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Unusual electric field waveforms produced by negative lightning strokes terminated on a 257-m tower

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***Abstract*— Simultaneous electric field and high-speed video camera records of two flashes, labeled 1593 and 1594, were obtained at the Lightning Observatory in Gainesville (LOG), Florida, in the summer of 2014. Flash 1593 was an upward negative flash whose upward positive leader initiated from a 257-m high tower and propagated upward with an average frame-to-frame speed of 2.8×10^{5} m/s. Flash 1593 contained six downward leader/return stroke sequences, all terminated on the tower. This flash followed and possibly was initiated by a nearby intracloud discharge. Flash 1594 was a downward bipolar flash that occurred 8 minutes after flash 1593. The first stroke of flash 1594 was positive and terminated on a 60-m tower. It was followed by two negative strokes that terminated on the same 257-m tower as the six strokes of flash 1593. The peak current reported by the NLDN for the eight negative strokes in the two flashes ranged from 5.7 to 20.7 kA, with an average of 8.8 kA. Out of the eight negative strokes, six were misclassified by the NLDN as cloud pulses. All the eight negative strokes that terminated on the 257-m tower exhibited very similar damped oscillatory electric field waveforms. Characteristics of those electric field waveforms are compared to similar observations found in the literature.**

Keywords—electric field; tower; bipolar event;

I. Introduction

Bipolar electric field waveforms were observed by Ishii and Saito (2009) for 21 negative "ground-to-cloud discharges" associated with transmission-line faults during winter storms in Japan. Those field waveforms were very different from those produced by "normal" lightning. Wu et al. (2014), using a low-frequency lightning location network, observed 374 "large bipolar events (LBEs)", also in winter storms in Japan. They speculated that LBEs occurred when the negative charge layer in the cloud was very close to the top of a tall grounded object. Additionally, Ishii et al. (2013) , Ishii et al. (2014), and Saito et al. (2015) reported unusually narrow electric field waveforms produced by upward lightning strike to the 634-m high Tokyo Skytree in Japan in summer, while the causative current waveform measured at the tower was similar to that of a normal negative return stroke (relatively fast rise to peak and relatively slow decay). The electric field signatures of "ground-to-cloud" discharges and of the Tokyo Skytree strokes are probably similar to LBEs. Chen et al., (2015) simulated far-field waveforms characteristic of LBEs by using the bouncing-wave model and found the simulated electric field waveforms to be similar to those observed by Wu et al. (2014), but only when the injected current waveform was a symmetric Gaussian pulse.

In this paper, we will present two lightning flashes containing a total of eight negative strokes that terminated on a 257-m tower and produced unusually narrow, damped oscillatory electric field waveforms. Simultaneous high-speed video camera records were also obtained for these two flashes. The observed electric field waveforms exhibit some similarities to LBE-type events found in the literature. The 257-m tower in the field of view of the camera was obscured by trees, but the azimuth of the 8 strokes and NLDN data clearly indicate that their termination points were on the tower.

II. Instrumentation

Two flashes were recorded at the Lightning Observatory in Gainesville (LOG), Florida, by electric field measuring systems and Megaspeed HHC-X2 high-speed video camera in the summer of 2014. The electric field measuring systems include the low-gain and high-gain electric field measuring systems and the electric field derivative (dE/dt) measuring system. The low-gain electric field measuring system includes a circular flat-plate antenna followed by an amplifier with an RC time constant of 10 ms. The high-gain electric field measuring system includes an elevated-plate antenna followed by a different amplifier having a higher gain and an RC time constant of 420 µs, which allows us to accentuate relatively small field pulses. The bandwidths are 16 Hz to 10 MHz and 360 Hz to 10 MHz for the low-gain and high-gain electric field measuring systems, respectively. The upper frequency response of the dE/dt measuring system is 10 MHz. The record length for the field measuring systems was 1 s with 200 ms pretrigger time. The Megaspeed HHC-X2 camera, equipped with a fish-eye lens to provide a wider field of view (about 185º), was operated as 1000 frames per second (fps) with 1 ms exposure time and resolution of 832×600 pixels. The record length of the camera was 1.2 s with 200 ms pretrigger. The electric field records and high-speed video records were GPS time stamped. More detailed information on LOG can be found in the works of Rakov et al. (2014) and Tran and Rakov (2015).

III. Observations and Analysis

A. *General Description of Two Flashes terminated on the 257-m Tower in Gainesville, Florida*

Flash 1593 was recorded at 12:10:58 UT (at 08:10:58 local time) on July 16th, 2014. It was an upward negative flash whose upward positive leader initiated from a 257-m high tower (located 8.8 km from LOG) and contained 6 negative strokes, all terminated on the 257-m tower. This flash followed and possibly was initiated by a nearby intracloud discharge. Flash 1594 was a downward bipolar flash that occurred 8 minutes after flash 1593. Natural downward bipolar flashes are rare with only several observations being found in the literature (Fleenor et al., 2009; Jerauld et al., 2009; Saba et al., 2013; Saraiva et al., 2014; Chen et al., 2015b; Xue et al., 2015). During the 8 minutes interval between flashes 1593 and 1594, only one cloud discharge was reported by the NLDN within 40 km of LOG, which indicates that the thunderstorm was dissipating during that time period. The first stroke of flash 1594 was positive and terminated on a 60 m tower (3.6 km from the 257-m tower). It was followed by two negative strokes that terminated on the same 257-m tower as the 6 strokes of flash 1593. The peak current reported by the NLDN for the 8 negative strokes in flashes 1593 and 1594 ranged from 5.7 to 20.7 kA, with a mean of 8.8 kA. For the positive stroke in flash 1594, the NLDN-reported peak current was 193 kA. Out of the 8 negative strokes, 6 were misclassified by the NLDN as cloud discharges. All the 8 negative strokes terminating on the 257-m tower exhibited very similar electric field waveforms, characterized by a narrow pulse followed by a damped oscillatory tail.

B. *NLDN Responses to the 257-m and 60-m Tower Strokes*

The NLDN information for the two flashes is summarized in Table 1 and Table 2. The 8 negative strokes had peak currents ranging from 5.7 to 20.7 kA with a mean of 8.8 kA. Out of 8 negative strokes, 6 were misclassified as cloud discharges by the NLDN. The peak currents for the 2 correctly classified events were 20.7 and 6.6 kA. Warner et al. (2012) reported that the NLDN misclassified 30% (46/151) of "subsequent events" (leader/return stroke sequences and ICC pulses) in upward flashes initiated from towers as cloud discharges. The peak-to-zero times and pulse durations of electric field pulses produced by misclassified events were smaller than those for correctly-classified events. The NLDN-reported locations for the 8 negative strokes and the actual tower location are shown in Figure 1. The distances between NLDN-reported locations and the tower location range from 40 m to 140 m, all being less than 200 m, the median error (assumed to be equal to the semi-major axis length of the location error ellipse) reported by the NLDN for each located event.

For the first, positive stroke of the bipolar flash 1594, the NLDN-reported peak current is 192.9 kA and the distance between the NLDN-reported location and the 60-m tower is 30 m. This stroke is not further discussed in this paper.

Table 1 NLDN data on 8 negative strokes in flashes 1593 and 1594, all terminating on the 257-m tower.

Flash Type	**Stroke ID**	**Peak Current (kA)**	**Preceding Interstroke Interval (ms)**	**NLDN Classification (C for cloud events and G for cloud-to-ground events)**	**Semi-Major Axis Length (m)**	**Semi-Minor Axis Length (m)**	**Number of Reporting Sensors**	**Distance between the NLDN Location and the 257-m Tower (m)**
Upward Negative Flash	1593-1	7.6	-	C	200	200	4	110
	1593-2	5.7	18	C	200	200	5	50
	1593-3	20.7	64	G	200	200	5	40
	1593-4	6.5	56	C	200	200	4	80
	1593-5	6.6	18	G	200	200	4	60
	1593-6	6.7	14	C	200	200	5	90
Downward Bipolar Flash*	1594-2	6.5	148	C	200	200	5	70
	1594-3	10.2	20	C	200	200	5	140
	Mean	**8.8**	**42**	**-**	**200**	**200**	**5**	**80**

* The information on the first, positive stroke of this bipolar flash is given in Table 2.

Table 2 NLDN data on the first, positive stroke of bipolar flash 1594, which terminated on the 60-m tower, located 3.6 km from the 257-m tower.

Flash Type	Stroke ID	Peak Current (kA)	Preceding Interstroke Interval (ms)	NLDN Classification (C for cloud events and G for cloud-to-ground events)	Semi-Major Axis Length (m)	Semi-Minor Axis Length (m)	Number of Reporting Sensors	Distance between the NLDN Location and the 60-m Tower (m)
Downward Bipolar Flash*	1594-1	192.9	-	G	100	100	20	30

* The information on the second and third stroke of this bipolar flash is given in Table 1.

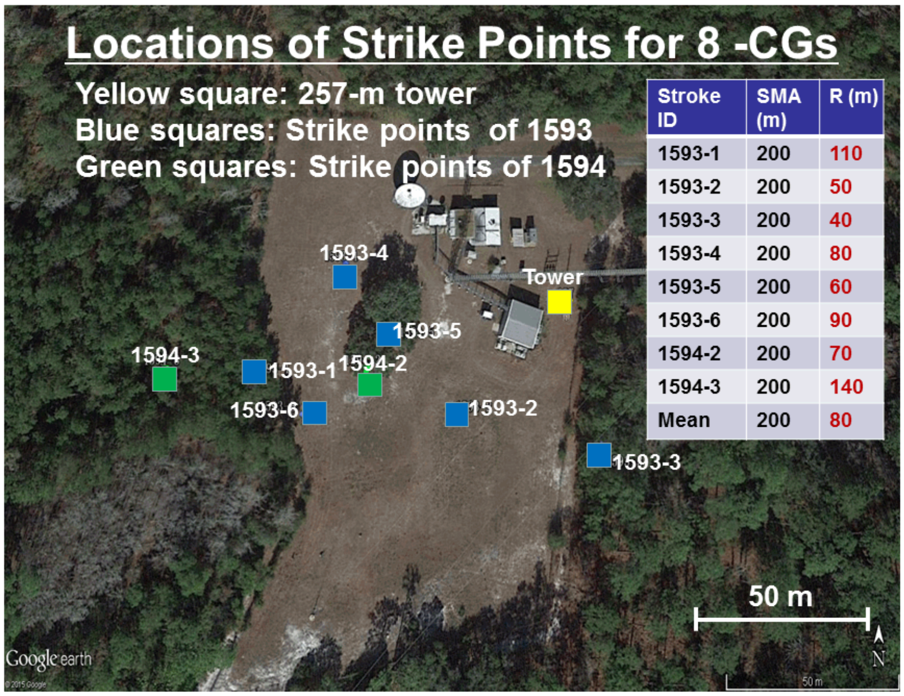

Figure 1 Locations of strike points reported by the NLDN for 8 negative strokes terminating on the 257-m tower. Blue squares are strike-points of flash 1593 and green squares are strike points of flash 1594. The yellow square is the location of the tower. SMA stands for the semi-major axis length and R stands for the distance from the NLDN-reported location to the tower (yellow square). Note that the yellow square, whose position is determined by the geographical coordinates (available from: http://www.cellreception.com/towers/details.php?id=1029807), is about 25 m from the location of the tower base seen in the Google Earth map. The reason for this offset is unknow.

C. High-Speed Camera and Electric Field Data

1) Upward Positive Leader of Flash 1593 Initiated from the 257-m Tower

The upward positive leader was initiated 3 ms after a predominantly horizontal intracloud discharge that appeared to develop toward the tower. The NLDN reported a cloud pulse of -4.6 kA corresponding to this intracloud discharge and preceding the first return stroke by 203 ms. The polarity of the upward leader was determined to be positive (positive charge moving up) from the corresponding electric field change. Five consecutive frames that clearly show the development of the upward leader were selected to calculate its speed (see Figure 2, 5 bottom panels). The frame-to-frame speeds are 3.9×105 m/s, 3.4×105 m/s, 2.4×105 m/s, and 1.4×105 m/s with an arithmetic mean of 2.8×105 m/s. The leader extended to about 1.9 km above the inferred position of the tower top and then became invisible, possibly because it became too faint to be imaged. From top panel in Figure 2, the end of the intracloud discharge was approximately above the tower from which the upward leader was initiated. It is likely that the upward leader was triggered by the electric field change produced by the transportation of significant amount of negative charge toward the tower by the preceding intracloud discharge.

2) Eight Negative Leader/Return Stroke Sequences of Flashes 1593 and 1594

Frames showing the channels of the eight negative strokes from the two flashes and the corresponding electric field waveforms are shown in Figure 3 and Figure 4, respectively. From the high-speed video camera data, the time interval between the initiation of upward leader and the first return stroke in flash 1593 was 184 ms. It is interesting that the shapes of channels for individual strokes in flash 1593 were different from each other, and the channel length progressively increased with increasing stroke order. However, the corresponding electric field waveforms (Figure 4) were very similar to each other. Except for 1593-R4 having a relatively slow rising field wavefront (including a shoulder), all the eight strokes had very fast rise and fall times (<2 μs) of the field initial half-cycles. The waveforms of all eight strokes show damped oscillatory tails, which might be caused by the transient response of the tower. The waveform parameters of the seven negative strokes are defined in Figure 5, in the same manner as in Wu et al., (2014), and summarized in Table 3 (1593-R3 is excluded due to saturation). Table 4 compares field waveform parameters obtained in the present study with parameters of somewhat similar bipolar field waveforms found in the literature (Ishii and Saito, 2009; Wu et al., 2014). Events in the other two studies occurred in winter in Japan, while events in our study were recorded in summer in Florida. The NLDN-reported peak currents and LOG electric field pulse widths for our events are considerably smaller than those reported for the bipolar events from other studies. Also, the ratio of the first (positive) and the second (negative) field half-cycles for our events is larger than that for so-called large bipolar events (LBEs) studied by Wu et al., (2014).

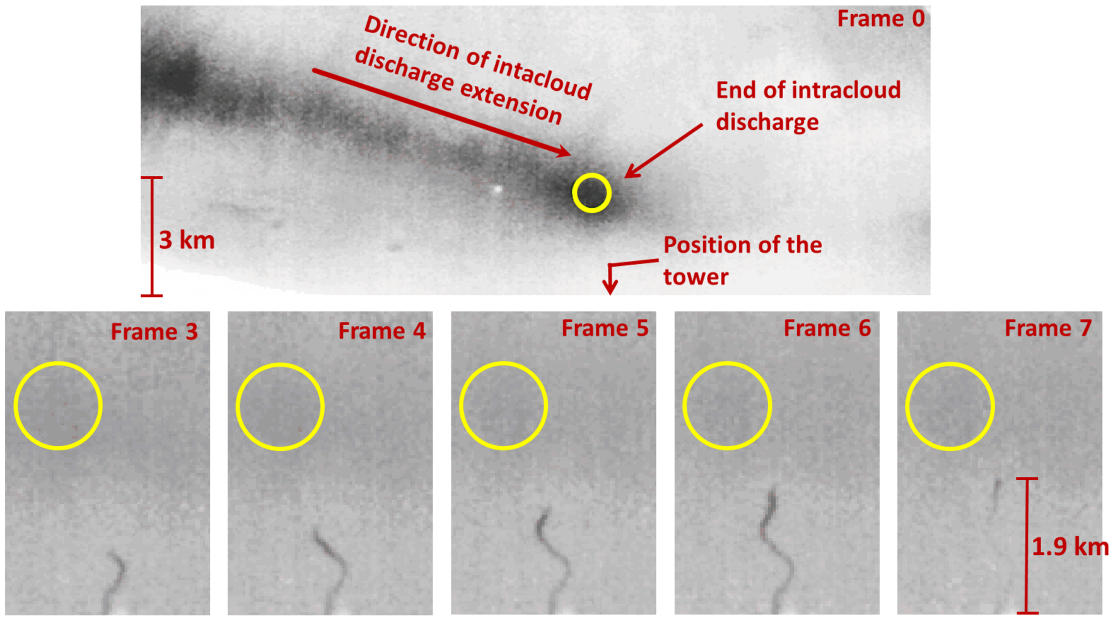

Figure 2 Top panel shows the intracloud discharge and bottom five panels show the upward positive leader initiated from the tower. The apparent end of intracloud activity is marked by a yellow circle in all the panels. Time interval between bottom five consecutive frames was 1 ms. Frames 1 and 2 are not shown because no clear upward leader can be seen in those frames.

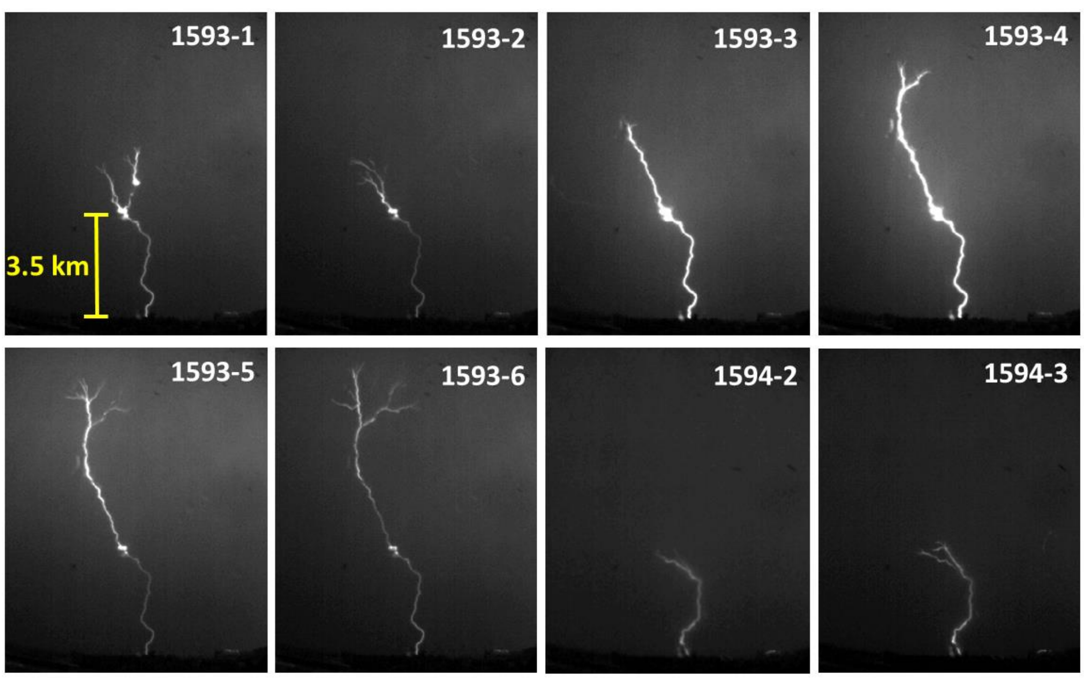

Figure 3 Frames showing the channels of eight negative strokes terminated on the 257-m tower.

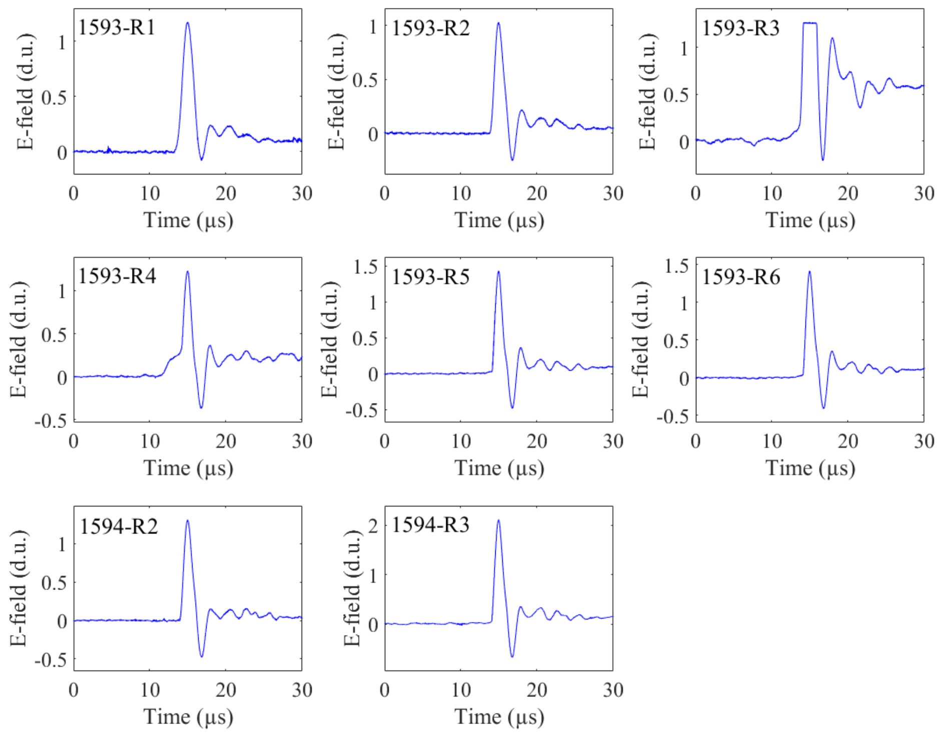

Figure 4 Electric field waveforms of 8 negative strokes terminated on the 257-m tower. The electric field waveform of 1593-R3 is saturated. Atmospheric electricity sign convention is used in this figure.

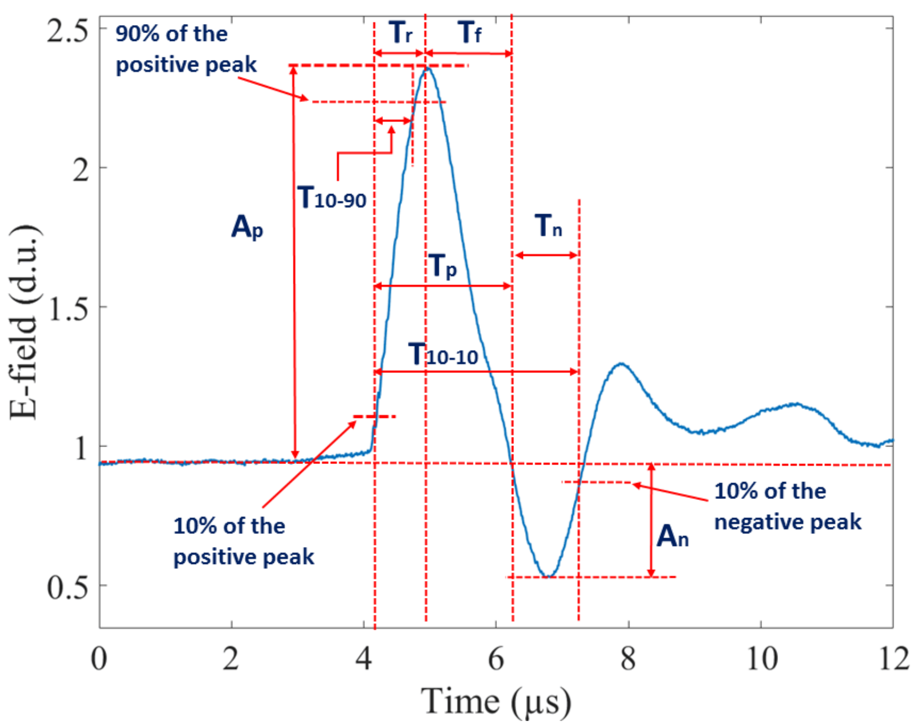

Figure 5 Electric field waveform of event 1593-R6. Measurements (definitions) of waveform parameters are illustrated.

Table 3 Electric field waveform parameters for the seven negative strokes (1593-R3 is excluded due to saturation) terminated on the 257-m tower.

Stroke ID	T_p (μs)	T_{10-90} (μs)	T_{10-10} (μs)	T_r (μs)	T_f (μs)	T_r/T_f	T_n (μs)	T_p/T_n	A_p/A_n	A_p	A_n
1593-1	2.82	0.98	3.43	1.24	1.58	0.78	0.61	4.60	19.5	1.17	0.06
1593-2	2.25	0.80	3.22	0.93	1.32	0.70	0.97	2.32	4.1	1.03	0.25
1593-4	3.91	2.45	5.08	2.71	1.20	2.26	1.17	3.34	3.3	1.2	0.36
1593-5	1.92	0.55	3.06	0.72	1.20	0.60	1.14	1.68	2.7	1.39	0.51
1593-6	2.04	0.59	3.12	0.79	1.25	0.63	1.08	1.89	3.0	1.37	0.44
1594-2	2.10	0.62	3.33	0.85	1.25	0.68	1.23	1.71	2.7	1.30	0.48
1594-3	2.02	0.57	2.95	0.82	1.20	0.68	1.14	1.78	2.9	2.06	0.71
AM	2.44	0.94	3.46	1.15	1.29	0.90	1.05	2.47	5.5	1.36	0.40

Table 4 Comparison with field waveform parameters for similar lightning events from other studies

References	Location and Season	Sample size	T_p (μs)	T_{10-90} (μs)	T_{10-10} (μs)	Peak current (kA)	T_r/T_f	T_p/T_n	A_p/A_n
Ishii and Saito, 2009	Hokuriku region, Japan, winter	21	-	AM=12.3	AM=53	>70	-	-	-
Wu et al., 2014	Western Japan, winter	356	AM=15.1	-	-	AM=-68.8	>1 for 92.4% of events	Median around 1	Median around 1
This study	Florida, USA, summer	8	AM=2.4	AM=0.9	AM=3.5	AM=-8.8	AM=0.9	AM=2.47	AM=5.5

IV. Summary

Simultaneous electric field and high-speed video camera records of two flashes, labeled 1593 and 1594, were acquired at the Lightning Observatory in Gainesville (LOG), Florida, in the summer of 2014. Flash 1593 was an upward negative flash whose upward positive leader (UPL) initiated from a 257-m high tower after a nearby intracloud discharge. The UPL propagated with an average frame-to-frame speed of 2.8×10^5 m/s. Flash 1593 contained 6 downward leader/return stroke sequences, all terminated on the tower. Flash 1594 was a downward bipolar flash that occurred 8 minutes after flash 1593. The first stroke of flash 1594 was positive and terminated on a 60-m tower. It was followed by two negative strokes that terminated on the same 257-m tower as the six strokes of flash 1593. The peak current reported by the NLDN for the 8 negative strokes ranged from 5.7 to 20.7 kA, with an average of 8.8 kA. Out of the 8 negative strokes, 6 were misclassified by the NLDN as cloud discharges. All the 8 negative strokes that terminated on the 257-m tower exhibited very similar damped oscillatory electric field waveforms. The average widths of the first, positive and second, negative half-cycles were 2.44 µs and 1.05 µs, respectively, considerably shorter than for the previously reported "large bipolar events".

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