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Positive leader characteristics from high-speed video observations

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[1] Based on analyses of high-speed video recordings of cloud-to-ground lightning in Brazil and the USA, the characteristics of positive cloud-to-ground (+CG) leaders are presented. The high frame rates permitted the average, 2-dimensional speeds of development along the paths of the channels to be resolved with good accuracy. The values range from 0.3 to 6.0 $\times$ 10^5 ms^{-1} with a mean of 2.7 $\times$ 10^5 ms^{-1}. Contrary to what is usually assumed, downward +CG leader speeds are similar to downward −CG leader speeds. Our observations also show that the speeds tend to increase by a factor of 1.1 to 6.5 as they approach the ground. The presence of short duration, recoil leaders (RLs) during the development of positive leaders reveal a highly branched structure that is not usually recorded when using conventional photographic and video cameras. The existence of the RLs may help to explain observations of UHF-VHF radiation during the development of +CG flashes. **Citation:** Saba, M. M. F., K. L. Cummins, T. A. Warner, E. P. Krider, L. Z. S. Campos, M. G. Ballarotti, O. Pinto Jr., and S. A. Fleenor (2008), Positive leader characteristics from high-speed video observations, *Geophys. Res. Lett.*, *35*, L07802, doi:10.1029/2007GL033000.

1. Introduction

[2] Although much is known about negative leaders [*Rakov and Uman*, 2003], the characteristics of leaders that precede positive flashes to ground are not as well understood. Positive leaders usually do not radiate at VHF and UHF frequencies as strongly as negative leaders, and therefore they are often not detected by VHF-UHF lightning mapping systems. This fact partially explains the paucity of information about positive leaders in the literature. According to *Mazur* [2002, p. 1405], "the inability of the lightning mapping techniques (time of arrival and interferometric) to map positive leaders and the absence of other methods to trace downward positive leaders prevents us from discovering the origin of the complex positive CG flashes." *Shao et al.* [1999], after discussing the discrepancy between their results and the bidirectional leader model, claim that more optical investigations are needed to resolve some questions posed in their work.

[3] To date, there have been only two direct measurements of the average vertical speed of a downward-propagating positive leader (although there have been estimates based on the channel length and leader duration [*Brook and Ogawa*, 1977; *Fuquay*, 1982]). The first measurement was by *Berger and Vogelsanger* [1966] who used a streak camera in Switzerland. These authors reported that the propagation speed increased from 3.6 $\times$ 10^5 to 24 $\times$ 10^5 ms^{-1} as the leader approached ground. This leader was identified by *Berger and Vogelsanger* [1966] as positive solely on the basis of its luminosity being similar to upward, positive leaders from towers. Based on this result, positive leader speeds have been thought to be considerably faster than negative leader speeds [*Shao et al.*, 1999; *Rakov and Uman*, 2003], although subsequent studies that have tried to match their observations to this sole measurement have had difficulty [e.g., *Mazur et al.*, 1998; *Shao et al.*, 1999]. A more recent measurement in China by *Kong et al.* [2007], using a high-speed camera operating at 1,000 frames per second, showed that the speed of a single positive leader increased from 0.1 $\times$ 10^5 to 3.8 $\times$ 10^5 ms^{-1} during its descent.

[4] In this report, we will summarize the characteristics of downward-propagating, positive leaders that were recorded with high-speed video cameras. We will also report the existence of negative recoil leaders (RLs) that appear during the leader propagation toward ground. The RLs reveal branching structures that are not usually recorded when using conventional photography or video cameras. The characteristics of the RLs will be described and compared to previously observed features of +CG flashes.

2. Instrumentation

2.1. High-Speed Cameras

[5] Three different high-speed digital video cameras (Photron Fastcam 512 PCI, Red Lake Motion Scope 8000S, and Phantom v7.1) with resolutions and exposure times between 135 microseconds (7,200 frames per second) and 1 ms (1,000 frames per second) were used to record images of cloud-to-ground flashes in southern and southeastern Brazil, in southern Arizona, and in South Dakota (USA) between February 2006 and August 2007. Images were GPS synchronized, time stamped and recorded without any frame-to-frame image persistence. For more details on the accuracy of high-speed cameras techniques for lightning observations see *Saba et al.* [2006a]. For recent high-speed video observations of +CG flashes see *Saba et al.* [2006b, 2007a].

2.2. Lightning Location System

[6] All recordings were obtained in regions that were well covered by lightning locating systems (BrasilDat in

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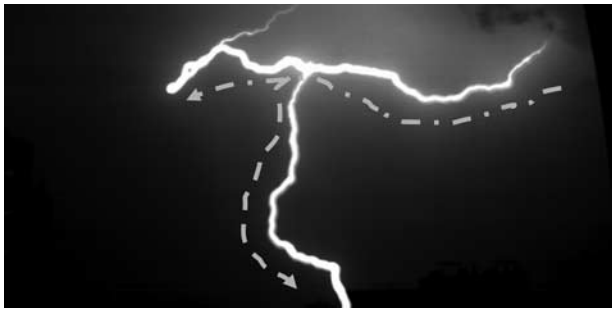

Figure 1. Image of a positive leader emanating from a previous horizontal channel (Tucson, 03:24 UT, July 31, 2007, 6 km from the camera). The dashed arrows show the directions of progression of the horizontal and vertical leaders.

Brazil, and the NLDN in the USA). More information on the characteristics of these networks is found in the works by *Pinto et al.* [2006] and *Cummins et al.* [1998, 2006]. Data from the locating systems were used to obtain the stroke polarity, an estimate of the peak current near the ground, and the location of the ground strike point.

[7] Based on the distances between the camera and the flashes studied (6 to 53 km) and on the geometric characteristics of the camera and lenses used, the 2-D leader speeds were determined. Considering the lightning location errors [*Ballarotti et al.*, 2006; *Biagi et al.*, 2007], we estimate that the errors in the 2-D speed values are less than 30%.

3. Results and Discussion

[8] Although more than 30 +CG flashes were recorded with high-speed video, only 12 cases showed a visible progression of positive leaders (9 events) and/or the presence of recoil leaders (7 events). Distance and rain were the most frequent obstacles to a clear observation. Some characteristics of these flashes are presented in Table S1, available in the auxiliary material[1].

3.1. General Characteristics

[9] Most of the leaders observed in this study began during the occurrence of long and intense intracloud activity. This intense activity preceding +CG was previously observed in electric field records by *Fuquay* [1982] and *Mazur et al.* [1998]. All positive leaders showed a continuous progression toward ground, and no discrete steps could be resolved at the time-resolution of the cameras (135 μs to 1 ms). The tip of the leader was usually brighter, and left behind a channel that was faintly illuminated by a continuing current. When the positive leader tip approached ground, the luminosity of the channel increased. Similar observations were reported by *Mazur et al.* [1998].

[10] Other leader channels that did not reach ground were often present, and their horizontal development produced extensive horizontal channels near the cloud base. In one case it was possible to observe that all channels derived from a common initial channel. In two of our cases, the leader started from one spot of a previously formed horizontal channel and propagated towards ground (see example in Figure 1). Previous studies [e.g., *Fuquay*, 1982] have reported horizontal channels up to tens of kilometers in extent.

[11] The branching in positive leaders appears to be much less profuse than in negative leaders. In two cases, discrete and small branches were observed during the occurrence of the return stroke (see example in Figure 4a).

[12] During the progression of some leaders toward ground, very short duration (less than 135–250 μs) and short extension discharges appear near the path of the downward-propagating leader. This new aspect of channel development will be discussed in section 3.4.

3.2. Partial and Average Speeds

[13] Depending on the leader speed and on the camera frame rate, it was possible to determine the evolution of the speed of the leader along its path towards ground. The speeds measured along the path of the leader were termed *partial speeds*. The *average speed* is calculated by dividing the length of the entire 2-D trajectory by the time taken to cover it. *Berger and Vogelsanger* [1966] found three values for the partial speed in one leader event. These partial speeds were calculated for three heights: 3.6×10^5 ms^{-1} between 1,870–1,660 m; 17×10^5 ms^{-1} between 1,660–920 m; and 24×10^5 ms^{-1} between 920-320 m. Based on these values, we estimate that the average vertical (1-D) speed in this case would be 12×10^5 ms^{-1}. We believe that this value represents an extreme case when compared to our results.

[14] Table 1 summarizes the partial and averaged positive leader speeds obtained in our study, the measurements of *Berger and Vogelsanger* [1966] combined with the results from this study, and the values of negative leader speeds obtained in a previous study that used the same technique as in this work [*Saba et al.*, 2007b]. In Figure 2 we show distributions of the values of partial speed for negative and positive leaders. It was not possible to include the measurement obtained in China because no partial or averaged speeds were reported. However, the initial (0.1×10^5 ms^{-1}) and final speeds (3.8×10^5 ms^{-1}) are in the range of the values obtained in this study.

[15] Based on the statistical results presented in Table 1 and the similarity of the distributions in Figure 2, we can say that the speeds of positive and negative leaders are approximately equal. Their means are not significantly different at

Table 1. Comparison of the Partial and Averaged 2-D Speeds of Positive and Negative Leaders

	2-D Speed, $\times 10^5$ ms^{-1}					
Leader Type	Sample Size	Min.	Max.	Mean	Median	GM
Partial						
Positive (this study)	39	0.23	13.0	2.5	1.7	1.8
Positive (this study and *Berger and Vogelsanger* [1966])	42	0.23	24.0	3.4	1.7	2.1
Negative [*Saba et al.*, 2007b]	*303*	*0.26*	*19.8*	*3.0*	*2.3*	*2.5*
Averaged						
Positive (this study)	9	0.33	6.0	2.7	2.1	1.9
Positive (this study and *Berger and Vogelsanger* [1966])	10	0.33	12.0	3.7	2.7	2.3
Negative [*Saba et al.*, 2007b]	*59*	*0.90*	*19.8*	*3.4*	*2.3*	*2.7*

[1]Auxiliary materials are available in the HTML. doi:10.1029/2007GL033000.

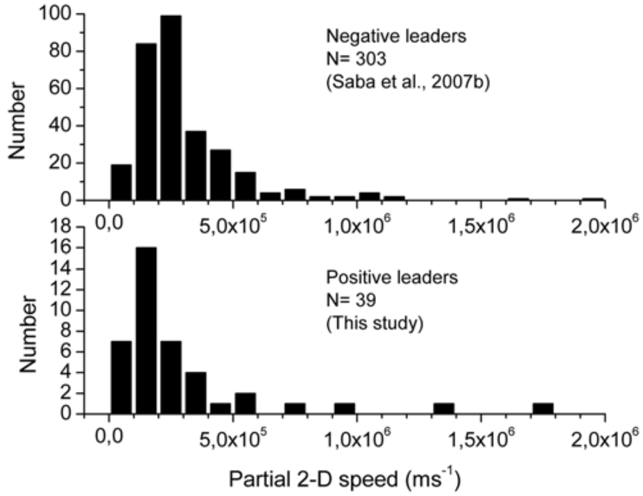

Figure 2. Histograms of the partial speeds of negative and positive leaders.

the 5% level of confidence using the Student's *t* test even when the measurements of *Berger and Vogelsanger* [1966] are included.

3.3. Variation of Partial Speed With Height

[16] Eight out of the 9 +CG leaders recorded in this study permitted multiple speed measurements. Our observations show that the speeds tend to increase by a factor of 1.1 to 6.5 as they approach the ground (Figure 3). For example, the vertical positive leader that started from a middle point of the horizontal channel in Figure 1, had a propagation speed that, increased from 1.2 to 2.5 $\times$ 10^5 ms^{-1} as it approached ground (average speed of 1.6 $\times$ 10^5 ms^{-1}). Note that the two previous measurements of positive leader speed [*Berger and Vogelsanger*, 1966; *Kong et al.*, 2007] also showed an increase in speed as the leader approached ground.

[17] A similar analysis was done for negative leaders by *Saba et al.* [2007b] and did not show a clear increase in speed; however, a re-analysis of these data has shown a slight increase in speed. This re-analysis was done by grouping all partial speeds into two groups, above and below 500 m. We found that the mean speeds of the two groups were 2.0 $\times$ 10^5 ms^{-1} and 2.8 $\times$ 10^5 ms^{-1} above and below 500 m, respectively, and that these values are significantly different at a 5% level of confidence using the Student's t test.

[18] The horizontal leader segment in Figure 1 that propagated between altitudes of 2200 m and 2700 m and traced the horizontal channel showed no increase in speed. The speed oscillated between 0.3 and 1.0 $\times$ 10^5 ms^{-1} (average speed of 0.6 $\times$ 10^5 ms^{-1}), and this average speed is similar to what has been found for negative and positive leaders that travel at a constant height [*Mazur et al.*, 1998; *Kong et al.*, 2007].

3.4. Recoil Leaders

[19] According to *Mazur* [2002], recoil leaders (RLs) are self-propagating, negative leaders that move along previously developed paths of the positively charged portions of bi-directional leaders. They start from the tips of the HF/VHF invisible positive leaders and move backward toward the origin. Negative RLs usually retrace the paths of positive leaders inside the cloud in −CG or in intracloud flashes.

[20] In this study, the high-speed images of 7 +CGs appear to show negative RLs retracing the paths of positive leaders during their progression toward ground. These RL events are the first ones observed, and were registered prior to two +CG strokes in Brazil, and five in the U.S.A. The RLs began 45 to 120 ms before the occurrence of the return stroke and most of them are visible for only one frame (135−250 μs). They appear as bright channel segments (compared to the faint positive leaders) and an example of a RL retracing a faint but still visible positive leader path is indicated by arrows in Figures 4b and 4c. It should be noted that in cases where the RLs lasted for more than one frame (when observed at 7,200 fps), they propagated in a retrograde fashion (i.e. upward, toward the leader origin; see Figures 4d, 4e, and 4f). From the length (approximately 1−2 km) and duration of these segments, we estimate that

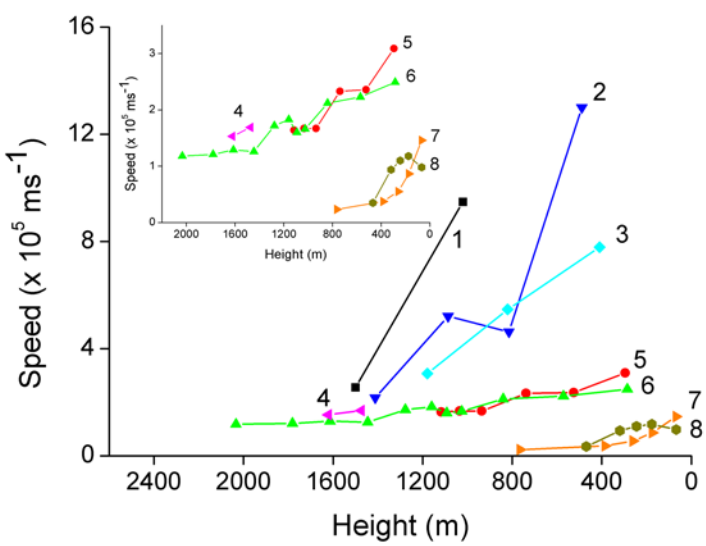

Figure 3. The partial speeds of positive leaders vs. height. The inset shows a magnified view of the lower speed leaders.

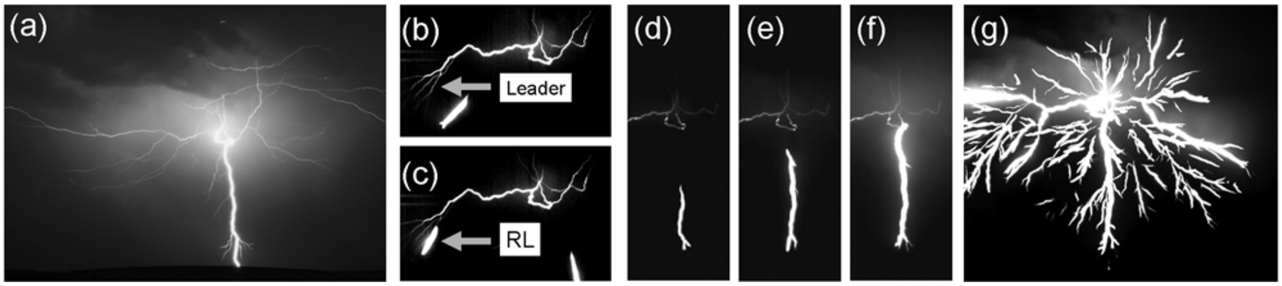

Figure 4. Still image and video frames of a positive CG flash in South Dakota (04:41 UT, July 22, 2007) that struck 16 km from the camera. (a) Photograph (ISO 400, f/11) of the flash showing extensive horizontal channel and discrete branching along the vertical channel; (b and c) an example of a RL retracing a faint but visible positive leader path; (d, e, and f) the retrograde movement of the RL; (g) time-integrated image of all video frames during the descent of a positive leader.

their minimum speed of development is about 4×10^6 ms^{-1}. This speed is in agreement with the speed of RLs (about 10^7 ms^{-1}) estimated by *Mazur* [1989]. Our review of more than 200 negative flashes recorded on high-speed video showed no indication of RL processes during the development of downward negative leaders.

[21] Figure 4g shows the integrated luminous development produced by all the RLs during the descent of a positive leader. The retracing of the positive leaders by RLs reveals an abundant fine structure that is not usually seen or is very faint. Note that the fine structures observed with high speed video do not appear in the still photograph of the flash that is associated with these positive leaders (Figure 4a). This is probably due to the extremely short duration of these RLs and due to the fact that there was a sensitivity difference between the still camera and high speed camera of about a factor of 10.

[22] It is well known that when an upward moving, negative return stroke reaches a branch, the rapid movement of charge in the branch will illuminate it [*Schonland*, 1956]. Similarly, when the brief and short negative RLs retrace the positive paths of branches in positive leaders (as described above), they may neutralize charge in the branches and produce a brief illumination. This may explain why, contrary to the profuse branching that appears in the photography (or low-speed video) of −CG flashes, the photographs (or low-speed video) of +CG flashes show little or no branching [*Beasley et al.*, 1983].

[23] It is also known that positive leaders do not produce enough RF radiation to be well-mapped by lightning mapping systems [*Mazur et al.*, 1998; *Shao et al.*, 1999; *Rison et al.*, 1999]. On the other hand, negative leaders produce a dense pattern of RF sources, and therefore negative RLs associated with positive leaders can be imaged using VHF mapping although they are highly dispersed and have a less well organized pattern [e.g., *Rison et al.*, 1999, Figure 3; *Mazur*, 2002, Figures 1 and 4]. We believe that the lower altitude, dispersed and less well organized pattern of RF that appears in some maps of +CG flashes [e.g., *Mazur*, 2002, Figure 6] are probably generated by RL processes similar to those that have been imaged for the first time in this study.

4. Summary

[24] We have presented some high-speed video observations of positive leaders. This is the first work to show statistical data on the values of the average downward speed of positive leaders. Contrary to what is usually assumed based on a single observation by *Berger and Vogelsanger* [1966], we show that downward +CG leader speeds are similar to downward −CG leader speeds. A clear increase in speed was observed for all positive leaders as they descended toward ground.

[25] The analysis of these images has shown, for the first time, that during the leader propagation toward ground, recoil leaders are observed that retrace fine branch structures that are usually not recorded using conventional photography or video. The existence of the RL may assist in the interpretation of UHF-VHF lightning radiation (and maps thereof) during the propagation of positive leaders.

[26] The statistics on positive leader speed and the existence of the RL may lead to a better understanding of the physical processes that occur during positive breakdown and the development of bi-directional discharges [*Kasemir*, 1950; *Rison et al.*, 1999; *Shao et al.*, 1999; *Mazur*, 2002]. In the future, combining high-speed video observations such as these with VHF mapping and electric field measurements should lead to a better understanding of +CG flashes.

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