An upward negative lightning flash triggered by a distant +CG from a tall tower in Florida: Observations and modeling

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***Abstract*—We examined in detail the morphology and evolution of an upward negative flash terminated on a 257-m tower in Florida. The upward flash was induced (triggered) by a single-stroke 50-kA +CG that occurred about 45 km from the tower. The 257-m tower flash contained 6 leader/return stroke sequences. Electric field waveforms produced by the return strokes were bipolar (at a distance of 8.8 km) and abnormally narrow (exhibited earlier zero crossing). In order to examine the origin of the observed earlier zero crossings, we used two return-stroke models of TL type (MTLL and MTLE) and varied model parameters in wide ranges. Within the limits of our models, the observed early zero crossings could be explained only by a narrow input current waveform or/and its fast decay with height.**

Keywords— Atmospheric electricity; lightning; tall strike object

I. INTRODUCTION

Tall objects are preferred targets for lightning strikes. Understanding of how lightning interacts with tall objects is important for characterizing the various lightning processes and improving lightning protection schemes. In contrast with short objects that experience only normal downward cloud-to-ground lightning, a tall object can initiate upward lightning developing from its tip toward the overhead thundercloud. Initiation of upward lightning can occur in response to another lightning some tens of kilometers away (e.g., Schumann et al., 2017; Warner et al., 2018). In this lecture, based on optical and other observations, we will present a detailed picture of how a positive cloud-to-ground lightning flash (+CG) triggered an upward negative lightning flash from a 257-m tall tower located at a distance of 45 km from the positive flash. Based on our high-speed video camera records, we observed how subsequent leader/return stroke sequences (a total of 6) in the upward negative flash were initiated and how each stroke progressively increased the length of the luminous channel created by the preceding stroke. The return-stroke electromagnetic signatures were abnormally narrow, compared to their counterparts for lightning strikes to ground or to short grounded objects. Two approaches to modeling of those signatures will be discussed. Additional information on the flash presented in this lecture is found in works of Zhu et al. (2017, 2018, 2019).

II. OBSERVATIONS

Using high-speed optical and electric field records obtained at the Lightning Observatory in Gainesville (LOG), Florida, we examined in detail the morphology and evolution of an upward negative flash containing 6 downward leader/upward return stroke sequences terminated on a 257-m tall tower in Florida. This flash was unusual in that the upper part of its channel, normally hidden inside the cloud, was visible for each of its 6 strokes up to a height of about 10 km above the tower top. It was induced (triggered) by a single-stroke 50-kA +CG (positive cloud-to-ground flash) that occurred about 45 km from the tower and whose in-cloud part was optically detected to extend (primarily horizontally with a descending trend) toward the tower and appeared to stop at a height of about 3 km above the tower top. The ENTLN (Earth Networks Total Lightning Network) and radar data (see Fig. 1) indicate that the +CG apparently originated from a relatively distant thunderstorm cell separated by a lower-reflectivity gap of about 15 km from the cell located above the tower. The distance from the tower to the LOG was 8.8 km.

The in-cloud part of the +CG in effect transported negative charge to the cloud region above the tower and caused the initiation of an upward positive leader (UPL) from the tower. The UPL extended during about 8 ms to a height of about 2 km above the tower top, as the in-cloud part of the +CG (including its continuing current) faded away, and was followed by an initial continuous current (ICC). The UPL speed decreased from 5.8 x 105 m/s to 1.4 x 105 m/s with a mean of 2.2 x 105 m/s. The ICC was associated with heavy branching in different directions. Most of the branches were faint and were revealed only via detection of moving bright leader tips and/or re-illumination of channels by transient recoil leaders. The branches extending predominantly upward were utilized by attempted downward leaders and leader/return-stroke sequences that occurred later in the flash.

Six negative downward-leader/upward-return-stroke sequences occurred 177 ms after UPL's becoming optically undetectable. Each of them was initiated by what appeared to be a predominantly vertical bidirectional leader. Electric field signatures of bidirectional leaders were similar to those of K-changes. That is they appeared as ramps with durations of the order of 1 ms (from 1.3 to 3.0 ms with a mean of 1.7 ms, measured in high-gain electric field records that were compensated for instrumental decay), superimposed on which are often irregular microsecond-scale pulses and regular pulse bursts. In fact, the bidirectional leader is probably the process (or one of the processes) giving rise to K-changes in electric field records. Electric field signatures of return strokes were bipolar, which is not expected for strikes to ground at 8.8 km, and abnormally narrow: initial half-cycles ranged from 2.0 to 3.9 μs. The NLDN-reported peak currents were relatively low, ranging from 5.7 to 10.2 kA.

The upper end of the return-stroke channel in all 6 strokes exhibited upward branching. The channel length tended to increase with increasing stroke order, up to a maximum height of about 10 km above the tower top. It is important to note, however, that the upper part of the channel could have extended toward LOG, in which case the maximum vertical extent would be smaller. The optical images and corresponding electric field waveforms for Strokes 1 and 4 are shown in Fig. 2. NLDN-reported peak currents for these two strokes are 7.6 and 6.5 kA, respectively.

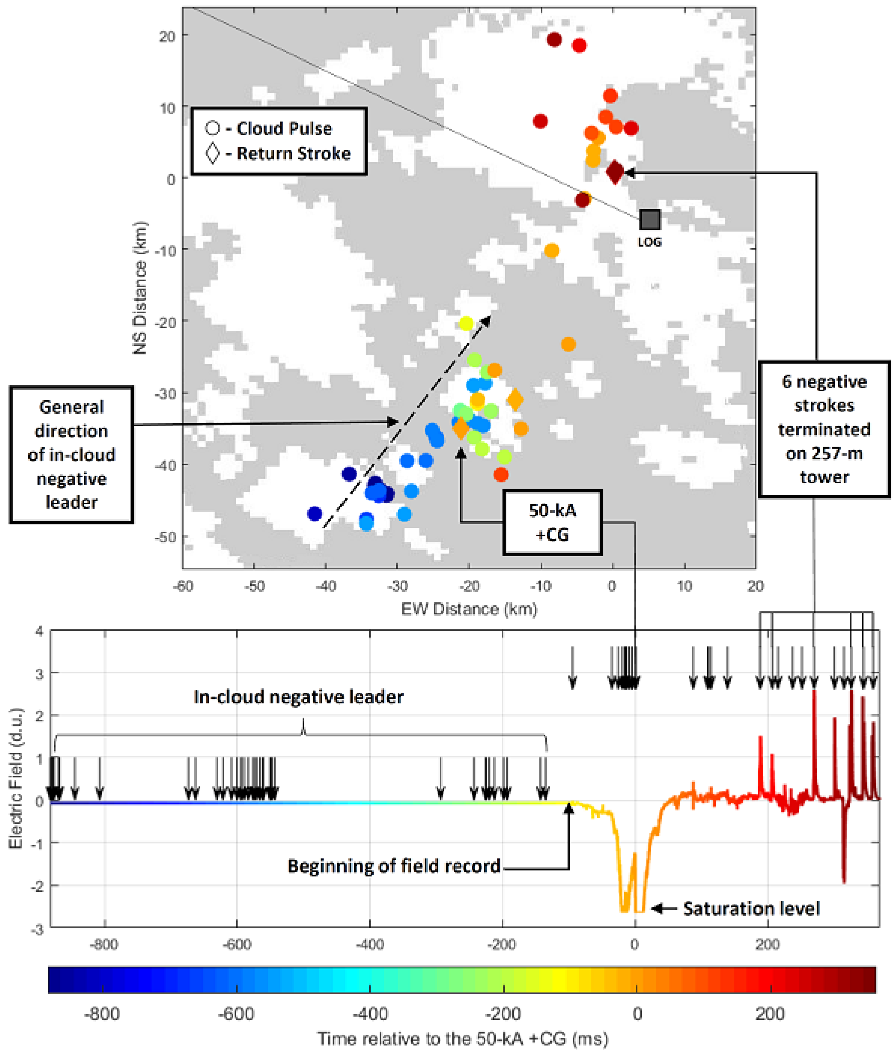

Fig. 1. (Top) ENTLN data (circles representing cloud pulses and diamonds representing return strokes) superimposed on a radar map showing only 2 levels of reflectivity, ≥35 dBZ (white areas) and <35 dBZ (gray areas). (Bottom) High-gain (τ = 440 μs) electric field waveform measured at LOG. The time sequence of cloud pulses and return strokes (a total of 66) shown in the top panel is color coded. Downward arrows in the bottom panel indicate the occurrence times of ENTLN-detected events

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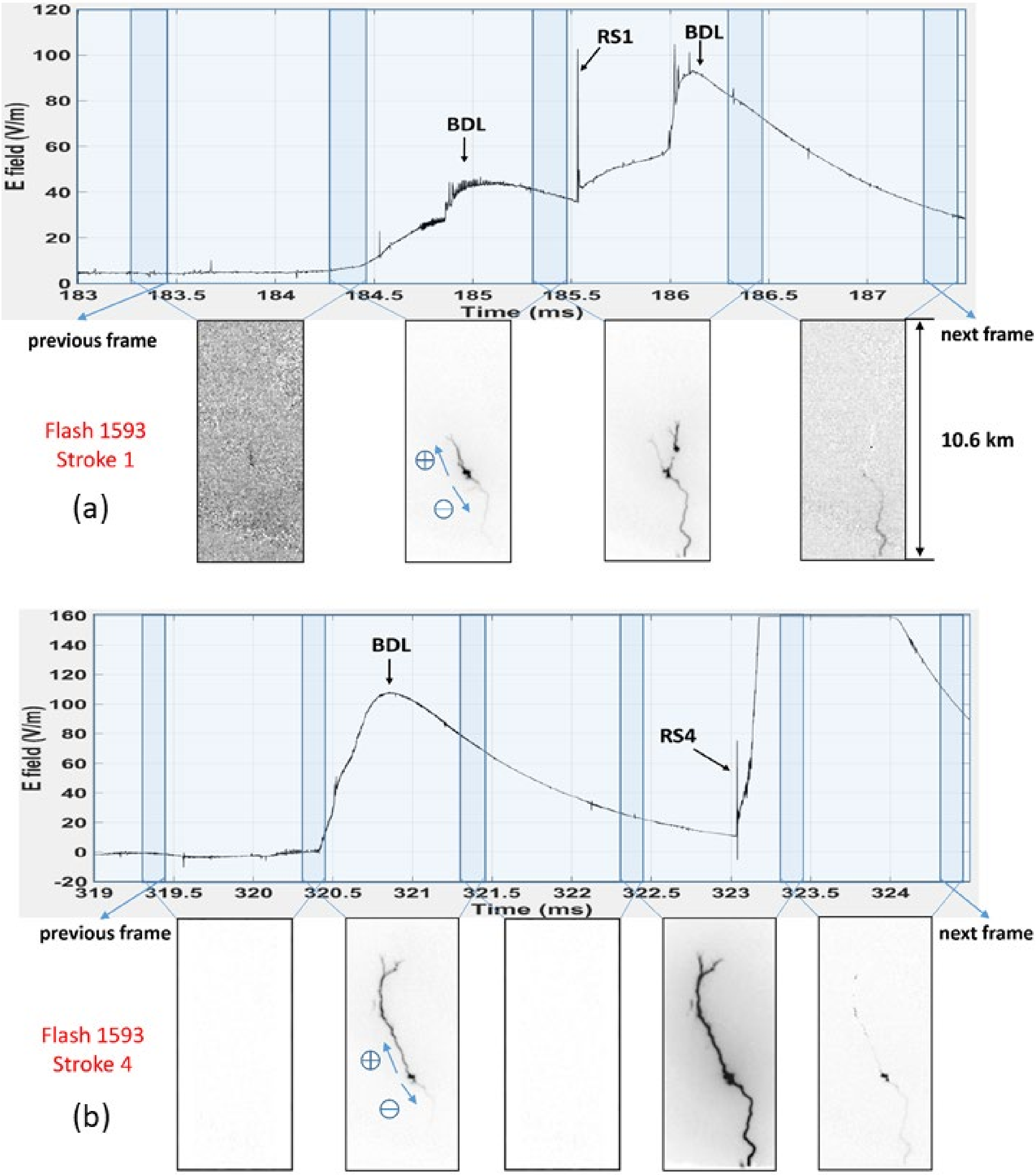

Fig. 2. High-gain (τ = 440 μs) electric field waveforms of (a) Stroke 1 (7.6 kA) and Stroke 4 (6.5 kA) aligned with their optical images (1 ms between frames). Alignment uncertainty is represented by darker areas in electric field panels. BDL stands for bidirectional leader and RS stands for return stroke. The inferred bidirectional extension of leaders is indicated by small arrows with the polarity of positive and negative ends being represented by encircled plus and minus signs. Note that the actual positions of starting (neutral) points of bidirectional leaders are unknown.

III. Modeling

As noted in Section 2, the electric field signatures of return strokes were abnormally narrow. Actually, lightning striking tall objects often produces electric field waveforms with first zero-crossing times ranging from 2 to 15 µs or so (Ishii & Saito, 2009; Pavanello et al., 2007; Pichler et al., 2010; Wu et al., 2014; Zhu et al., 2017), which are significantly smaller than the typical values ranging from 30 to 50 µs (Rakov & Uman, 2003, Ch. 4). In order to examine the origin of earlier zero-crossings observed in electric field signatures produced by lightning strikes to towers, we used the lumped voltage source excitation proposed by Baba and Rakov (2005b) and two return-stroke models of TL type (MTLL and MTLE). Model input parameters were varied in wide ranges. Tower heights ranging from 100 to 600 m were considered, and the lightning channel was assumed to be straight and vertical. It was found that the observed narrow field signatures cannot be reproduced by traditional return stroke models (Rakov & Uman, 2003, Ch. 12) and require a narrower input current waveform or/and its faster decay with height. For towers with heights exceeding 100 m or so, contribution to the total electric field peak from the tower was greater than that from the lightning channel. At distances of 2 to 50 km, the electric field signature due to the tower current was found to be bipolar, while that due to the lightning channel current was unipolar. It appears that the tower often behaves as an electrically short antenna (Hertzian dipole) whose radiation field is proportional to dI/dt, as opposed to being proportional to I, which is expected for the traveling wave-type antenna (lightning channel, whose length is measured in kilometers).

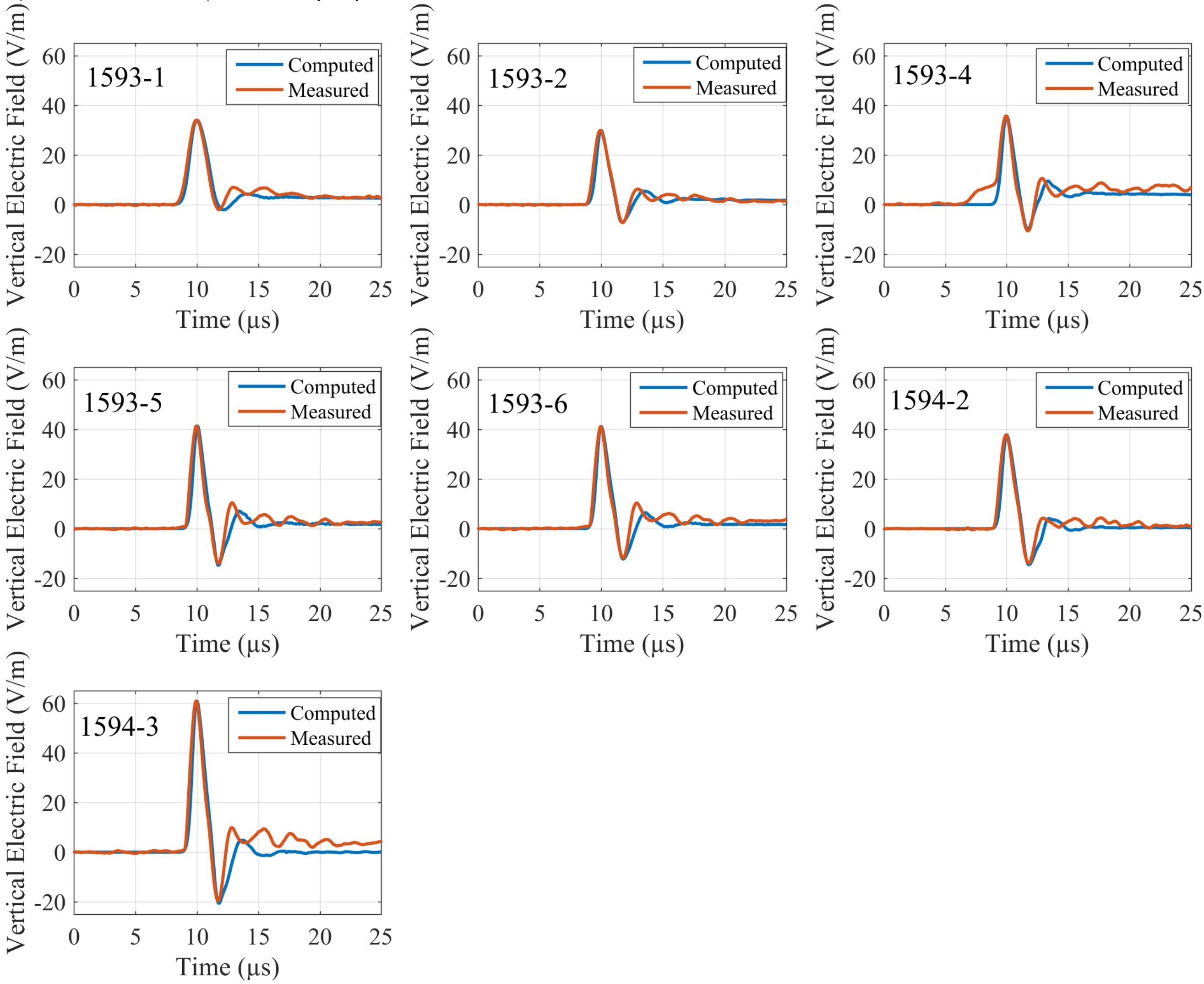

Fig. 3. Measured and computed electric field waveforms at 8.8 km. Narrow channel base (input) current waveforms and the transmission line model with linear current decay with height (normal current decay with height) were used. Steady-level components with magnitudes ranging from 200 to 1,200 A were attached to the tail of the impulsive current components, whose peaks ranged from 3.6 and 7.8 kA and half-peak widths from 1.0 to 2.3 µs. The current waveforms were optimized (adjusted) to achieve the best match between the computed and measured electric field waveforms

The characteristics of initial half-cycle (both its amplitude and width) of the electric field waveform are strongly influenced by the channel-base current rise-time. The opposite polarity overshoot increases with decreasing the current rise-time or fall-time and with increasing the current decay with height (the narrower the current pulse and faster its amplitude decays with height, the larger the overshoot). An increase in return-stroke speed serves to increase the initial half-cycle peak and to decrease the opposite-polarity overshoot. When the speed was assumed to exponentially decrease with height, the rate of decrease was found to have a relatively small effect on the field waveform. The initial electric field peak, which is insensitive to the choice of return-stroke model, increases as the object height increases from 100 to 200 m and remains about the same for heights varying from 200 to 600 m. An increase of the absolute value of reflection coefficient at tower top leads to an increase of both the initial half-cycle and opposite-polarity overshoot peaks, while the reflection coefficient at ground has relatively little influence on these peaks, particularly on the initial half-cycle peak.

The narrow (initial half-cycle width ranging from 2.0 to 3.9 μs) bipolar electric field waveforms produced by lightning striking the 257-m tower in Florida were reproduced using two approaches. In the first one, we employed a typical channel-base (input) current waveform (HPW ranging from 36 to 106 μs) and the MTLE (exponential current decay with height) model with a very small (tens to hundreds of meters) attenuation distance (very high decay rate). In the second approach, we used a narrow impulsive current component (HPW ranging from 1.0 to 2.3 μs) followed by a steady-level tail as the channel-base (input) current waveform and the MTLL (linear current decay with height) model. In both approaches, the computed electric field waveforms matched well the corresponding measured waveforms for the initial half-cycle and opposite-polarity overshoot, while the oscillatory tail in the measured field waveforms was not well reproduced. Fig. 3 shows the observed and model-predicted electric field waveforms for the 6 return strokes of the 257-m tower flash. The model-predicted waveforms correspond to the second approach in which narrow current pulses and the MTLL model were used.

IV. Concluding Remarks

We presented an upward negative flash triggered from a 257-m-high tower by an approaching negative in-cloud leader associated with the continuing current of a single-stroke, 50-kA +CG, whose ground termination point was about 45 km from the tower. It is likely that the in-cloud leader causing the initiation of UPL propagated through and ended in the positive charge region above the tower, at a height of about 3 km above ground level. Further, it appears that the positive charge was not completely neutralized, since the UPL has slowed down and faded away before reaching the 3-km altitude. The transition from UPL to ICC was undetectable with our camera. The ICC created an extensive network of channels branching in different directions, some of which were utilized by the following leader/return stroke sequences.

Electric field waveforms produced by the return strokes were bipolar (at a distance of 8.8 km) and abnormally narrow (exhibited earlier zero crossing). In order to examine the origin of the observed earlier zero crossings, we used two return-stroke models of TL type (MTLL and MTLE) and varied model parameters in wide ranges. Our modeling results illustrate that, within the limits of our model, the observed earlier zero crossings in electric field waveforms can be explained only by a narrow input current waveform or/and its fast decay with height. Beyond the limits of our model, other explanations are possible (e.g., lightning channel turning horizontal, whose effect was examined by Saito et al. (2015) and Araki et al. (2018)). Clearly, further research is needed.

All 6 return strokes in the flash examined here were characterized by unusually low charge transfer (Zhu et al., 2018). They each could be a by-product of a relatively small, K-change type in-cloud discharge. Most of such discharges do not contact ground or grounded object. In our study, 6 such events were capable of touching the tower apparently because of (1) the electric field enhancement by the tall tower; (2) the presence of remnants of UPL/ICC channels, as well as remnants of the in-cloud channels of the initiating +CG; and (3) the presence of pockets of charge formed in the course of cloud electrification processes or deposited by the various discharge processes in the vicinity of the tower. Clearly, further research of lightning interaction with tall towers is needed.

The results of this study will be useful in improving our understanding of the interaction of lightning with tall man-made objects, including wind turbines. This, in turn, will help in designing better lightning protection means and developing advanced approaches to classification of lightning events terminating on tall objects and estimation of their peak currents by modern lightning locating systems.

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