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Optical and electric field signarues of lightning interaction with a 257-m tall tower in Florida

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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. Flash 1593 was an upward negative flash whose upward positive leader initiated from a 257-m high tower, located 8.8 km from LOG. It contained six leader/return-stroke sequences, all of which developed along the upward leader path and terminated on the 257-m tower. Flash 1594 was a three-stroke downward bipolar flash whose first stroke was positive and terminated on a 60-m tower. The two subsequent strokes were negative and terminated on the same 257-m tower as the six strokes of flash 1593. All strokes terminated on the 257-m tower exhibited very similar narrow bipolar electric field waveforms with damped oscillatory tails. Characteristics of those electric field waveforms are examined and compared to similar observations found in the literature.

1. Introduction

Several research groups reported narrow bipolar electric field pulses (initial-half-cycle durations ranging from 5 to 15 μs or so), most of which, if not all, being associated with lightning strikes to tall towers. Pavanello et al. [1] observed that for lightning striking the 553-m tall CN tower (Canada), the electric and magnetic field waveforms measured at 16.8 km and 50.9 km exhibited a very short first zero-crossing time of about 5 μs followed by a narrow (<5 μs) opposite-polarity overshoot (see Fig. A1). They attributed these unusual field signatures to the transient process excited by lightning along the tower. The CN-tower observations were performed in summer. Ishii and Saito [2] reported bipolar electric field waveforms produced by 21 negative "ground-to-cloud (GC) discharges" in winter storms in Japan. Examples of those waveforms are shown in Fig. A2. Ishii and Saito [2] suggested that GC discharges involved an upward leader making contact with a horizontal in-cloud channel, as illustrated in the left panel of Fig. A2(b). In this scenario, the source is located in the cloud, as opposed to being located at ground level in the case of normal cloud-to-ground (CG) lightning (see right panel of Fig. A2(b)). Pichler et al. [3] presented simultaneous current and electric field records of 73 subsequent return strokes terminated on the 100-m Gaisberg tower (Austria) and found that the arithmetic mean zero-crossing time of the electric field waveforms of those strokes was 11.2 μs, which is more than a factor of 3 shorter than that for "normal" subsequent strokes not involving tall objects. Examples of current and electric field waveforms of a stroke terminated on the Gaisberg tower are shown in Fig. A3. Most of the Gaisberg-tower events occurred during the cold season. Wu et al. [4], using a low-frequency lightning location network, observed 374 electric field waveforms, which they termed "large bipolar events (LBEs)", in winter storms in Japan. They speculated that LBEs involved tall grounded objects and occurred when the negative charge layer in the cloud was very close to the top of the strike object. The LBE label was also used for the discharge giving rise to the observed electric field waveforms, examples of which are shown in Fig. A4. Ishii et al. [5] and Saito et al. [6] reported unusually narrow electric field waveforms produced by return strokes in upward and downward lightning discharges to the 634-m high Tokyo Skytree in Japan, observed in spring and summer. Observed and calculated electric field waveforms for one subsequent return stroke recorded at three stations, along with their causative current waveform, are shown in Fig. A5. Note that the current waveform measured at the tower is similar to those typical for normal negative return strokes (relatively fast rise to peak and relatively slow decay).

Chen et al. [7] simulated far-field waveforms (see Fig. A6) characteristic of LBEs observed by Wu et al. [4] assuming that they

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Table 1
NLDN data on 8 negative strokes in flashes 1593 and 1594 terminated 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 of the NLDN location error ellipse (m)	Semi-minor axis length of the NLDN location error ellipse (m)	Number of reporting NLDN sensors	Distance between the NLDN-reported 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	100	5	40
	1593-4	6.5	56	G	200	200	4	80
	1593-5	6.6	18	C	200	200	4	60
	1593-6	6.7	14	C	200	200	5	90
Downward bipolar flash[a]	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

[a] Information on the first, positive stroke of this bipolar flash is given in Table 2.

occurred in relatively short channels (500–1000 m) attached to strike objects of 100–300 m in height. They used the bouncing-wave model for two different positions of the source representing the RS-like and ICC-pulse-like processes and found that the electric field waveforms observed by Wu et al. [4] could be reproduced in either case, but only when the injected current waveform was a symmetric Gaussian pulse. Note that Chen et al. [7] used the field sign convention that is opposite to the one used by Wu et al. [4].

In this paper, we present two lightning flashes containing a total of eight negative strokes that terminated on a 257-m tower and produced unusually narrow bipolar electric field waveforms with damped oscillatory tails. High-speed video camera records were also obtained for these two flashes. The observed electric field waveforms exhibit some similarities to the events reviewed above. In the camera's field of view, the 257-m tower was obscured by trees, but the azimuth of the 8 strokes and NLDN data clearly indicate that all of them terminated on the tower.

2. Instrumentation

The two flashes presented in this paper 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 (located on the roof of a five-story building) include a low-gain and a high-gain electric field measuring systems and an electric field derivative (dE/dt) measuring system. The low-gain electric field measuring system includes a circular flat-plate antenna, installed nearly flush with the roof surface, followed by an amplifier with an RC time constant of 10 ms. The high-gain electric field measuring system includes a similar but elevated flat-plate antenna followed by a different amplifier having a higher gain and a shorter RC time constant of 440 μs, which allowed us to accentuate relatively small field pulses. The bandwidths are 16 Hz–10 MHz and 360 Hz–10 MHz for the low-gain and high-gain 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. The Megaspeed HHC-X2 camera, equipped with a fish-eye lens to provide a wider field of view (about 185°), was operated at 1000 frames per second (fps) with 1 ms exposure time (no deadtime) and resolution of 832 × 600 pixels. The record length of the camera was 1.2 s with 200 ms pretrigger. No processing of optical images was done to remove the fish-eye effect. Since the imaged channels were near the lens center, the distortion was not significant. The electric field records and high-speed video records were GPS time stamped. More detailed information on LOG can be found in the review paper by Rakov et al. [8].

3. Observations and analysis

3.1. General description of two flashes terminated on the 257-m and 60-m towers in 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 the 257-m high tower (located 8.8 km from the LOG). This upward leader was clearly seen in six consecutive frames (for about 6 ms) moving at an average 2D frame-to-frame speed of 3.2×10^5 m/s. It was optically detectable up to a height of 1.9 km. Flash 1593 contained 6 negative strokes, all of which terminated on the 257-m tower. This flash occurred after and possibly was initiated by a nearby intracloud discharge. Flash 1594 was a downward bipolar flash that occurred 8 min after flash 1593. Natural downward bipolar flashes are rare with only several observations being found in the literature [9–16]. During the 8 min interval between flashes 1593 and 1594, only one cloud discharge was reported by the NLDN within 40 km of the LOG. The first stroke of flash 1594 was positive and terminated on the 60-m tower located 3.6 km from the 257-m tower and 8.9 km from the LOG. It was followed by two negative strokes that terminated on the same 257-m tower as the 6 strokes of flash 1593. All the 8 negative strokes that terminated on the 257-m tower exhibited very similar electric field waveforms, characterized by a narrow bipolar pulse with a damped oscillatory tail. The electric field waveform of the positive stroke terminated on the 60-m tower was unipolar and exhibited initial, predominately radiation field peak followed by a large electrostatic ramp, as expected.

3.2. NLDN responses to the 257-m and 60-m tower strokes

The NLDN information for the two flashes is summarized in Table 1 (negative strokes) and Table 2 (positive stroke). The 8 negative strokes had NLDN-reported peak currents ranging from 5.7 to 20.7 kA with a geometric mean of 8 kA and an arithmetic mean of 8.8 kA. Out of 8 negative strokes, 6 were misclassified by the NLDN as cloud discharges. The peak currents for the 2 correctly classified events were 20.7 and 6.5 kA. Warner et al. [17] reported that the NLDN misclassified as cloud discharges 30% (46/151) of "subsequent events" (leader/return stroke sequences and ICC pulses) in upward flashes initiated from towers. They found that the peak-to-zero times and pulse durations of field pulses produced by

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