region just above or adjacent to the negative charge region, the polarity of the measured current would change. The exact reasons for multiple current-polarity reversals during the IS of Type 1M flashes remain unknown. One reason for their occurrence could be a more complicated "lumpy" cloud charge structure with pockets of negative and positive charge formed in the vicinity of each other at any given height inside the cloud. A leader extending upward and producing extensive predominantly horizontal branching could successively encounter charge pockets of opposite polarity, resulting in multiple reversals in the polarity of the measured current. More current measurements of bipolar flashes in conjunction with LMA and/or interferometer observations are needed to examine this speculative scenario.

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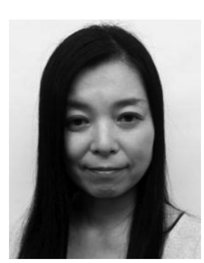

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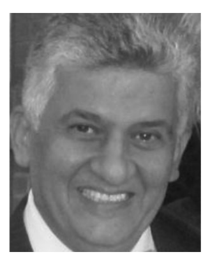

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