Four ways of how downward and upward leaders make connection during the lightning attachment process

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ABSTRACT: The high-speed images of 18 downward negative lightning flashes to tall structures in Guangzhou are selected to analyze the connecting behavior of the downward and upward leaders during the attachment process. The leaders' connecting behavior can be grouped in four types: Type I, the tip of downward leader (DL) to the tip of upward connecting leader (UCL), accounts for 33% (6/18); Type II, the DL's tip to the lateral surface of UCL, accounts for 50% (9/18); Type III, the UCL's tip to the lateral surface of DL, accounts for 6% (1/18); and Type IV, the combination of at least two of the aforementioned three types, accounts for 11% (2/18). The presence of multiple leader branches (DL, UCL, or both) or multiple UCLs is likely to be the main reason for the diversity of the leaders' connecting behavior.

INTRODUCTION

The lightning attachment process is one of the least understood lightning processes. Understanding of the lightning attachment process is vital for improving lightning protection techniques [e.g., Rakov and Uman, 2003; Uman, 2008]. Dwyer and Uman [2014] compiled a list of the top ten unanswered questions in lightning research, in which the third one is "What is the physical mechanism of leader attachment to elevated objects on the ground and to the flat ground? What are the characteristics of upward connecting leaders from those objects or from the ground?".

Recent introduction of advanced instrumentation for the optical imaging of lightning enables us to make new insights into the lightning attachment process [e.g., Warner, 2010; Wang et al, 2011; Lu et al., 2012, 2013]. Warner [2010] presented high-speed video observations (up to 11,000 frames per second, fps) of 6 downward negative stepped leaders and associated non-connecting and connecting upward leaders from tall towers in Rapid City, South Dakota, USA. A new high-speed optical imaging system for studying lightning attachment process, named LAPOS (Lightning Attachment Process Observation System), has been developed by Wang et al. [2011] and used to observe the attachment process of both

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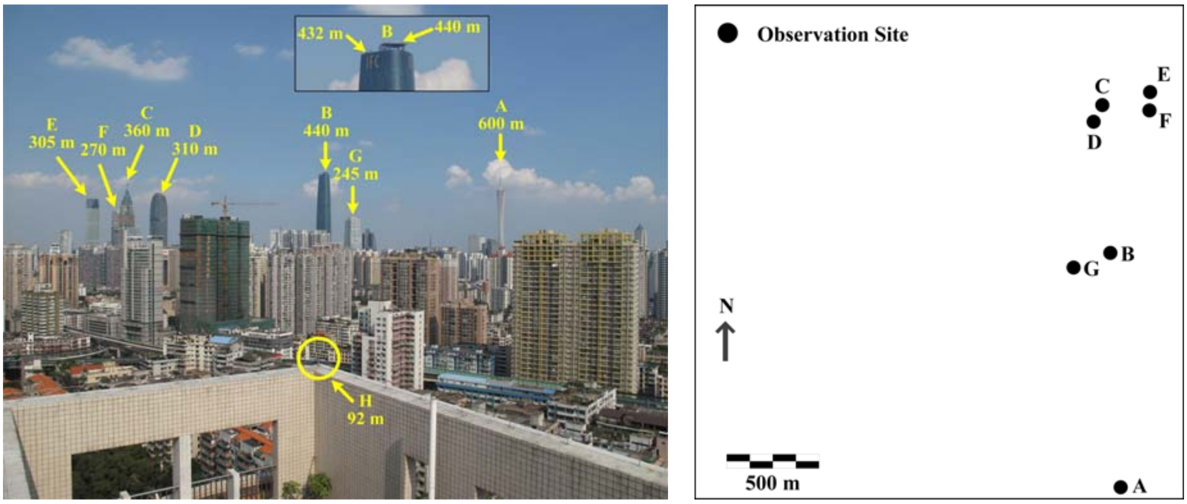
natural and rocket triggered lightning. Lu et al. [2012] analyzed the characteristics of 45 unconnected upward leaders that occurred in 19 downward negative flashes to tall structures in Guangzhou.

As the downward leader (DL) and the upward connecting leader (UCL) approach each other, it is generally thought that the DL's tip and the UCL's tip will come in contact with each other. However, Lu et al. [2013] presented a negative lightning flash with the junction point between the DL's tip and the lateral surface of UCL. Are there any other scenarios when the DL and the UCL make contact? This paper will discuss this by analyzing lightning flashes to tall structures observed in Guangzhou during 2009-2012.

EXPERIMENT

A field experiment, mainly focusing on the observation of lightning flashes terminating on tall structures, has been conducted since 2009 in Guangzhou, Guangdong, China. The Tall-Object Lightning Observatory in Guangzhou (TOLOG) was established. Detailed information about the experiment and the instruments installed at the TOLOG can be found in Lu et al. [2012, 2013]. Three high-speed cameras, two Photron FASTCAM SA5 (HC-1 and HC-2) and one Photron FASTCAM SA3 (HC-3), are installed to capture the high-speed images of the flashes. They are operated at sampling rates of 10,000 fps (100 μs per frame), 50,000 fps (20 μs per frame), and 1000 fps (1 ms per frame), respectively. The higher the sampling rate, the smaller the field of view (FOV) of the high-speed camera.



(a) (b)

Figure 1. The tall structures in the field of view. (a) A photo captured on July 5, 2011. (b) The plan view of the positions of the tall structures higher than 200 m. Structures labeled A through E are taller than 300 m. Adapted from Lu et al. [2012].

The tall structures in the FOV of HC-3 are shown in Fig. 1. As we known, the higher the structure, the earlier the UCL can be initiated from the top of the structure and the longer the UCL can extend. If the length of the UCL is not long enough, it is hard to capture it by our high-speed cameras and, hence, it is almost impossible to analyze the leaders' connecting behavior during the attachment process. In this paper, only those flashes to the five structures higher than 300 m, A-E in Fig. 1, are analyzed. All of the flashes observed at the TOLOG are numbered as "FYYsn," in which "YY" denotes the last two digits of the year and "sn" denotes the sequential number of the flash in all flashes recorded in the year "YY".

ANALYSIS AND RESULTS

During 2009-2012, a total of 29 lightning flashes with terminations on the structures labeled A-E were captured by our high-speed cameras. All of them are downward negative flashes. Among the 29 flashes, the number of flashes that struck each structure is given in Table 1. It should be noted that the actual numbers of flashes terminated on structures A-E should be larger than the numbers given in Table 1 for the following reasons: the high-speed cameras need some time (dead time) to save images to computers for each event and those flashes that happen during the dead time cannot be captured; the FOVs of the high-speed cameras were not fixed during the experiment and sometimes some structures were out of the FOVs; sometimes the visibility was very low (mostly caused by heavy rain) and some flashes even in the FOVs could not trigger our systems.

Table 1 Number of lightning flashes observed during 2009-2012

Structure#	Height	Number of cases observed	Number of cases that can be used to analyze the leaders' connecting behavior
A	610 m (2009) 600 m (after 2009)	11	5
B	440 m	9	8
C	360 m	7	4
D	310 m	0	0
E	305 m	2	1
Total	-	29	18

Structures A and B were erected in 2009. Structures C, D, and E were erected in 2010.

Although a total of 29 flashes were captured, the high-speed images of 11 flashes are not suitable for the analysis of the connecting behavior of the DL and the UCL during the attachment process for the following two reasons. The first one is the invisibility of the lightning channel (part or whole) due to the low visibility or the cloud obscuration, which is the reason for 6 flashes to A, 1 flash to B, and 1 flash to E. The second reason is the low sampling rate of the high-speed images captured by HC-3, which is the reason for 3 flashes to C.

Overall, there are 18 flashes to 4 structures (A, B, C, and E) that can be used to analyze the leaders' connecting behavior during the attachment process. The preliminary analysis results show that the connecting behavior can be grouped in four types.

Type I: Tip-to-Tip

In Lu et al. [2010], two flashes (one, flash F0905, to A and the other one, flash F0911, to B) were presented. Both of them exhibit the connection of the DL's tip to the UCL's tip (Tip-to-Tip, Type I). Fig. 2 shows another case, flash F1263, observed in 2012. It can be seen that under the influence of the DL with many branches, there are three long upward leaders initiated from A, B, and C. For the three upward leaders, although each tip moves obviously higher than the lowest tip of the nearby DL branch in the two-dimensional (2-D) image (Fig. 2a), only the upward leader initiated from A makes contact with a branch of the DL (Fig. 2b). From the high-speed images captured by HC-1 (Fig. 2) and HC-2 (not shown here), it can be determined that the DL and the UCL of F1263 exhibit the “Tip-to-Tip” connection, which is also evidenced by the smooth shape of the lightning channel near the junction point (which is between the tips of the DL and the UCL seen in Fig. 2a). Among the 18 flashes, only 1/3 (6, 33%) exhibit the Type I connecting behavior (“Tip-to-Tip”).

(a) -0.1 ms (b) 0.6 ms

Figure 2. (a and b) High-speed video camera (HC-1) images of flash F1263 captured with a sampling rate of 10,000 fps. Time 0 is set at the beginning of the first return stroke.

Type II: the DL’s Tip to the lateral surface of UCL

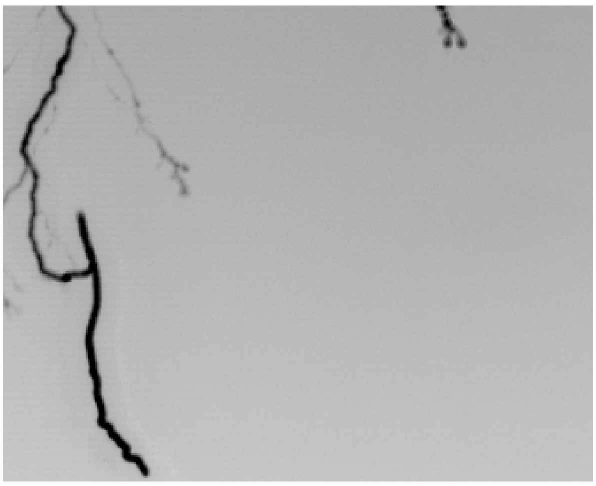
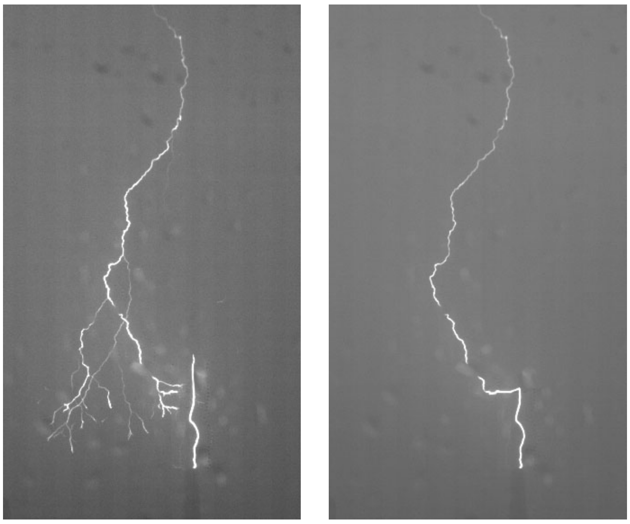


Figure 3. A 76-frame composite image of flash F1111 acquired using HC-2 operating with a sampling rate of 50,000 fps. The image is inverted for a better view. Adapted from Lu et al. [2013].

The non-“Tip-to-Tip” connecting behavior during the lightning attachment process was first reported by Lu et al. [2013]. From Fig. 3 (Fig. 2f in Lu et al. [2013]), it can be clearly seen that the connection occurs between DL’s tip and the lateral surface of UCL, a point over 67 m below the UCL’s tip. In this flash, it is found that: The effect of the DL on the UCL is significant, especially during the final 160 μs preceding the beginning of return stroke, during which the UCL’s speed quickly increase from the order of 10^5 m/s to the order of 10^6 m/s and the UCL’s luminosity exhibits fast increase too; While the effect of the

UCL on the DL appears to be negligible until the distance between the leaders decreases to less than approximately 60 m. After that, the DL bends sharply toward the UCL and both the speed and the luminosity of the DL show significant increasing trend; the ratio of the DL's speed and the UCL's speed exhibits an overall trend to decrease and can be significantly less than 1, which means the UCL's speed can significantly exceed that of the downward leader.

Fig. 4 shows two high-speed images of another flash, which terminated on structure B. In this flash, the 2-D length of the UCL part above the junction point is over 130 m. From the high-speed images of the return stroke channel, e.g. Fig. 4b, it can be seen that the shape of the lightning channel near the junction point is not smooth but is turning abruptly, at almost right angle.



(a) -0.1 ms (b) 0.6 ms

Figure 4. (a and b) High-speed video camera (HC-1) images of flash F1247 captured with a sampling rate of 10,000 fps. Time 0 is set at the beginning of the first return stroke. The brightness and contrast of this figure are enhanced for a better view.

50% (9) of the 18 flashes exhibit the connection of the DL's tip to the lateral surface of UCL (Type II). In the 2-D images, most of the flashes showing Type II connecting behavior have return stroke channels with abrupt turns near the junction point, like that seen in Fig. 4b. Among the flashes to structures higher than 300 m in Guangzhou, Type II flashes are more common than Type I ones.

Type III: the UCL's Tip to the lateral surface of DL

Two frames of the HC-1 images of flash F1222 are shown in Fig. 5. The termination of this flash is on structure C, which is 360 m high. In flash F1222, it looks like that the UCL directly strikes a point (makes it a junction point) on a branch of the DL over its tip, i.e. strikes the lateral surface of the DL. From the HC-1 images, there is no distinguishable DL sub-branch initiated at the junction point before the first return stroke. The connection of the UCL's tip to the lateral surface of DL constitutes Type III connecting behavior.

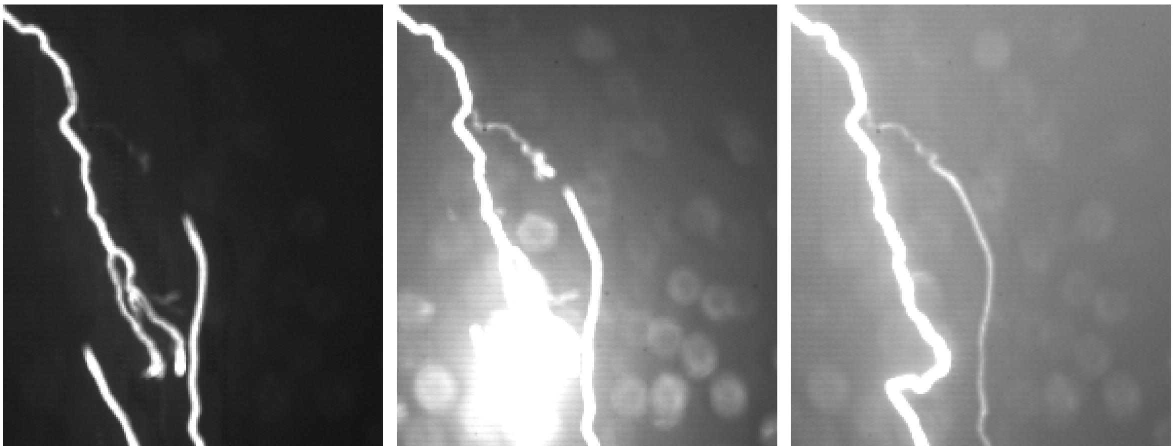
The 2-D length of the UCL in flash F1222 is longer than 530 m. In Fig. 5a, the last frame before the first return stroke, the height difference between the tips of the UCL and the DL branch that facilitated connection to the UCL is over 360 m. The 2-D channel length of the DL branch (facilitating connection to the UCL) below the junction point is approximately 495 m.

Although 16 (89%) of the 18 flashes have upward leaders with tips higher than the lowest tips of the DLs (in the 2-D images) before the final connection and 9 of them exhibit Type II connecting behavior, only flash F1222 exhibits Type III connecting behavior in our data set.

(a) -0.1 ms (b) 1.1 ms

Figure 5. (a and b) High-speed video camera (HC-1) images of flash F1222 captured with a sampling rate of 10,000 fps. Time 0 is set at the beginning of the first return stroke.

Type IV: Combination type



(a) -20 μs (b) 0.00 ms (c) 0.30 ms

Figure 6. (a, b, and c) High-speed video camera (HC-2) images of flash F1248 captured with a sampling rate of 50,000 fps.

Fig. 6 shows three frames of HC-2 images of flash F1248, which terminated on structure B. It can be seen that there are two upward leaders initiated from the top of B and both of them make contact with the

DL in this flash. The left UCL makes contact with the DL a little earlier than the right UCL. The left attachment process exhibits Type II connecting behavior and the right one exhibits Type I, so that the connecting behavior of flash F1248 is assigned to Type IV, which includes combinations of at least two of the other three types.

Besides flash F1248, there is another flash (F1264, not shown here) that exhibits Type IV connecting behavior, which is also combination of Type I and Type II.

CONCLUSIONS

High-speed video camera records, with sampling rates of at least 10,000 fps, of 18 lightning flashes to tall structures in Guangzhou are examined. The diversity of the connecting behavior between the downward and upward leaders during the attachment process is revealed. Only 1/3 of the 18 flashes exhibit "Tip-to-Tip" connection and 2/3 of them exhibit non-"Tip-to-Tip" connection. Half of the 18 flashes exhibit the connection of the DL's tip to the lateral surface of UCL. Only one flash exhibits the connection of the UCL's tip to the lateral surface of DL. Two flashes exhibit the combination-type connecting behavior.

The presence of multiple leader branches or multiple upward leaders is likely to be the main reason for the diversity of the leaders' connecting behavior during the attachment process. This paper presents some preliminary analysis results. More detailed analysis of the data is in progress.

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REFERENCES

Dwyer, J. R. and M. A. Uman, 2014: The physics of lightning. *Physics Reports*, **534**: 147-241.

Lu, W., Y. Zhang, L. Chen, E. Zhou, D. Zheng, Y. Zhang, and D. Wang, 2010: Attachment processes of two natural downward lightning flashes striking on high structures, paper presented at *30th International Conference on Lightning Protection*, Power and Energy Soc., Cagliari, Italy.

Lu, W., L. Chen, Y. Zhang, Y. Ma, Y. Gao, Q. Yin, S. Chen, Z. Huang, and Y. Zhang, 2012: Characteristics of unconnected upward leaders initiated from tall structures observed in Guangzhou, *J. Geophys. Res.*, **117**, D19211, doi:10.1029/2012JD018035.

Lu, W., L. Chen, Y. Ma, V. A. Rakov, Y. Gao, Y. Zhang, Q. Yin, and Y. Zhang, 2013: Lightning attachment process involving connection of the downward negative leader to the lateral surface of the upward connecting leader, *Geophys. Res. Lett.*, **40**, 5531–5535, doi:10.1002/2013GL058060.

Rakov, V. A., and M. A. Uman, 2003: *Lightning: Physics and Effects*, Cambridge University Press, New York, USA.

Uman, M. A., 2008: *The Art and Science of Lightning Protection*, Cambridge University Press, New York, USA.

Wang, D., T. Watanabe, and N. Takagi, 2011: A high speed optical imaging system for studying lightning attachment process, in *Proc. of 7th Asia-Pacific Lightning Conference*, Chengdu, China.

Warner, T. A., 2010: Upward leader development from tall towers in response to downward stepped leaders, paper presented at *30th International Conference on Lightning Protection*, Power and Energy Soc., Cagliari, Italy.