Correlated luminosity and magnetic field peaks produced by canton tower-strokes

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\textbf{ABSTRACT}

Simultaneously measured luminosity and magnetic field induced by the return strokes in typical upward and downward flashes occurring on the 600 m-tall Canton Tower were presented. The correlation between peak relative luminosity and peak relative magnetic field induced by return strokes were examined for 4 upward and 4 downward flashes. All the flashes contained 3 or more return strokes and all the return strokes in a same flash followed the same path. Luminosity of the lightning channel close to the top of the Canton Tower exhibited characteristics of pronounced initial peak with 20–90% rise time of about 5.2 μs (arithmetic mean value, based on 43 samples) for subsequent strokes, which was inferred to be related to the secondary (typically largest) peak current at the top of the Canton Tower. The magnetic field induced by subsequent strokes exhibited characteristics of pronounced initial peak with 20–90% rise time of about 1.2 μs (arithmetic mean value, based on 47 samples). The initial peak magnetic field was modified to proportionally represent the largest peak current at the top of the Canton Tower. Roughly linear and quadratic relation between the initial peak luminosity and modified peak magnetic field were found for subsequent strokes in both upward and downward flashes. The quadratic relation fit the data slightly better than the linear relation. The ratio of peaks of luminosity to magnetic field of the downward first stroke were considerably larger than those of the subsequent strokes, the possible reasons were also discussed.

1. Introduction

Lightning return stroke is an intense current pulse propagating along the lightning channel accompanied with strong optical and electromagnetic emissions. Compared to the lightning current signal, the optical signal is more convenient and feasible to be measured. The optical measurement can be focused at certain segments of the lightning channel which will provide a practical way to reveal current variation in the return stroke channel. During the past decades, the relation between lightning current and light has attracted the interests of many researchers (Idone and Orville, 1985; Wang et al., 2005, 2013, 2014; Qie et al., 2011; Zhou et al., 2013; Zhou et al., 2014; Carvalho et al., 2014, 2015; Quick and Krider, 2015, 2017).

Based on the classical rocket-and-wire-triggered lightning experiments, the relation between lightning current and light during different discharge processes of a flash has been studied extensively. For example, based on the observations of 39 subsequent return strokes in two triggered lightning flashes, Idone and Orville (1985) found that there is evident correlation between peak relative light intensity (obtained from photographic streak recordings using calibrated film) and peak current at the channel base. Using photodiode array module, Wang et al. (2005) compared the channel-base current and the light signal for four rocket-triggered lightning flashes and found a linear relationship between the current and the light signals in their rising portions. Zhou et al. (2014) and Carvalho et al. (2015) both found that the peak luminosity at the artificially-triggered lightning channel bottom is roughly proportional to the square of the peak current. Recently, using calibrated radiometers, Quick and Krider (2017) found that both peak optical power per unit length and averaged optical power per unit length are approximately proportional to the square of the peak current at the channel base.

Due to the fact that it is difficult to measure current for natural flashes, only a few documented cases on light/current relation for natural flashes were reported. Diendorfer et al. (2003) analyzed the
high-speed video and current measurement of the upward lightning flashes to the Gaisberg Tower, and found linear correlation between the lightning channel brightness and current. But they also pointed out that the 2 ms exposure time of the high-speed video frames only allows recording by HC-1(a) and HC-2(b). Note that there is a strong correlation between the peak current and the peak radiation field produced by lightning return stroke (Rakov et al., 1992; Mallick et al., 2014). Some researchers have tried to reveal the correlation between the optical and electromagnetic field signals produced by natural lightning return strokes. Ganesh et al. (1984) reported that both the peak luminosity and the logarithm of the peak luminosity emitted by lightning channels were correlated with the peak electric field produced by natural return strokes. Quick and Krider (2013) found that the average luminous power increased with increasing Lightning Location System (LLS)-estimated peak current for subsequent strokes that re-illuminated a preexisting channel.

In this paper, optical and electromagnetic measurements for both upward and downward multiple-stroke flashes occurring on the 600 m-tall Canton Tower are presented. The characteristics of the optical and electromagnetic waveforms were analyzed in detail. The correlation between peak relative luminosity and the peak relative magnetic field induced by return strokes is then analyzed for each flash respectively.

2. Experimental setup

The field experiment mainly focusing on lightning flashes striking tall objects has been conducted since 2009 at the Tall-Object Lightning Observatory in Guangzhou (TOLOG), Guangdong Province, China (Lu et al., 2012, 2013). The TOLOG is located on a structure with a height of approximately 100 m and it is 3.3 km far away from the 600 m-tall Canton Tower. The luminosity produced by lightning flashes occurring on and around the Canton Tower was measured by a high-speed optical imaging system called Lightning Attachment Process Observation System (LAPOS, see Wang et al., 2011). Two LAPOSs, named LAPOS1 and LAPOS2, were both equipped with a 16-mm-lens and used in the experiment. Each LAPOS has 8 horizontal lines of fibers and the corresponding photodiodes, and each photodiode detects the integral luminosity in a view range with horizontal and vertical view angles being about 97 degree and 1.2 degree (68 m vertical spatial resolution at the distance of 3.3 km), respectively. Two types of photodiodes with similar spectral response but different sensitivity are used for LAPOS1 and LAPOS2. The photodiodes used by LAPOS1 is more sensitive. The simultaneous measurements from LAPOS1 and LAPOS2 together provide a wider dynamic measuring range. The vertical centers of the field of view (FOV) of both LAPOSs were pointed at the area above the top of the Canton Tower. Two loop antennas with a bandwidth from 100 Hz to 5 MHz were used to measure the azimuthal magnetic field produced by the lightning flash. Before 2015, one loop antenna (named loop antenna A) was installed in a way that the plane of the loop was approximately parallel to the direction from southwest to northeast, and the other one (named loop antenna B) was approximately parallel to the direction from southeast to northwest. From Aug 2015, loop antenna A was adjusted to be north-south orientated and the other one west-east orientated. Note that the operation status of loop antenna B was not steady, only the measurements of loop antenna A were used for this study. One Yokogawa DL850 digital oscilloscope was used to record the signals from all the 16 channels of the two LAPOSs at a sampling rate of 10 MHz and with 1 s record length. Besides, the signals from one channel of LAPOS1 and one channel of LAPOS2 were also guided to another one Yokogawa DL850 digital oscilloscope for recording simultaneous signals from the magnetic field antennas. In addition, three high-speed cameras, one Photron FASTCAM SAZ (HC-1), one Photron FASTCAM SA5 (HC-2) and one Photron FASTCAM SA3 (HC-3), were used to capture the images of the lightning flashes. They were operated at 20000, 50000 and 1000 frames per second (fps), respectively. The HC3, especially designed to record the entire process of a lightning flash in a larger FOV, was equipped with a 8-mm lens, and set at a recording length of 1.5 s with a 33% pre-trigger time. For each triggering event,
the GPS time stamp of the triggering signal, with an accuracy of 30 ns, was provided by a high-precision GPS timing system. Note that no lightning current measuring devices have been installed at the Canton Tower so far. In this study, the peak current of the return strokes were estimated from the records of the Guangdong-Hongkong-Macao Lightning Location System (GHMLLS) which contains 11 LS700X sensors and 6 IMPACT sensors provided by the Vaisala Inc. The Canton Tower is located at the center of the GHMLLS.

3. Data and analysis

3.1. Data overview

Although the effects of scattering or absorption of light by the intervening atmosphere between TOLOG and the Canton Tower varies from time to time, the visibility condition can be assumed to be constant for each return stroke in a Canton Tower-flash. For the study presented in this paper, we look through the Canton Tower-flashes observed by TOLOG during 2009–2017 and select the cases according to the criteria as follows:

1) The lightning channel in the FOV of LAPOSs can be clearly distinguished without severe obstruction by cloud or rain.
2) All the subsequent return strokes re-illuminated a preexisting channel in the flash, which should be confirmed by the records of high speed camera (HC3).
3) At least 3 return strokes are contained in the flash.
4) Simultaneous measurement of LAPOSs and broad-band magnetic

The de-noised and normalized relative luminosity. (c) The relative magnetic field.

**Fig. 2.** Simultaneously measured luminosity and magnetic field produced by UF1-R1, time 0 is set at the max slope position of CH8. (a) The output of LAPOS1. (b) The de-noised and normalized relative luminosity. (c) The relative magnetic field.

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<th>20–90% rise time of initial peak magnetic filed (μs)</th>
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**Table 2**
Summary of the parameters associated with strokes contained in upward Canton Tower-flashes.
antenna are both available.

A total of 4 upward lightning flashes (named UF1–UF4) and 4 downward lightning flashes (named DF1–DF4) occurring on the top of the Canton Tower were selected. All the 51 return strokes involved in the 8 flashes lowered negative charge to ground according to the electric field records of the flat plate antennas. In addition, it can be confirmed that there were no branches in the lightning channel section within FOV of the LAPOSs for all the subsequent return strokes involved in the selected Canton Tower-flashes. The basic information for each flash, such as occurrence time, the flash type and the number of return strokes detected by the GHMLLS, is presented in Table 1. Note that the return strokes of UF1 and UF2 were all missed by the GHMLLS because of system maintenance. A total of 32 out of the 37 return strokes in the remaining 6 Canton Tower-flashes were detected by the GHMLLS.

3.2. Upward lightning flashes

Compared to LAPOS2, LAPOS1 has better signal-to-noise ratio but a smaller measuring range. Fortunately, none of the measurements of LAPOS1 were saturated for all return strokes in UF1–UF4. In this section, only the measurements of LAPOS1 are used for analysis.

Fig. 1 shows the FOV of LAPOS1 as well as the lightning channel of UF1, a typical upward Canton Tower-flash in our dataset.
As a representative example, the simultaneously measured luminosity and magnetic field waveforms produced by the first return stroke of UF1 (named UF1-R1) are shown in Fig. 2. It can be found in Fig. 2a that the peak values and the wave shapes record by the 8 channels of LAPOS1 differ from each other, which may be partly due to the current attenuation and dispersion along the lightning channel, as well as the tortuosity of the lightning channel. In general, the luminosity waveforms exhibited common characteristics that an initial peak with a fast rising of several microseconds is followed by plateau or a secondary maximum occurring tens of microseconds after the initial peak, which were somewhat similar to the irradiance waveforms observed in the triggered lightning experiments (Wang et al., 2005; Quick and Krider, 2017). In a whole, the initial peak luminosity at CH8 appeared to be more distinct than those at the other channels. The 20–90% rise time (20% of the peak was less affected by noise and hence chosen as the reference point rather than 10% of the peak for analysis in this paper) of the initial peak luminosity recorded by CH8, the section closest to the top of the Canton Tower, is about 5.0 μs. The 20–90% rise time of the initial luminosity peak and the other parameters associated with the return strokes contained in UF1~UF4 were summarized in Table 2. The 20–90% rise times of the initial peaks recorded by CH8 are in the range from 3.6 to 7.8 μs with the arithmetic mean value and median value of 5.0 μs and 4.6 μs. Current waveforms measured at the top of a tall tower are often characterized by an initial peak followed by a secondary (typically largest) peak due to the reflection from the bottom of the tower (Pavanello Pavanello et al., 2007; Shindo et al., 2014). Comparing with Fig. 3c, it can be found that the rise time of the initial peak luminosity is significantly larger than that of the initial peak magnetic field which in general corresponds to the initial peak current at the top of the tall object. Considering that a round-trip time for the current travelling along the 600 m-tall Canton Tower is about 4 μs, we inferred that the initial peak luminosity with rise time of about 5 μs corresponds to the secondary peak current above the top the Canton Tower.

In addition, although no distinctive two peaks can be distinguished, the rising portion of the initial peak luminosity at CH8 appeared to experience two phases of rising, which is in accordance with that inference. Hence, the initial peak will be used as the peak light intensity in the following analysis.

In Fig. 2b, all the luminosity waveforms were de-noised using wavelet analysis and normalized to the peak. It can be clearly distinguished that the return stroke wavefront propagated upward from the initial point to the top of the Canton Tower (590 m).
Fig. 7. Simultaneously measured luminosity and magnetic filed induced by DF4-R1, time 0 is set at the max slope position of CH2. (a) The output of LAPOS2. (b) The de-noised and normalized relative luminosity. (c) The relative magnetic field.

Fig. 8. Expanded waveforms of DF4-R1 in Fig. 7b and c, waveforms were normalized to the peak, time 0 is set at the max slope position of CH2.
A sliding time window with a width of 0.5 μs was applied to each waveform to determine the max slope position as the referenced time of the return stroke wavefront arrival. The one dimension (1D) return stroke velocity of UF1-R1 was then estimated to be about 9.5 × 10⁷ m/s.

As shown in Fig. 2c, the magnetic field waveform is characterized by pronounced initial (also largest) peak with narrow undershoot and followed by periodic oscillations, which is similar to the magnetic field waveform produced by the return strikes occurring on the 533 m-CN Tower and measured at a 2 km distance (Pavanello et al., 2007). The 20–90% rise time of the initial peak magnetic field of UF1-R1 is about 1.2 μs. The rising onset of the magnetic field appeared to be slightly earlier than that of the luminosity at CH8, which may be mainly due to the fact that the FOV of CH8 was more than 100 m above the top of the tower. All the return strokes contained in UF3 and UF4 were detected by the GHMLLS. As illustrated in Fig. 3, the initial peak magnetic field showed pretty good linear relationship with the peak current inferred by GHMLLS, which indicated that the initial peak magnetic field essentially related to the radiation component. The slope of the two linear fitting lines in Fig. 3a and b were similar, and the slight difference between them may be due to the different lightning channel morphology.

In the case of strokes with vertical lightning channel to tall object of height \( h \), the relation between the largest peak current at the object top and the peak of azimuthal magnetic field at far distance \( d \) on perfectly conducting ground can be estimated by:

\[
I_{\text{top peak}} = \frac{2\pi cd}{v + c} [1 + \rho_{\text{bot}}(1 + \rho_{\text{top}})] H_{\text{peak}}
\]

(1)

where \( v \) denotes the return stroke velocity, \( c \) denotes the light speed, \( \rho_{\text{bot}} \) and \( \rho_{\text{top}} \) denote the current reflection coefficient at the bottom and the top of the tall object for upward-propagating waves (Baba and Rakov, 2007). Note that (1) is valid only for the RT (zero-to-peak rise time of the current injected initially into the top of tall object) ≤ 2h/c when \( \rho_{\text{bot}} = 1 \) and for RT ≤ h/c when 0 ≤ \( \rho_{\text{bot}} < 1 \). In the case of subsequent strokes to the 600 m-tall Canton Tower, such conditions are expected to be satisfied. It is also assumed that all the field-to-current conversion factors in (1) except \( v \) are constant for each subsequent stroke contained in a same Canton Tower-flash, considering that the geometrical parameters and the physical characteristics of the lightning channel remained almost unchanged. In order to facilitate the comparison of \( I_{\text{top peak}} \) of each stroke in a same flash, we attempted to modify the initial peak magnetic fields measured at TOLOG to be proportional to \( I_{\text{top peak}} \) by:

\[
H_{\text{peak,m}} = \frac{H_{\text{peak}}}{(v + c)}
\]

(2)

For the analysis in this paper, the \( v \) in (2) adopted the value of 1D-return stroke velocity measured by the LAPOS.

Fig. 4 shows the plots of the modified initial peak luminosity (recorded by LAPOS) versus the initial peak magnetic field together with the linear and quadratic fits to the strokes in UF1 ~UF4 individually. The record of CH8 is adopted here for UF1 ~UF4. Positive correlation can be found between the initial peak luminosity and the modified initial peak magnetic field. Furthermore, the quadratic relation curve seemed to fit the data with better significance than the linear relation curve for UF1~UF3. In Fig. 4d, the plot of UF4-R1 seemed to have abnormal high ratio of luminosity to magnetic field. The quadratic relation curve will be improved and have better significance than the linear relation curve if the plot of UF4-R1 was excluded.
3.3. Downward lightning

The luminosity profile for downward negative first stroke to the Canton Tower is more complex than those for the subsequent strokes. For examples, the downward stepped leader exhibits much more branches, and the upward connecting leader (UCL) induced by the downward stepped leader is significantly longer (which can extend up to hundreds of meters). Figs. 5 and 6 show the morphology of the lightning channels just before and after the first stroke of a typical downward Canton Tower-flash (DF4). Note that the all the 8 channels of LAPOS1 were saturated for the first strokes of DF3 and DF4, so that the records of LAPOS2 was used as an alternative.

From Fig. 6a, it can be found that the branches of the downward stepped leader entered into the upper half of the FOV of LAPOS2. The UCL branched into two parts at the height of 720 m. It is difficult to distinguish the left part of UCL due to the weak luminosity in Fig. 6a. The right part of the UCL was much brighter and attached to the downward propagating to the peak magnetic field. The luminosity waveform at CH2 exhibited transition from relatively fast-rising portion to relatively slow rise at time of about 9 μs, and no apparent initial peak was distinguished.

Table 3 summarized the parameters associated with the return strokes contained in DF1~DF4. The UCL preceding the first stroke was long for DF2 and DF3. Similar to DF4-R1, the initial peak luminosity at the attachment point exhibited very sharply rising characteristics, and the initial peak magnetic field was followed by secondary (larger) peak, for DF2-R1 and DF3-R1. The luminosity of the lightning channel in the lowest FOV of LAPOS appeared to have transition from relatively fast-rising portion to relatively slower rise, but no apparent initial peaks, for the first strokes contained in DF2, DF3 and DF4.

The GHMLLS detected all the strokes contained in DF1~DF4. For DF1-R1, the preceding UCL was short, and the attachment point was found to be below the FOV of the LAPOS1. Both the luminosity recorded by CH8 of LAPOS1 and the magnetic field of DF1-R1 exhibited characteristics of pronounced initial peak and low secondary peak followed the initial peak magnetic field was found. The UCL preceding the first stroke was long for DF2 and DF3. Similar to DF4-R1, the initial peak luminosity at the attachment point exhibited very sharply rising characteristics, and the initial peak magnetic field was followed by secondary (larger) peak, for DF2-R1 and DF3-R1. The luminosity of the lightning channel in the lowest FOV of LAPOS appeared to have transition from relatively fast-rising portion to relatively slower rise, but no apparent initial peaks, for the first strokes contained in DF2, DF3 and DF4.

The plots of subsequent strokes were marked with hollow circles, while the first strokes with solid circles. Only the plots of subsequent strokes were used for the curve fitting. It can be found that the initial peak magnetic field of subsequent stroke contained in a single flash was approximately proportional to the LLS-inferred peak current. The plots of subsequent strokes were marked with hollow circles, while the first strokes with solid circles. Only the plots of subsequent strokes were used for the curve fitting. It can be found that the initial peak magnetic field of subsequent stroke contained in a single flash was approximately proportional to the LLS-inferred peak current. The slope of the linear fitting line in Fig. 10a was close to that in Fig. 10b, it is because of that DF1-R1 and DF2-R1 both occurred in 2014 and the orientation of the loop antenna remained unchanged for the meantime. Accordingly, the slope of the linear fitting lines for the data acquired during 2016–2017 were similar too (see Figs. 3, 10c and d). The secondary (larger) peak magnetic field was found for DF2-R1 and DF3-R1 (DF1-R1 has no secondary peak) in Fig. 10. The ratio of LLS-inferred peak current to the peak magnetic field of the first stroke appeared to be similar to that of the subsequent stroke for DF1 and DF2, but lower than that of the subsequent stroke for DF3 and DF4.

Fig. 11 shows the plots of the initial peak luminosity versus the modified initial peak magnetic field for the strokes contained in DF1~DF4. The data of the subsequent strokes were chosen and treated by the similar method described in 3.1. For comparison with the subsequent strokes in Fig. 11, the record of CH8 of LAPOS1 was adopted for return stroke velocity from CH2 to CH1 was estimated to be about 6.8 × 107 m/s, similar to that from CH2 to CH3. The 1D-return stroke velocity from CH3 to CH8 was estimated to be about 1.0 × 107 m/s. At the beginning of the return stroke process, the luminosity waveform at CH2 exhibited much faster increase than those at the other channels. It reached an initial peak with 20–90% rise time of about 2.4 μs, then rose slowly to a secondary rounded peak. The luminosity waveform at CH8 exhibited transition from relatively fast-rising portion to relatively slow rise at time of about 9 μs, and no apparent initial peak was distinguished.

The magnetic field waveform appeared to have an initial peak followed by a secondary (larger) peak for DF4-R1. The 20–90% rise time of the initial (secondary) peak was estimated to be about 4.7 (6.8) μs. We speculated that the initial peak magnetic field related to the current initially injected into the attachment point, while the secondary peak may relate to the transient processes when the downward propagating current arrived at the top of the Canton Tower. In addition, the initial peak of the luminosity waveform at CH2 seemed to correspond to the initial peak magnetic field, as shown in Fig. 8.

None of the measurements of LAPOS1 is saturated for all the subsequent return strokes contained in DF1~DF4. As an example, the simultaneously measured luminosity and magnetic field waveforms induced by the secondary return stroke of DF4 (named DF4-R2) is presented in Fig. 9. In general, the luminosity and magnetic field waveforms induced by the subsequent return strokes of downward flashes are similar to those of the upward flashes as showed in Fig. 2. It should also be pointed out that the output of LAPOS2 was too weak and noisy to be used to identify the initial peak luminosity for most subsequent strokes.
Fig. 10. Peak magnetic field versus absolute value of GHMLLS-inferred peak current together with linear fits to the measurements for (a) DF1 (b) DF2 (c) DF3 (d) DF4. The numbers beside the plots indicate the stroke number in a flash, and the fitting curves only concern the subsequent strokes.

Fig. 11. Peak luminosity versus modified peak magnetic field together with linear and quadratic fits to the measurements for (a) DF1 (b) DF2 (c) DF3 (d) DF4. The numbers beside the plots indicate the stroke number in a flash, and the fitting curves only concern the subsequent strokes.
all the first strokes, although the attachment points of the first strokes except DF1-R1 were much higher than the top of the Canton Tower. For DF2-R1, the luminosity at the transition point recorded by CH8 of LAPOS was adopted as the peak light intensity. For DF3-R1 and DF4-R1, the record of CH8 of LAPOS was saturated before the appearance of such transition, and the saturation value was simply adopted as the peak light intensity. In addition, for the first strokes of DF2–DF3, the secondary peak magnetic field as well as the upward 1D-return stroke velocity (which was lower than the downward one) were used in formulation (2) to calculate the modified peak magnetic field. Note that the fitting curves in Fig. 11 only concerned the subsequent strokes. In addition, the plot of DF4-R6 in Fig. 11d appeared to have abnormal high ratio of luminosity to magnetic field, and was excluded from the curve fitting. In a whole, the quadratic relation curve appeared to fit the data with better significance than the linear relation curve for subsequent strokes contained in DF1–DF4, which is similar to the situation showed in Fig. 4. However, the ratio of peak luminosity to magnetic field of the first stroke appeared to be much larger than those of the subsequent strokes.

4. Summary and discussion

In this study, simultaneously measured luminosity and magnetic field induced by the return strokes in typical upward and downward flashes occurring on the 600 m-tall Canton Tower, about 3.3 km away from the observatory, were presented and analyzed.

Luminosity of the lightning channel section, with a 1D-vertical length of about 68 m and about 100 m above the top of the Canton Tower, exhibited characteristics of apparent initial peak for subsequent strokes contained in both upward and downward flashes. The 20–90% rise times of the initial peak luminosity induced by subsequent strokes are in the range from 3.5 to 7.8 μs with the arithmetic mean value and median value of 5.2μs and 4.9 μs (based on 43 samples). The magnetic field induced by subsequent strokes contained in both upward and downward flashes of exhibited characteristics of pronounced initial peak. The 20–90% rise times of the initial peak magnetic field are in the range from 0.9 to 2.3 μs with the arithmetic mean value and median value of 1.2 μs and 1.2 μs (based on 47 samples). It is inferred that the initial peak luminosity corresponded to the secondary (typically largest) peak current at the top of the Canton Tower. According to the far field-to-current conversion for strokes on tall object proposed by Baba and Rakov (2007), an attempt was made to modify the initial peak magnetic field to be proportional to the secondary peak current at the top of the Canton Tower. Roughly linear and quadratic relation between the initial peak luminosity and modified peak magnetic field were found for subsequent strokes in both upward and downward flashes. In a whole, the quadratic relation seemed to fit the data slightly better than the linear relation, which is consistent with the situation in triggered lightning flashes reported previously (Zhou et al., 2014; Carvalho et al., 2015; Quick and Krider, 2017).

For the first strokes with preceding long UCL entering into the FOV of LAPOS, the luminosity right at the attachment point exhibited sharp-rising initial peak, and the luminosity close to the top of the tower appeared to have transition from fast-rising portion to relatively slower rise without apparent initial peaks. The magnetic field was characterized by initial peak followed by a secondary (larger) peak.

The ratio of peak luminosity to peak magnetic field of the first strokes seemed to be much larger than that of the subsequent strokes. We speculated that may be due to the following reasons:

(1) The rise time of the initial peak magnetic field of the first strokes were much larger than that of subsequent strokes, implying that the RT of first strokes were much longer too. Then, \( \text{I}\text{ops. peak}/H\text{peak} \) of the first stroke will be smaller than that of subsequent strokes (Baba and Rakov, 2007). In another word, \( \text{I}\text{ops. peak} \) represented by the modified peak magnetic of the first stroke was underestimated relative to that of the subsequent stroke. On the other hand, assuming that two current pulses with the same amplitude flow through a constant resistance, the pulse with larger RT will generate more heating energy during the rising portion. Note that the rise time of initial peak magnetic field induced by D4-R6 was much longer than the other subsequent strokes (see Table 3), and the rate of peak luminosity to peak magnetic field happened to be abnormally higher than the others.

(2) The conductance in the lightning channel of the first stroke is expected to be smaller than that of the subsequent stroke, and the heating energy is also expected to be larger.

(3) According to the high speed camera records, the downward stepped leader and the UCL exhibited branches in the FOV of the LAPOS before the first stroke and then be lighted up during the return stroke process, which may enhance the light emission.

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The simultaneous optical and electromagnetic field observation data for the Canton Tower-flashes analyzed in this paper can be obtained upon request from Weitao Lyu (wtlu@ustc.edu).

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