Electromagnetic Characteristics of Upward Leader Initiated From the Canton Tower: A Comparison With Rocket-Triggered Lightning

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Abstract By using the synchronous observation data obtained at the Tall-Object Lightning Observatory in Guangzhou (TOLOG) of 2019, the electromagnetic characteristics of upward positive leader (UPL) ascending from the 600-m high Canton Tower are examined, and are compared with the magnetic field (B-field) radiation of UPL in rocket-triggered lightning. Before the inception of sustained UPL, small electric field (E-field) pulses are superposed on the fast E-field changes. The timescale of B-field pulses corresponding to the E-field pulses ranges from 5 to 9 μs, and the inter-pulse interval is about 30 μs, which are both similar to the B-field pulses associated with the precursors of rocket-triggered lightning. Measurements show that the precursor-like stage is likely common for upward lightning initiated from the Canton Tower. Moreover, the UPL channel of tower-initiated upward lightning extends significantly in the first several ms with the initial average two-dimensional (2-D) velocity of 8.77 × 103 m/s (3-D velocity of 11.0 × 103 m/s), which is one order of magnitude faster than the UPL initiated from the wire tip of rocket-triggered lightning, indicating that initiation of UPL from Canton Tower benefits from a substantial E-field enhancement of nearby lightning discharges. However, this favorable condition is rapidly consumed during the UPL development, causing the average 2-D velocity of UPL to decrease rapidly and maintain at about 0.5 × 103 m/s. It is noted that the variation in the 2-D speed of sustained UPL differs from tower-initiated upward lightning reported in the literature, which is possibly associated with the physical and geometric properties of the tower.

1. Introduction

Rocket-triggered lightning and tower-initiated lightning are two effective ways for the observations of the upward positive leader (UPL). With the development of observation techniques, more findings about the propagation characteristics of the UPL were revealed recently (Fan et al., 2020; Jiang et al., 2020; Srivastava et al., 2019; Wang et al., 2020, 2016). The latest observations shown in the above literature support the view that UPL exhibits discontinuous manner during the propagation, which is different from the traditional understanding that positive leaders usually propagate continuously (Rakov & Uman, 2003; Saba et al., 2015), in both rocket-triggered lightning and tower-initiated lightning. As for the propagation mechanism of a positive leader, Wang et al. (2016) inferred that the pause of positive leader corresponded to the charge accumulation stage, and the stepping was related to the abrupt movement of leader hops as the electric field enhanced; Jiang et al. (2020) observed that residual structure of the luminous crown blooming connected with the positive leader head, and such process caused the next stepping.

By replacing the triggering wire with a grounded tall structure, the phenomenology of tower-initiated lightning is similar to that of the rocket-triggered lightning. Even though it occurs more unpredictably in comparison with the rocket-triggered lightning, tower-initiated lightning has been a long-term concern (Fuchs et al., 1998; Flache et al., 2008; Jiang et al., 2014; Miki et al., 2005; Qi et al., 2018; Visacro et al., 2017; Wu et al., 2019; Wang et al., 2008; Warner, 2012; Yuan et al., 2017), and the electromagnetic characteristics of UPL during the initial stage are important parts of it. Miki et al. (2005) compared Florida rocket-triggered
lightning flashes and tower-initiated lightning flashes that are initiated from several different towers, and found that the overall characteristics of the initial stage and the parameters of initial continuous current pulses (ICCPs) were generally similar between the two kinds of flashes. According to whether or not the upward lightning flashes were triggered by prior lightning activity near the high structure, Wang et al. (2008) classified them into self-initiated and other-triggered upward flashes. Jiang et al. (2014) analyzed the characteristics of upward lightning flashes, including both self-initiated and other-triggered events, from a 325-m meteorology tower in Beijing, and found an impulsive electric field (E-field) waveform associated with the UPL superposing upon the base E-field slope during its very initial stage, indicating a step-like leader development. In addition, Visacro et al. (2017) compared the initial stage of the other-triggered upward lightning and that of the negative cloud-to-ground flash by using the simultaneous current and close E-field data. However, the resolution of existing electromagnetic field data is relatively low, which cannot discern the weak discharge processes clearly.

Benefitting from the high sensitivity of the self-developed magnetic field (B-field) antenna, some weak discharge processes during the initial stage of tower-triggered lightning were well discerned and analyzed (Fan et al., 2018, 2019, 2020; Lu et al., 2014, 2016). Note that the B-field antenna was firstly applied into the SHAndong Triggering Lightning Experiment (SHATLE) in 2013 (Lu et al., 2014), and then was introduced to the rocket-triggered lightning experiment of Field Experiment Base on Lightning Sciences, China Meteorological Administration (CMA-FEBLS), formerly known as Guangdong Comprehensive Observation Experiment on Lightning Discharge (GCOELD), in 2015. As another important part of the CMA-FEBLS, the Tall-Object Lightning Observatory in Guangzhou (TOLOG) has been conducting the observation of lightning flashes initiated from or striking to the tall structures since 2009 (Lu et al., 2012, 2013). The high-sensitivity B-field antenna was deployed in the TOLOG in the summer of 2018, mainly focusing on the weak discharge processes during the initial stage of tower-initiated upward lightning, and the circuit parameters were adjusted in the summer of 2019 according to the observations of the previous year.

This paper shows the high-sensitivity electromagnetic field measurements of upward lightning flashes that are initiated from the 600-m Canton Tower, which is the tallest structure in the viewing range and about 3.3 km from the TOLOG. Combining with the high-speed video observations, the paper analyzes the electromagnetic characteristics of UPL in different stages of tower-initiated upward lightning. The new measurements are also examined by comparing with observations of rocket-triggered lightning during the GCOELD campaign.

2. Measurements and Data

The TOLOG is located on the top of a 25-storied building of the Guangdong Meteorological Bureau with a height of approximately 100 m, and the experiment settings and equipment layout have been described in detail by Lu et al., 2012, 2013. Figure 1 gives the schematic diagram for the comprehensive measurements of the upward lightning initiated from the Canton Tower, which is about 3.3 km away from the TOLOG. After the circuit adjustment of the B-field antenna, six observed lightning flashes were confirmed as upward lightning initiated from the Canton Tower in 2019, and all the six upward lightning flashes were triggered by nearby lightning flashes. In addition, the B-field signals of rocket-triggered lightning obtained during the GCOELD campaign of 2019 are also used in the paper. The detailed information about the campaign and the improved B-field antenna has been introduced by Fan et al. (2020) and Zhang et al. (2014). For the convenience of discussions, in Table 1, we provide the relevant information of the cases examined in the paper.

The image of upward lightning shown in Figure 1 was obtained at 0956:46 UTC on 12 June 2019 (TI#05) by the Photron FASTCAM high-speed video camera SA3 with a frame rate of 1,000 fps. One of the orthogonal induction coils of the high-sensitivity B-field antenna is deployed in the circumferential tangential direction centered on the Canton Tower, in order to acquire the magnetic signals of initial UPL to the greatest extent. The frequency response of the magnetic antenna from the calibration in the laboratory is also shown in Figure 1. The E-field signals are measured by both fast antenna (with time constant of 0.1 ms and bandwidth of 1.6 kHz–2.5 MHz) and slow antenna (with time constant of 6 s and bandwidth of 0.03 Hz–2.5 MHz), and the optical brightness signals of the upward flash are also recorded by the Lightning Attachment Process Observation System (LAPOS) (Wang et al., 2011), which is focused on the attachment process occurring...
near the Canton Tower top. The signals from the B-field antenna, the fast/slow antenna, and the LAPOS used in the paper were recorded synchronously, with a recording rate of 5 MHz and a recording duration of 2 s.

3. Overviews of Canton-Tower-Initiated Upward Lightning Flashes of TI#05 and TI#03

Figure 2 provides comprehensive observations of TI#05. As mentioned above, this upward lightning belongs to the other-triggered upward lightning. The black waveform shown in Figure 2a gives the fast E-field change during all stages of the upward lightning. Note that in Figure 2a and other figures in this paper, we use the “atmospheric electricity” convention of E-field, and therefore the positive-going change in E-field indicates increasing positive charges aloft. The three shadows with different colors separate the E-field change processes with different trends. In particular, the overall trend of the fast E-field during Stage 1 (S1)

| Flash name | Flash type       | Data         | UTC         | Figure(s)    |
|------------|------------------|--------------|-------------|--------------|
| TI#01      | Tower-initiated  | June 10, 2019| 0933:51     | Figure 8a    |
| TI#02      | Tower-initiated  | June 10, 2019| 0935:43     | Figure 8b    |
| TI#03      | Tower-initiated  | June 10, 2019| 0940:30     | Figures 4 and 8c |
| TI#04      | Tower-initiated  | June 12, 2019| 0952:21     | Figure 8d    |
| TI#05      | Tower-initiated  | June 12, 2019| 0956:46     | Figures 1–3, 5, 6, 7, 8e |
| TI#06      | Tower-initiated  | June 24, 2019| 0627:00     | Figure 8f    |
| RT#01      | Rocket-triggered | July 7, 2019  | 1006:44     | Figure 9     |
is declining, and this stage is associated with nearby discharges triggering the upward lightning. This stage lasts about 137 ms. Synchronized video observation from the high-speed camera indicates that Stage 3 (S3) corresponds to the propagation of UPL initiated from the Canton Tower, and the right boundary of S3 corresponds to the time when the extension of UPL channel cannot be well discerned due to cloud cover. For Stage 2 (S2) that lasts about 13 ms, the fast $E$-field generally shows an upward trend, but with smaller rising rates than the inception of S3.

The blue waveform shown in Figure 2a gives the real $E$-field change that has been corrected (de-drooped) to compensate for the time constant of the fast antenna (Sonnenfeld et al., 2006). It can be seen that the waveform of de-drooped fast $E$-field is highly similar to that of the slow $E$-field shown in Figure 2b, whose time constant is 6 s. Even though the fast $E$-field of S2 shows an upward trend, the real $E$-field change during this stage is still declining until the inception of S3. Since the fast $E$-field can reflect the instantaneous change of the $E$-field, the observation indicates that there exist some discharges during S2, whose polarity is same as that of the sustained UPL of S3. It is inferred that these discharges are associated with attempted leaders, like the precursors in rocket-triggered lightning (Willett et al., 1999). Thus, S2 are also called precursor-like stage in the paper, and the detailed characteristics of the stage are analyzed in Section 4. However, the
discharges triggering the upward lightning continue during S2, and their strengths are stronger than the precursor-like discharges, which maintains the decline of the $E$-field.

Figure 2c shows the $B$-field signals measured by the same magnetic antenna design used for the rocket-triggered lightning experiments (e.g., Fan et al., 2018, 2019; Lu et al., 2016). Unlike the fast/slow $E$-field, the overall characteristics of the $B$-field signals present abundant magnetic pulses during the entire stage of the upward lightning. Since the sensitivity of the magnetic antenna was chosen to capture the UPL of the initial stage, the $B$-field signals associated with strong discharge processes are saturated, especially for the ICCPs and return strokes. It can be seen that the magnetic-pulse density of S1 is much lower than that of S2 and S3, which provides another criterion for dividing different stages. The detailed characteristics of the $B$-field signals are also analyzed in Section 4.

Figure 2b also gives the optical brightness signals of the upward lightning (black waveform) recorded by the LAPOS. The brightness begins to increase upon the inception of the sustained UPL of S3. In addition, Figures 3a–3d show the images of UPL channel at different development stages of the upward lightning. These images were captured by the high-speed video camera with a frame rate of 1,000 fps, and were color-inverted and contrast-enhanced (hereinafter inclusive) to show the leader channel more clearly. Figure 3e shows the three-dimensional (3-D) lightning channel reconstructed by the dual-station optical systems, as reported previously by Qi et al. (2018). Note that only the lightning channel before 46.313987 s was reconstructed, mainly due to the limitation on the camera field-of-view. Like the measurements from LAPOS, the leader channel cannot be identified until the inception of S3. The first image that identifies the leader inception from the tower is at 46.306987 s (Figure 3a), and its detail is shown in the zoomed view (Figure 3b). The first subsequent return stroke occurs at about 46.7 s (Figure 3d), about 400 ms after the inception of sustained UPL.

To the best of our knowledge, the precursor-like stage observed before the inception of sustained UPL has not been reported previously. However, it is likely a common stage for other-triggered upward lightning initiated from the Canton Tower. Figure 4 shows the electromagnetic field observations for another Canton-Tower-initiated upward lightning, which was obtained at 0940:30 UTC on 10 June 2019 (TI#03). The electromagnetic characteristics of the case is quite similar to the upward lightning analyzed above, and the discharge processes can be also divided into three stages using the same criterion shown in Figure 2a. The inset of Figure 4a shows that the occurrence of $E$-field pulses is accompanied by a rising change of fast
E-field, indicating that the source of ascending variation during S2 is these E-field pulses associated with the attempted leaders. Similarly, there also exists some declining phases during S2, since nearby discharges triggering the upward lightning are in progress. As a matter of fact, the de-drooped E-field (blue waveform) is monotonic decreasing until the inception of S3, demonstrating that nearby discharges are dominant in S2 relative to the discharges of attempted leaders.

4. Analyses and Results

4.1. Electromagnetic Radiation of Attempted UPL During Precursor-Like Stage

Figure 5 shows the fast E-field (Figure 5a) and B-field (Figure 5b) before and after the boundary of S1 and S2 of TI#05. The insets in Figure 5b give some details of the B-field with the time window of 200 μs, and the corresponding E-field of the enlarged portions are also marked with numbers in Figure 5a. It can be seen from Figure 5a that small E-field pulses are superposed on the E-field variations during S2, and these E-field pulses are probably corresponding to the attempted leaders initiated from the Canton Tower, just like the precursors measured before the inception of sustained UPL of rocket-triggered lightning. The timescale of B-field pulses (zoom in 3) corresponding to the E-field pulses (marked with 3) is 5–9 μs, and the typical inter-pulse interval is about 30 μs. The duration of the precursor-like stage in the case lasts about 13 ms.

Note that the boundary (red dashed line) in Figures 5a and 5b is set before the E-field pulses tentatively, since we cannot sure the rising phases before the boundary is causing by the effect of the time constant or by the E-field pulses that are not discerned. The fast E-field generally shows an upward trend during S2, but it exhibits a declining trend at about 46.3 s. The zoomed view shows that the polarity of the magnetic pulses around 46.3 s (zoom in 4) is opposite to that of the magnetic pulses corresponding to the E-field pulses (zoom in 3), but is same with that of the magnetic pulses during S1 (zoom in 2). The observation indicates
that the declining phase of S2 is attributed to nearby discharges triggering the upward lightning, which are same with the processes of S1. It is noteworthy that some abnormal E-field pulses (marked with 1) are recorded during S1, and the detailed B-field signals corresponding to these E-field pulses are shown in the inset of “zoom in 1”. These B-field pulses exhibit similar characteristics to the B-field pulses shown in the inset of “zoom in 3”, at least with the same polarity, but the trends of the E-field change during the two phases are opposite. It is suspected that these abnormal E-field pulses are also caused by the attempted leaders with weak discharge intensity, but it is difficult to recognize the exact beginning of the precursor-like stage based on the existing observations. The precursor-like stage of the upward lightning should initiate no later than the time marked by the red dashed line.

4.2. Correlation of Pulse Rate and UPL Velocity During Sustained Stage

Figure 6 shows the fast E-field (Figure 6a) and B-field (Figure 6b) before and after the boundary of S2 and S3 of TI#05. The insets in Figure 6b give the details of the B-field associated with the sustained UPL, and the enlarged portions with the time window of 700 μs (200-μs S2 & 500-μs S3, zoom in 1) and 500 μs (zoom in 2) are marked in Figure 6b. In comparison with the boundary between S1 and S2 of the upward lightning shown in Figure 5, the boundary between S2 and S3 is much easier to distinguish from the observations of B-field. It can be seen that the B-field pulses become much denser after the inception of sustained UPL, and the corresponding fast E-field increases rapidly. The B-field pulses shown in the 500-μs part of “zoom in 1” overlap each other, so that the individual B-field pulse cannot be identified. The observations strongly suggest that the initial velocity of the sustained UPL of the upward lightning is very high, for the photographically measured leader extension rate is approximated by the pulse rate. Therefore, it is probable that the velocity of the sustained UPL decreases with time, since the B-field pulses shown in “zoom in 2” are no longer overlapped, that is, a reduction in pulse rate corresponds to a reduction of leader velocity.
Figure 7 gives 20 consecutive images of sustained UPL by SA3. The first image that identifies the leader is at 46.306987 s (see Figure 3b for details), about 330 μs after the inception of the sustained UPL, and the last image shown in Figure 7 is at 46.321987 s. Starting with the second image, the extension length of the UPL channel relative to the previous frame is given in the image, and the average 2-D velocity of the UPL between the two frames is calculated, which is also superposed in Figure 6b (blue solid circles). Since the 3-D lightning channel was partially reconstructed in the paper, the estimated average 3-D velocity of upward leader channel shown in the first eight images is also superposed in Figure 6b (red solid circles). It can be seen that the UPL channel extends significantly in the first few milliseconds, with the initial average 2-D velocity of $8.77 \times 10^5$ m/s (3-D velocity of $11.0 \times 10^5$ m/s), but the propagation speed decreases rapidly and maintains at about $0.5 \times 10^5$ m/s (2-D) as the further development of UPL. The variation trend of the average velocity corresponds to the density of the $B$-field pulses shown in Figure 6b well.

In order to make it clear that the velocity of sustained UPL decreases with time is a common phenomenon or a special case, Figure 8 compares the 4-ms $B$-field signals after the inception of sustained UPL of all the six upward lightning flashes listed in Table 1. The $B$-fields exhibit consistent characteristics, indicating that the velocity trends during the propagation of the UPL are similar in all the cases. The durations of the overlapped pulses shown in Figure 8 are from the inception of S3 to the moment of the occurrence of the first individual pulse. Although the inception of UPL was not captured by the high-speed camera for most cases shown in Figure 8, it can be inferred that the initial velocity of sustained UPL is very high for the occurrence of overlapped $B$-field pulses. Furthermore, the duration of the overlapped $B$-field pulses is within 2 ms for all the upward lightning flashes. Since the $E$-fields around the Canton Tower are distorted seriously, which may promote the development of UPL, the consistency in the duration of overlapped $B$-field pulses is probably associated with the enhancement range of tower on the environmental $E$-field.
4.3. Comparison of Precursors and Sustained UPL Between Rocket-Triggered and Tower-Initiated Lightning

Unlike the TOLOG that located in the downtown area of Guangzhou, the rocket-triggered lightning site is situated in the remote suburb. Even though the 3-dB bandwidth of the $B$-field antenna at rocket-triggered lightning site (20 kHz-1.2 MHz) is much wider than that at TOLOG (107–545 kHz), the intensity of the background noise measured at rocket-triggered lightning site is 3 times smaller. The signal to noise ratio (SNR) of the $B$-field is 45 and 33 dB, respectively for rocket-triggered lightning site and TOLOG. Figure 9 shows the $B$-field associated with the precursors (Figure 9a) and sustained UPL (Figure 9b) of the rocket-triggered lightning at 1,006:44 UTC on 7 July 2019 (RT#01). In accordance with the insets given in Figure 5b, some $B$-field pulses of the precursors are also shown with the time window of 200 μs in Figure 9a. Both the timescale and the typical inter-pulse interval of $B$-field pulses shown in the insets of Figure 9a are similar to the values of those pulses shown in the insets of Figure 5b, indicating that there exists similar development characteristics for rocket-triggered and tower-initiated lightning during the precursor stage. However, the duration of the precursor stage for RT#01 (about 900 ms) is much longer than that for the tower-initiated lightning (about 77 ms for TI#03 and 13 ms for TI#05), which is probably related to the different increasing rate of $E$-field intensity at the leader tip during its propagation of the two kinds of upward
flashes. It is interesting that the polarities of $B$-field pulses in Figures 5b and 9a are bipolar and unipolar, respectively. Since these pulses are recorded at range of about 3.3 km and 80 m, respectively, the observation mainly reflects the difference in the proportion of $B$-field components in the two cases, that is, the dominant $B$-field components for them are radiation and induction component respectively.

As analyzed above, the initial 2-D velocity of the sustained UPL of the tower-initiated lightning is up to $8.77 \times 10^5$ m/s, and the propagation speed decreases rapidly and maintains at about $0.5 \times 10^5$ m/s (2-D) as the further development of UPL. However, the UPL development velocity for the rocket-triggered lightning exhibits different characteristics. Lots of observations indicated that the 2-D velocity of UPL in rocket-triggered lightning was in the order of $10^4$ m/s when it occurred at the wire tip (Biagi et al., 2009; Fieux et al., 1978; Jiang et al., 2013), and increased to the order of $10^6$ m/s with the increasing height of UPL (Yoshida et al., 2010). The zoomed views with the time window of 500 ms shown in Figure 9b gives the detailed $B$-field pulses during the sustained UPL stage of the rocket-triggered lightning, and the inset of “zoom in 3” corresponds to the inception of sustained UPL. As reported by Lu et al. (2016), these $B$-field pulses shown in “zoom in 3” can be divided into impulsive pulses and ripple pulses by the red dashed line.

Figure 8. Comparison of the 4-ms $B$-field signals after the inception of sustained UPL of all the six upward lightning flashes listed in Table 1.
The impulsive pulses are produced by current pulses propagating downward along the high-conductivity steel wire, but the ripple pulses are caused by the attenuation of impulsive current along prolonging leader channel (Fan et al., 2018). In comparison with the initial stage of sustained UPL of tower-initiated upward flashes ("zoom in 1" in Figure 6b), the $B$-field pulses shown in "zoom in 3" in Figure 9b are separated with each other with the average inter-pulse interval of 21.9 μs, and then it decreases to 17.1 μs in "zoom in 4", showing an acceleration trend during the propagation.

The key of the inception of sustained UPL is that the $E$-field of leader tip exceeds the breakdown threshold, and a stronger electric field is expected to bring a faster initial velocity. The reason for the great difference in the development speed of sustained UPL is probably that the modes of $E$-field enhancement at the leader tip for the two kinds of lightning flashes differ a lot. For the rocket-triggered lightning, the $E$-field enhancement is caused by the ascending rocket dragging the steel wire into higher altitude with stronger environmental electric field. However, affected by the tower body (454 m) and the antenna mast (146 m), the electric fields at the tip of the Canton Tower are distorted seriously. Under the circumstances, the instantaneous $E$-field enhancement caused by the nearby discharge processes will create a favorable condition for the initiation of sustained UPL, making the $E$-field of leader tip largely exceeds the breakdown threshold. Nevertheless, this favorable condition is consumed significantly during the development of UPL, which is evident in the decrease in velocity of the UPL.

We note that Jiang et al. (2014) reported the observations of lightning flashes striking at a 325-m meteorology tower in Beijing. Since the frame rate of high-speed video camera used in their observations is 10,000 fps, we get the average velocity of UPL during the first millisecond by using the first ten average velocity of 100 microseconds in the paper. The average 2-D velocities for the UPL of two upward lightning flashes are $7.0 \times 10^4$ m/s and $6.2 \times 10^4$ m/s respectively for the first one millisecond, which are one order smaller than...

Figure 9. Measurements of $B$-field of (a) precursor stage and (b) sustained stage for the rocket-triggered lightning at 1006:44 UTC on 7 July 2019 (RT#01).
that of the Canton-Tower-initiated upward lightning, but exhibit an acceleration trend during the propagation. Considering that the height and size of the meteorology tower are much smaller than those of the Canton Tower, it is inferred that the initiation of sustained UPL of tower-initiated lightning is affected by the physical or geometric properties of the tower, that is, the initial velocity of the sustained UPL could be subject to more dispersion for different towers.

5. Conclusions

The electromagnetic characteristics of UPL for the other-triggered upward lightning initiated from the Canton Tower are examined in the paper. The discharge processes of the upward lightning can be divided into three stages from the fast E-field waveform, including nearby discharges stage triggering the upward lightning (S1), the precursor-like stage (S2) and the sustained UPL stage (S3). The overall trend of fast E-field during S2 is rising according to the atmospheric electricity convention, but the real E-field change that has been corrected to compensate for the time constant of the fast antenna during this stage is still declining. In addition, small E-field pulses are superposed on the E-field variations during S2, indicating that there exist some small-scale discharges. The timescale of B-field pulses corresponding to the E-field pulses is 5–9 μs, and the typical inter-pulse interval is about 30 μs, which are both similar to the values of B-field pulses associated with the precursors of rocket-triggered lightning. Thus, the small-scale discharges during S2 are probably the attempted UPL initiated from the Canton Tower, and the precursor-like stage is likely a common phase for other-triggered upward lightning initiated from the Canton Tower. For the tower-initiated upward lightning analyzed in the paper, the UPL channel extends significantly in the first few milliseconds, with the initial average 2-D velocity of 8.77 × 10^5 m/s (3-D velocity of 11.0 × 10^5 m/s), but the propagation speed decreases rapidly and maintains at about 0.5 × 10^5 m/s (2-D) as the further development of UPL. By contrast, the duration of the precursor stage for rocket-triggered lightning is much longer than that for the tower-initiated lightning. The initial 2-D velocity of the sustained UPL of rocket-triggered lightning is on the order of 10^6 m/s, and shows an acceleration trend during the propagation. These differences between the two kinds of flashes probably related to the different of increasing rate of E-field intensity at the leader tip during its propagation of the two kinds of upward flashes.

Data Availability Statement

The data examined in this paper can be downloaded from online (https://doi.org/10.5281/zenodo.5565580).

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