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Does the average downward speed of a lightning leader change as it approaches the ground? – An observational approach

Leandro Z. S. Campos[1,2,*], Marcelo M. F. Saba[1], Tom A. Warner[3], E. Philip Krider[4], Kenneth L. Cummins[4] and Richard E. Orville[5]

[1]INPE, National Institute for Space Research, São José dos Campos, São Paulo, Brazil
[2]also at UNESP, Departamento de Física e Química, Guaratinguetá, São Paulo, Brazil
[3]South Dakota School of Mines and Technology, Rapid City, South Dakota, USA
[4]Institute of Atmospheric Physics, University of Arizona, Tucson, Arizona, USA
[5]Department of Atmospheric Sciences, Texas A&M University, College Station, Texas, USA
*e-mail: leandro.zanella@gmail.com

Abstract

In the lightning literature, it is commonly assumed that the stepped-leaders that initiate the first return stroke in negative cloud-to-ground lightning flashes accelerate during the final stages of their development, but there have been only a few observational studies supporting this claim. Other studies have reported a tendency for positive leaders to accelerate and negative dart-leaders to decelerate. The aim of this investigation is to determine how the average two-dimensional (2-D) downward speed of lightning leaders changes as they approach the ground and to see if any such changes depend on the leader type, polarity, or instrumentation used to measure the speed. We have examined the optical properties of leaders that were recorded using high-speed video cameras at different sites in south and southeastern Brazil, southern Arizona, and South Dakota, in conjunction with data obtained by lightning locating systems. The GPS time-stamped cameras were operated at frame rates ranging from 1000 to 11,854 frames per second. Our dataset consisted of 46 negative stepped-leaders, 53 negative dart-leaders, and 28 positive leaders. Two different approaches were used in the data analysis; first, the average downward speed of individual leaders was computed over preset distance intervals above the ground, i.e. from 0 to 500 m, 500 to 1000 m, etc, and then the geometric mean (GM) was calculated for all the cases in a given interval. We computed and compared the GMs since the speeds of positive leaders and negative dart-leaders follow a lognormal distribution (at the 0.05 level, according to the Shapiro-Wilk test), and the negative stepped-leaders have a similar distribution (according to the Kolmogorov-Smirnov test). The GM of the positive leader speeds increases by about a factor of 10 as they get closer to the ground (i.e. from 10^4 to 10^5 m/s), and the GM speed of negative stepped-leaders varies between 2.5×10^5 and 3.0×10^5 m/s. On the other hand, the GM speed of negative dart-leaders shows a clear decrease as they approach the ground. The second approach involved analyzing the leaders individually over their measurable length, and we found that: a) 82% of the 20 positive leaders accelerated, 7% decelerated, and 11% oscillated around an average speed; b) 46% of the 46 negative stepped-leaders accelerated, 6% decelerated and 48% oscillated around an average speed; and c) 32.1% of the 53 negative dart-leaders accelerated, 54.7% decelerated, and 13.2% oscillated around an average speed. We conclude that the acceleration of negative stepped-leaders is not as strong as some authors have assumed, but the tendencies for positive leaders to accelerate and for negative dart-leaders to decelerate are clear and agree with previous studies. We believe that the presented behavior asymmetry between negative stepped- and positive leaders might suggest microphysical differences in their propagation which should be investigated further.

1. Introduction

It is a common assumption in some works of the lightning literature that the stepped-leaders that initiate the first return stroke in negative cloud-to-ground (CG) lightning flashes accelerate during the final stages of their development even though there have been only a few observational studies supporting this claim. For instance, Section 4.4 of Rakov and Uman [2003], which mentions the data presented by Schonland [1956] and Nagai et al. [1982], who have reported this behavior for only very sparse cases; Qie and Kong [2007], who have reported four negative stepped-leaders whose downward speed presented a measurable increase as it approached the ground, with all of the leaders belonging to the same flash; and also Nag and

Rakov [2009], who assumed that negative stepped-leaders accelerate as they approach the ground without citing any references throughout their work.

Other studies have reported a tendency for positive leaders to accelerate (e.g., Berger and Vogelsanger [1966], Berger [1967], Kito et al [1985], Saba et al. [2008]) and negative dart-leaders to decelerate (e.g., Jordan et al. [1992, 1997]). They are all based on data from a wide variety of instruments, though, making it hard to carefully compare the characteristics of each leader type.

The aim of this investigation is to determine how the average two-dimensional (2-D) downward speed of lightning leaders changes as they approach the ground and to see if any such changes depend on the leader type, polarity, or instrumentation used to measure the speed.

2. Instrumentation

2.1. High-speed cameras

The data presented in this work were provided by five different high-speed digital video cameras (Red Lake Motion Scope 8000S, Photron Fastcam 512 PCI, Phantom v7.1, v310 and v12.1) with exposure times ranging from 84.36 microseconds (at 11,854 frames per second) to 1 millisecond (at 1000 frames per second). They were used in various campaigns aiming to study CG flashes in southern and southeastern Brazil [Saba et al., 2006], southern Arizona [Saraiva et al., 2010] and western South Dakota [Warner and Orville, 2009], USA, between February 2003 and September 2009. All cameras are GPS synchronized and provide time-stamped images with no frame-to-frame brightness persistence.

The high-speed cameras were triggered manually by the operator at the termination of a flash with a pre-trigger recording time of at least 1 second ensuring that the beginning of the flash was captured. Total recording times ranged around 2 seconds for the various cameras used, a duration that has proven to be long enough to prevent the first strokes to be missed and allow the complete recording of the lightning flash considering its total duration [Saraiva et al., 2010]. In-depth discussions on the accuracy of high-speed cameras for the determination of lightning parameters are presented on previous works by Ballarotti et al. [2005], Saba et al. [2006] and Campos et al. [2007, 2009].

2.2. Lightning Location Systems

For the determination of 2-D speeds of lightning leaders it is necessary to know the geometric characteristics of the camera and the lenses used, and the distance between the observation site and the flash. This last parameter, as well as stroke polarity and return stroke peak current estimate, was obtained through data provided by lightning locating systems (LLS). GPS time synchronization allowed stroke matching between high-speed camera and LLS data [Saba et al., 2006]. All three observation sites were located in regions that are well covered by LLS (BrasilDAT for Brazil [Pinto et al., 2007; Naccarato and Pinto, 2009] and the NLDN for the USA [Cummins et al., 1998; Biagi et al., 2007; Cummins and Murphy, 2009]).

3. Results

3.1 General characteristics of the leaders

Our dataset consisted of 62 negative stepped-leaders, 76 negative dart-leaders, and 29 positive leaders. The terminology adopted in this analysis is the same as the one presented by Saba et al. [2008]: "speeds measured along the path of the leader were termed partial speeds", while "the average speed is calculated by dividing the length of the entire 2-D trajectory by the time taken to cover it" [Saba et al., 2008, p. 2]. A statistical analysis of the dataset has showed that the speeds of positive leaders and negative dart-leaders follow a lognormal distribution at the 0.05 level, according to the Shapiro-Wilk test [Shapiro and Wilk, 1965]. The negative stepped-leaders have a similar distribution, although according to the Kolmogorov-Smirnov test, usually considered to be not as strong [Stephens, 1974].

All the negative stepped- and dart-leaders and 28 of the 29 positive leaders presented at least two partial speed measurements, which allowed us to analyze how they change as the leader tip approaches the ground. As the slowest cases of each leader type tend to provide us with a larger number of partial speed measurements, we have computed statistical parameters (mean, median and geometric mean) and obtained histograms only for average speed measurements, restricting the presented data on partial speeds to minimum and maximum values in order to avoid any bias on the results (Tables 1 to 3).

The 29 positive leaders analyzed provided 449 partial speed measurements. Table 1 presents a statistical summary of this data and Figure 1 shows the histogram of average 2-D speeds. This analysis is an extension of the work by Saba et al. [2008], who studied 9 of the 29 cases presented in this paper.

Table 1 – Positive leader speeds. Min stands for minimum, Max for maximum and GM for geometric mean.

2-D speeds (x10^5 m/s)						
	Sample size	Min	Max	Mean	Median	GM
Partial	449	0.08	16.2	-	-	-
Average	29	0.24	11.8	2.76	1.80	1.81

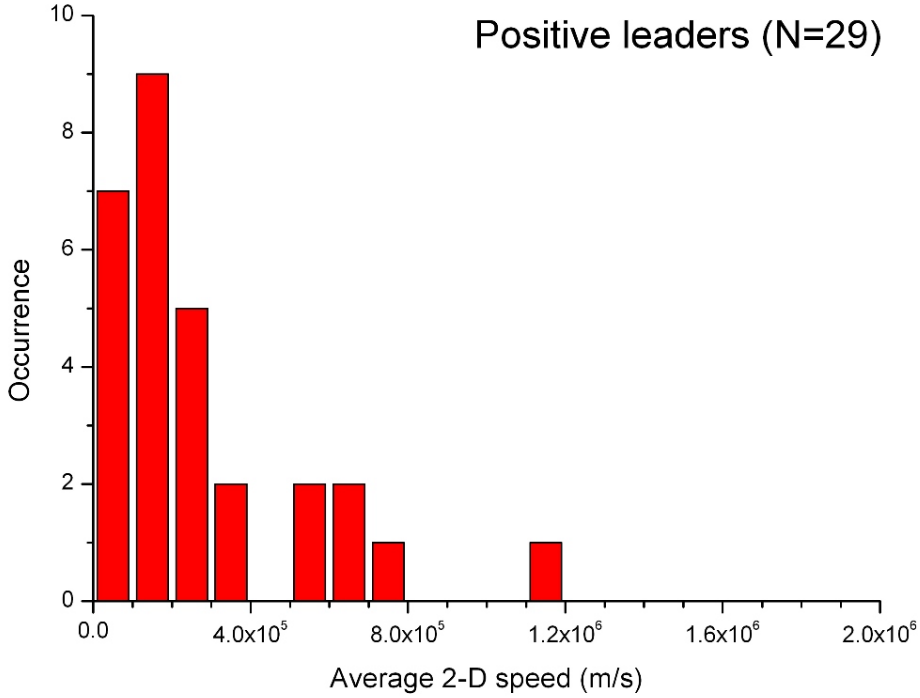


Figure 1. Histogram of the average 2-D speed of 29 positive leaders.

A dataset consisting of 62 negative stepped-leaders provided a total of 371 partial speed measurements. Table 2 presents a statistical summary of this data and Figure 2 shows the histogram of average 2-D speeds. By comparing Tables 1 and 2 and Figures 1 and 2 one can notice that, even though positive leaders tend to be relatively slower than negative leaders, both phenomena present speeds within the same range of values.

Table 2 – Negative stepped-leader speeds. Min stands for minimum, Max for maximum and GM for geometric mean.

2-D speeds (x10^5 m/s)						
	Sample size	Min	Max	Mean	Median	GM
Partial	371	0.26	19.8	-	-	-
Average	62	0.90	19.8	3.30	2.24	2.68

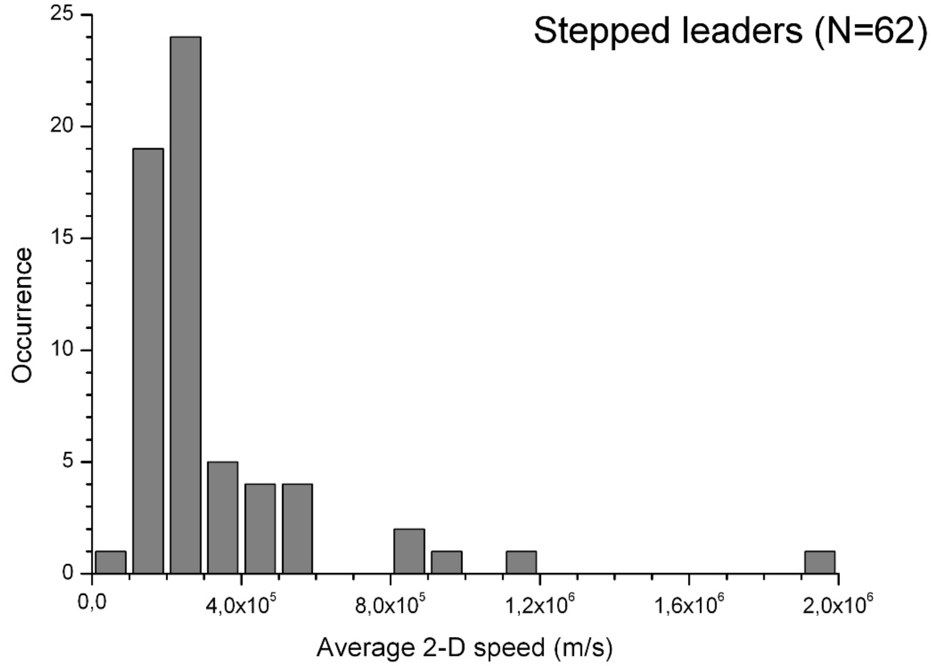


Figure 2. Histogram of the average 2-D speed of 62 negative stepped-leaders.

The 76 negative dart-leaders analyzed have allowed us to obtain 207 partial speed measurements. All the cases were recorded at frame rates ranging from 4000 to 8000 frames per second. Table 3 presents a statistical summary of this data and Figure 3 shows the histogram of average 2-D speeds. Given the high speeds observed in the phenomenon (commonly ranging from 10^6 to 10^7 m/s) and the fact that many dart-leaders observed could not be resolved by the high-speed cameras in more than one frame, we believe that our data do not cover the extreme faster cases and are biased to the lower speeds. Despite that fact, it was possible to measure the speed of faster cases than those available in literature, limited to 1.9×10^7 m/s [Schonland et al., 1935; Orville and Idone, 1982; Jordan et al., 1992, 1997], even though 98% of our partial speeds dataset fit below that value.

Table 3 – Negative dart-leaders speed. Min stands for minimum, Max for maximum and GM for geometric mean.

2-D speeds ($\times 10^5$ m/s)						
	Sample size	Min	Max	Mean	Median	GM
Partial	207	1.91	295	-	-	-
Average	76	3.33	295	46.1	28.5	27.6

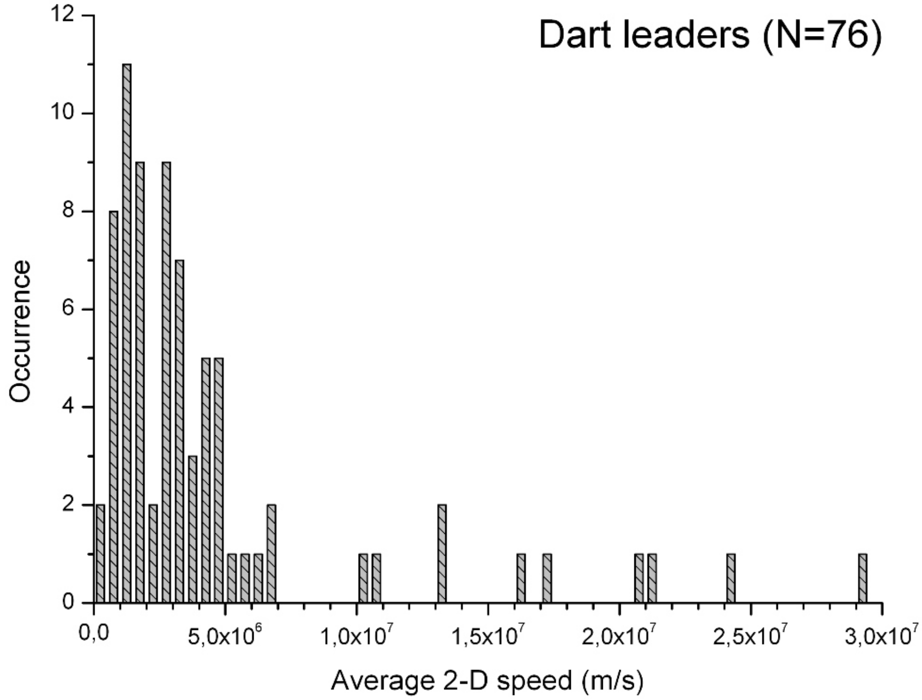


Figure 3. Histogram of the average 2-D speed of 76 negative dart-leaders.

3.2 Statistical analysis on leader speed change

In the first approach adopted to analyze the change of lightning leader speeds as they approach the ground, the average downward speed of individual leaders was computed over preset distance intervals above the ground, i.e. from 0 to 500 m, 500 to 1000 m, etc., and then the geometric mean (GM) was calculated for all the cases in a given interval of distances. We computed and compared the GMs since the speeds of positive leaders and negative stepped- and dart-leaders follow a lognormal distribution (as detailed in section 3.1, above). The GM of the positive leader speeds increases by about a factor of 10 as they get closer to the ground (i.e. from 10^4 to 10^5 m/s), and the GM speed of negative stepped-leaders varies between $2.5x10^5$ and $3.0x10^5$ m/s, as shown on Figure 1. On the other hand, the GM speed of negative dart-leaders shows a clear decrease as they approach the ground, as shown on Figure 2.

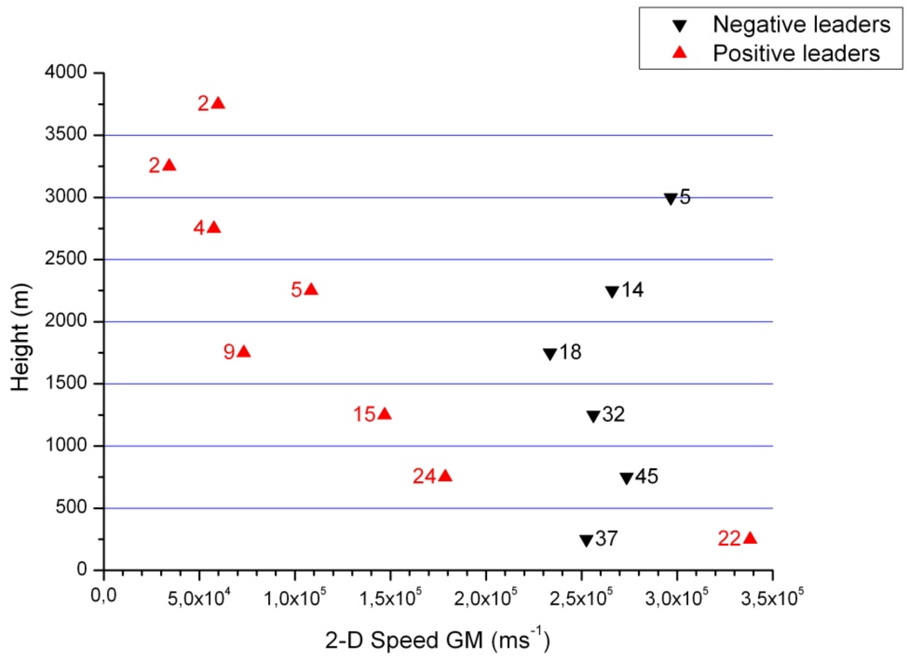


Figure 4. Variation of the speed of negative stepped- and positive leaders with height.

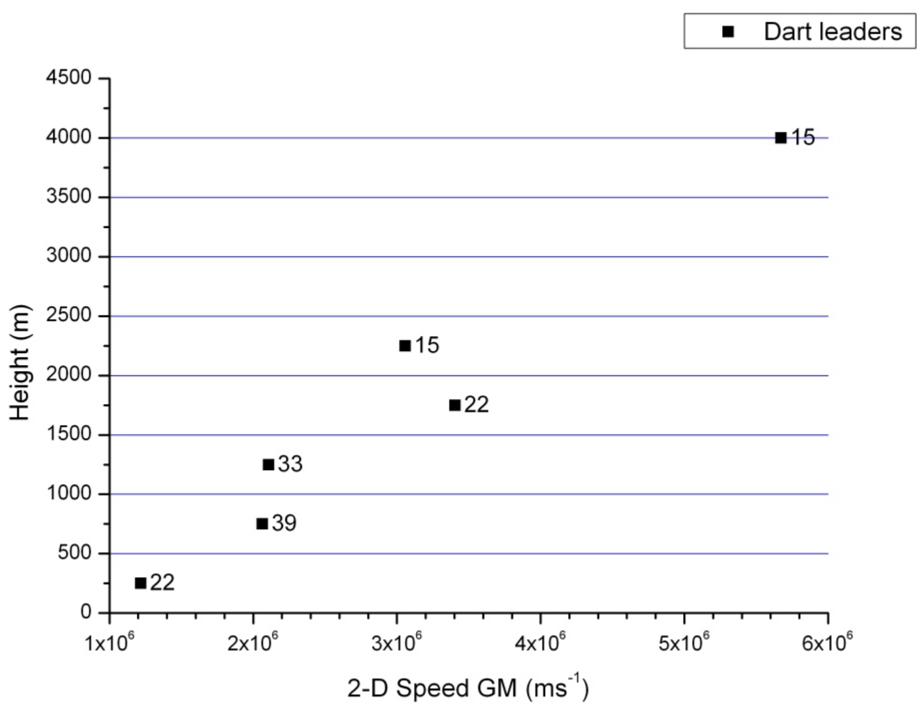
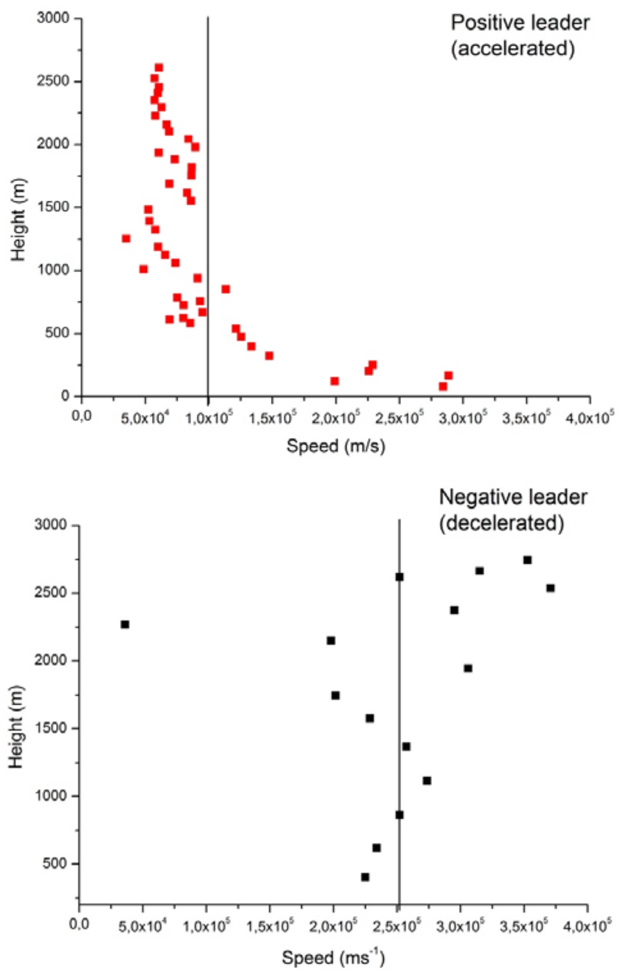


Figure 5. Variation of the dart leader speed with height.

3.3 Case-to-case analysis on leader speed change

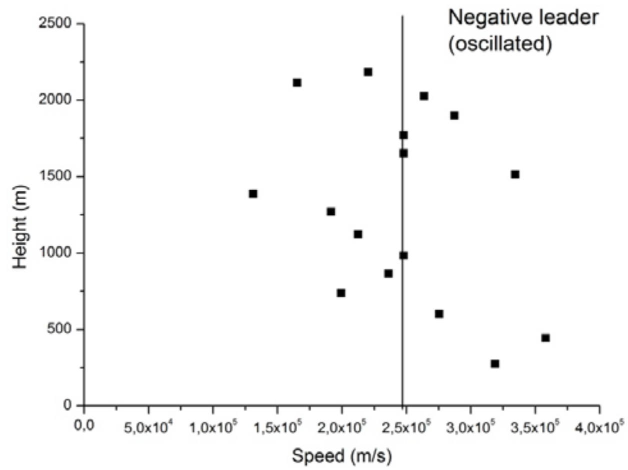
In the second approach used in the data analysis each leader case had their partial speed measurements studied individually over its total measurable length and classified in one (and only one) behavior: accelerated, decelerated and oscillated. In order to be classified as “accelerated” the partial speeds of a given leader needs to clearly increase as its tip approaches the ground, with the final partial measurement being necessarily higher than the first ones. The criteria for a case to be classified as “decelerated” is directly opposed to the “accelerated” criteria, so the leader needs to decrease its partial speeds and the final measurement was always lower than the first ones. Finally, for a leader to be considered as “oscillated”, its partial speed measurements need to oscillate around the average value, presenting as many lower values as higher values throughout its propagation towards the ground. This part of the analysis was made through a careful visual inspection of partial 2-D speeds *versus* leader tip height curves for each case. Figure 6 presents one example for each classification, illustrating the analysis that was made.



(a)

(b)

Figure 6. Examples of case-to-case analysis of leader speed change. The vertical lines indicate the value of the average speed.



(c)

Figure 6. (*continued*).

From this analysis we have found that: a) 82% of the 28 positive leaders accelerated, 7% decelerated, and 11% oscillated around an average speed; b) 46% of the 46 negative stepped-leaders accelerated, 6% decelerated and 48% oscillated around an average speed; and c) 32.1% of the 53 negative dart-leaders accelerated, 54.7% decelerated, and 13.2% oscillated around an average speed. These results are summarized on Table 4.

Table 4 – Individual analysis of leader speed variation with distance from the ground

Leader type	Accelerated	Decelerated	Oscillated
Positive leader	82%	7%	11%
Negative stepped-leader	46%	6%	48%
Negative dart-leader	32.1%	54.7%	13.2%

4. Concluding remarks

From the analysis made through both approaches adopted, we conclude that the acceleration tendency of negative stepped-leaders does not seem to be as strong as some authors usually assume (e.g., Schonland [1956], Nagai et al. [1982], Rakov and Uman [2003], Qie and Kong [2007], Nag and Rakov [2009]). On the other hand, the tendencies for positive leaders to accelerate and for negative dart-leaders to decelerate are much clearer and agree with previous studies (Berger and Vogelsanger [1966], Berger [1967], Kito et al [1985], Jordan et al. [1992, 1997], Saba et al. [2008]).

Up to now it is still not well established if positive leaders develop towards the ground either in a continuous or a stepped manner. Even though results from laboratory-produced sparks point towards a continuous mode of propagation (e.g., Les Renardières Group [1977], Gallimberti et al. [2002]), some experiments on natural [Qie and Kong, 2007] and triggered [Biagi et al., 2009] lightning presented evidence that positive leaders might develop through steps, so this question remains open. We believe that the presented behavior asymmetry between negative stepped- and positive leaders might suggest microphysical differences in their propagation which should be investigated further.

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