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Correlation Between Speed of the Leader and Peak Current of the Return Stroke in Negative Lightning Flashes

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Key Points:

- The return stroke peak current is better correlated with final speed than with the average speed of the stepped leader
- No significant correlation was found between dart leaders speed and stroke peak current
- The stepped leaders increase their propagation speed near the ground

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract This study analyzes the two-dimensional speed profiles of 107 stepped leaders and 93 dart leaders recorded by high-speed cameras in Utah (USA), together with data from lightning location system. The results shows that the final and average speed of the stepped leader has a very strong ($R = 0.82$) and strong ($R = 0.71$) correlation with the peak current of the return stroke. It also shows that 91% of the stepped leaders increased their speed near the ground (average increase of 69%). The same analysis for dart leaders shows weak correlation with the peak current of the prospective return stroke ($R = 0.39$ to average speed and $R = 0.28$ to final speed). This paper briefly discusses why peak current is better correlated with final speed than with the average speed, and why stepped leaders exhibit a significant correlation, while dart leaders do not.

Plain Language Summary This study looks at how fast stepped leaders and dart leaders of lightning flashes propagate from the cloud base to ground, using high-speed camera videos and data from a lightning location system. The results show that the final and average speed of the leaders are well correlated to the return stroke current, the return stroke current being more closely related to the final speed than the average speed. In contrast, dart leaders showed a weak correlation between their speed and the return stroke current. It also shows that most stepped leaders sped up as they got closer to the ground.

1. Introduction

Negative cloud-to-ground lightning flashes originate from bidirectional and bipolar leaders in thunderclouds (Mazur, 1989). The positive end of these bidirectional and bipolar leaders propagates within the cloud and the negative end propagates toward the ground. The development of the negative downward leader occurs in a stepped manner. The length of the steps can vary from 3 to 200 m in intervals between 0.2 and 100 μs. The observed average speed of the stepped leader varies between 0.6 and 39×10^5 m/s (Beasley et al., 1983; Berger, 1967; Campos et al., 2014; Chen et al., 1999; Krider, 1974; Lu et al., 2008; Mazur et al., 1995; Orville & Idone, 1982; Proctor et al., 1988; Schonland et al., 1935; Shi et al., 2019; Thomson et al., 1985).

When the stepped leader touches the ground, the first return stroke occurs. Then, after the decay of the lightning channel, subsequent return strokes may occur. A subsequent return stroke is originated by dart leaders or by dart-stepped leaders. Dart leaders re-ionize a previously ionized channel, developing with a higher average speed, which varies between 1 and 50×10^6 m/s (Jensen et al., 2021; Jordan et al., 1992; Loeb, 1966; Schonland et al., 1935; Shao et al., 1995; Stock et al., 2014). A dart-stepped leader is a leader that propagates in a stepwise manner, like a stepped leader, but through a residual channel instead of virgin air (Ding et al., 2024; Petersen & Beasley, 2013; D. Wang et al., 2016; J. Wang et al., 2022).

Past studies have found correlations between the amount of charge on the portion of the leader close to ground (i.e., the first few hundred meters) and the intensity of the peak current of the prospective return stroke (Cooray & Lundquist, 1985; Proctor et al., 1988).

Studies of the stepped leader propagation preceding the first return stroke of a lightning flash have shown that there is a relationship between the average speed of the stepped leader and the peak current that flows during the first return stroke. Zhu et al. (2015) and Nag and Cummins (2017) inferred this relationship from stepped leader duration measured from electric field records for negative cloud-to-ground flashes, and Wu et al. (2022) for positive cloud-to-ground flashes. They show that strokes with large peak currents are preceded by stepped leaders with short time intervals between the initial breakdown pulses and the peak of the return stroke, which has also been observed using 3D lightning mapping systems (Shi et al., 2019). Such relationship is expected if one considers that the higher the charge density at the tip of a leader, the higher is its speed and the following return stroke peak current (Cooray & Arevalo, 2017; Proctor et al., 1988).

Campos et al. (2014) compared, through high-speed camera analysis, the average speed of stepped leaders and dart leaders with their respective peak currents. However, in both analyses no correlation was found.

The present work refines the study of Campos et al. (2014) using larger database with a broader range of return stroke peak currents following stepped and dart leaders. We found a strong linear correlation between the average speed of the stepped leader and the resulting peak current of the first return stroke, similar to what was found by Shi et al. (2019). Furthermore, we show that it is in fact the final speed of the stepped leader that best correlates with the resulting peak current. The correlation is so strong that even leaders of different lightning events with large varying speeds along their paths to ground have the same final leader speed when the peak current of their return stroke is the same. Similarly to Kodali et al. (2005) and Campos et al. (2014), weak correlations were found for dart leaders.

2. Instruments

2.1. Lightning Location Systems (LLS)

Data from National Lightning Detection Network (NLDN) was used to identify the polarity, peak current and location of the analyzed lightning flashes. For more information on lightning detection network, see Biagi et al. (2007), Cummins and Murphy (2009), and Abarca et al. (2010). LLSs measure the radiated electromagnetic fields using multiple sensors at different locations. The time difference of arrival of these fields then allows for localization and the amplitude of the fields allows peak current inference. This is done by applying a simple "transmission line" model relating the measured electromagnetic field amplitude to the peak current along with the distance from the sensor to the termination location and the speed of light, see Cummins and Murphy (2009). This has been produced good estimates of peak current, mostly validated through rocket triggered lightning studies, with errors within 10%–15% for negative subsequent strokes, although there is still little experimental data for first return strokes and positive strokes (Rakov, 2005). In this research an error of 16% was assumed for the peak current data (Mallick et al., 2014).

2.2. High-Speed Cameras

In this work, a Phantom v2012 high-speed camera equipped with a 20 mm lens was used. The camera was installed west of Hinckley, Utah, in Millard County (USA). This is a desert region with flat relief, making it easier to observe the entire propagation of the leader, toward the ground. The lightning flashes were filmed at an acquisition rate of 40,000 fps, with a period of 25 μs, and image spatial resolution of 1,280 × 448 pixels, same settings used by Abbasi et al. (2023). Calculations of the two-dimensional (2-D) speed of the leaders were obtained with the analysis of the high-speed camera videos in conjunction with the LLS data. The method used for the calculations was the same as that used by Campos et al. (2014) and Saba et al. (2017, 2022, 2023).

3. Data

The data was obtained during the summers of 2021, 2022, and 2023. A total of 281 return strokes of 126 lightning flashes were analyzed: 126 negative first return strokes and 155 negative subsequent return strokes. The dart-stepped leaders were not included in the analysis, as they hold two types of propagation: stepped and continuous.

Excluding all dart-stepped leaders and the leaders whose distances were not possible to determine as the resulting return strokes were not detected, a total of 107 stepped leaders and 93 dart leaders had their 2-D speed profile analyzed. The return strokes from stepped leaders had an average peak current of −35 kA and occurred at an average distance of 18 km (with minimum distance of 3 km and maximum distance of 46 km) from the high-speed camera. Return strokes from dart leaders occurred at an average distance of 22 km (with minimum distance of 8 km and maximum distance of 44 km), with an average peak current of −17 kA (see Table 1).

Table 1
Return Stroke Peak Current and Average and Final Speed Values for Stepped and Dart Leaders

	Ip (kA)			Average speed ($\times10^5$ m/s)		Final speed ($\times10^5$ m/s)	
	AM	Min.	Max.	Min.	Max.	Min.	Max.
Stepped leader (N = 107)	−33	−6	−154	0.87	22	0.61	28
Dart leader (N = 93)	−17	−4	−57	13	340	6.2	350

Note. N is the number of stepped and dart leaders analyzed.

4. Analysis

4.1. Stepped Leader

Figure 1a shows the 2-D speed profiles of three stepped leaders from three different lightning flashes. It was possible to trace the speed profiles of the leaders from near the base of the cloud down to the ground. The three return strokes in Figure 1a have the same peak current (−51 kA). The lightning flashes were numbered in a sequence according to the filming time and year, in the format "#nn (yyyy)." They started with different speeds but during the development toward the ground, the final speeds converged to very close values. The final speed was measured using two leader tip locations from frames close to the ground, with the lowest height (final height H_F) located between 50 and 200 m and the second lowest height ($H_{F\text{-}1}$) located between 200 and 450 m above the ground. See Figure S1 in Supporting Information S1 and "data.xlsx" available in open research (the videos of these three stepped leaders in.cine format are also available at open research). The final speeds for these cases were 6.4 ± 1.3, 6.5 ± 3.1, and 6.3 ± 2.1 × 10^5 m/s for H_F of 145 ± 52, 131 ± 62, and 175 ± 63 m. These stepped leaders occurred 26, 31, and 32 km away from the high-speed camera, respectively. Measurement errors were calculated, where LLS errors ($\delta_{LLS} = \pm500$ m, see Cummins et al., 1998), camera tilt errors ($\delta_\theta = \pm0.017$ rad) and pixel location in high-speed camera videos ($\delta_{px} = \pm1$ px) were used.

Figure 1b shows the 2-D speed profiles of another three stepped leaders with return stroke current peaks of −26, −20, and −25 kA (videos in.cine format of these three stepped leaders are also available in Data Availability Statement). The values are approximately half of those in the previous cases, but also relatively close to each other. These leaders also started with different speeds and the final speed converged to close values. The final speed for these cases were 4.0 ± 1.2, 2.9 ± 0.44, and 3.7 ± 0.58 × 10^5 m/s the H_F were 153 ± 55, 148 ± 32, and 119 ± 19 m to the ground. The lightning flashes occurred 28, 15, and 8 km away from the high-speed camera, respectively.

Figure 1 indicates a possible correlation between the final speed of stepped leaders and the peak current of the return stroke. It also shows that the propagation speeds of the stepped leaders vary largely during the propagation thus making the average speed of the stepped leaders not well correlated with the peak current.

In order to better investigate the relation between leader speed and prospective return stroke peak current, Figure 2 shows the average and final speeds of the 107 stepped leaders plotted against the corresponding prospective return stroke peak current. The average speeds of these lightning flashes were calculated from a linear regression applied to a scatter plot of the distance propagated by the leader as a function of time. The angular coefficients of the linear fitting show the values of the average speeds. Statistics on return stroke peak current and speed values are shown in Table 1.

Considering that both the peak current and leader speed distributions are not normal, the Spearman correlation coefficient was used. The linear regression and Spearman correlation coefficients obtained in this research were calculated considering the uncertainties in the speeds and peak currents. For this, 100,000 Monte Carlo simulations were carried out to find the linear fit. The correlation coefficient was classified according to the criteria used by Evans (1996).

We also investigated the speed behavior of stepped leaders close to the ground, evaluating whether there is an increase or decrease (see the complementary data "data.xlsx" available in open research).

According to the physical model on the formation of negative leaders by Nag and Rakov (2016) and Cooray and Arevalo (2017), the speed of stepped leader increases as it approaches ground. This speed increase (as can be seen in Figure 1) was observed in 91% of 107 stepped leaders observed in this study. The average increase of the speed observed for heights lower than 500 m was 69%. A decrease in speed (average of 17%) was observed in only nine stepped leaders, and only one case maintained its speed (all them followed by return stroke peak currents less than −18 kA).

4.2. Dart Leaders

Figure 3 shows the 2-D speed profiles of three dart leaders (2nd return stroke of lightning flash #9, 10th return stroke of lightning flash #5 and 8th return stroke of lightning flash #31), all with the same prospective return

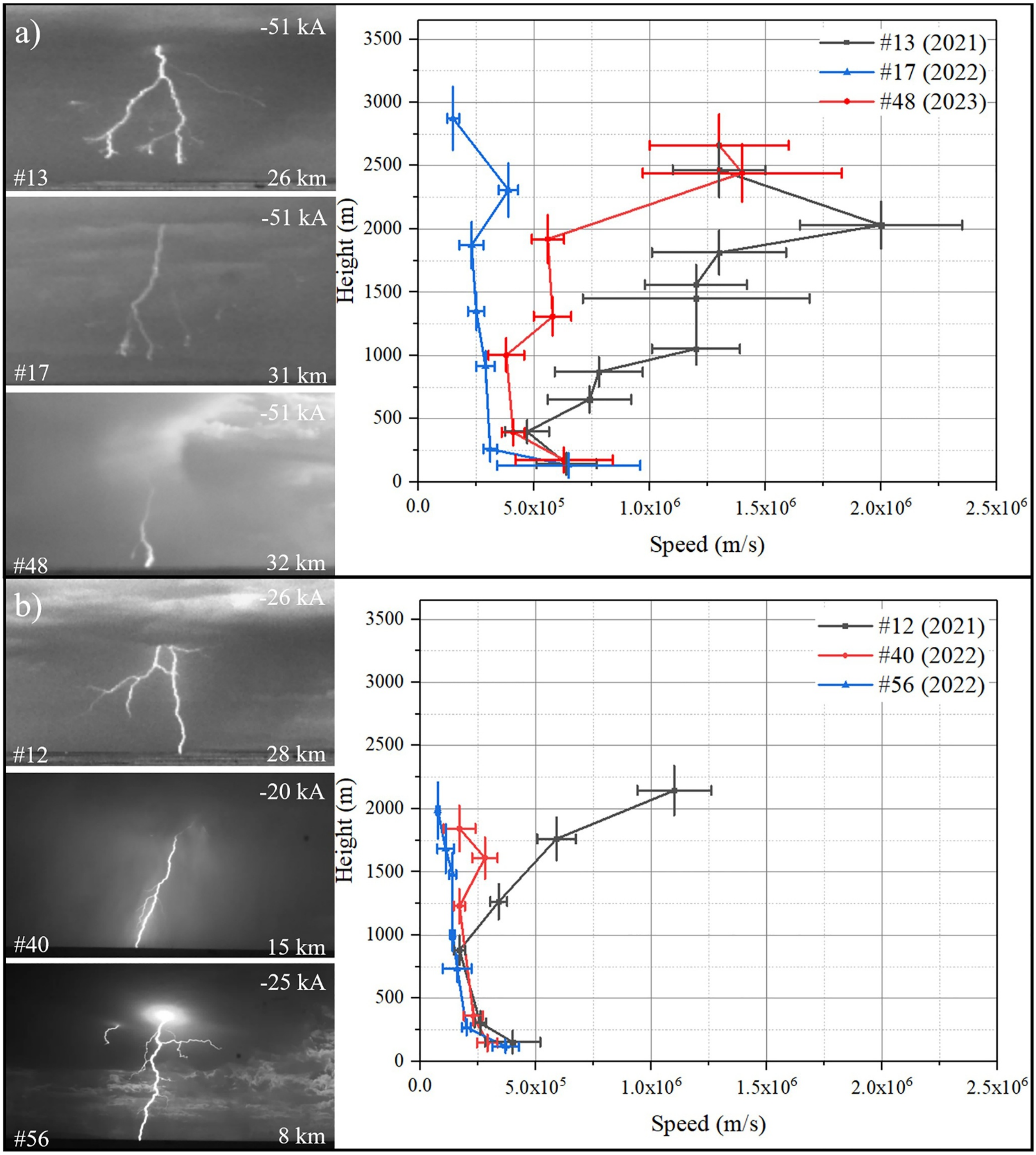

Figure 1. The 2D speeds of the stepped leaders versus height. On the left part of figures (a) and (b), the images of the stepped leaders are shown, together with peak current and distance from camera. On the right of the figures, the 2-D speed profiles of the stepped leaders as a function of height are displayed. The horizontal and vertical bars show the values of the speed and height errors.

stroke peak current (−13 kA). The dart leaders also started with variable speeds but showed different behavior than stepped leaders regarding the final speed. The final speed of the dart leaders did not converge to close values, being 6.1 ± 1.6, 23 ± 2.2, and $9.3 \pm 2.5 \times 10^6$ m/s in this case for heights of 140 ± 23, 342 ± 59, and 330 ± 42 m. The lightning flashes occurred 10, 27, and 17 km away from the high-speed camera, respectively.

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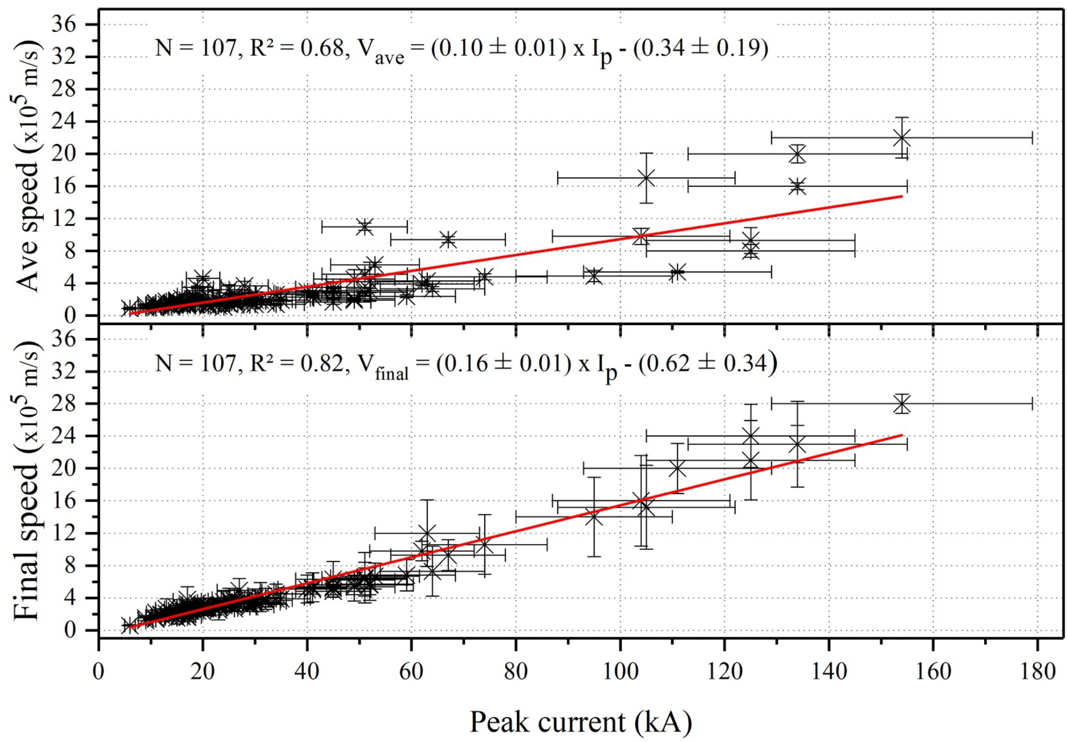

Figure 2. The image shows the average and final speed of the stepped leaders as a function of prospective return stroke peak current. R^2 represents the coefficient of determination and N indicates the number of analyzed stepped leaders. In the graphs, the negative sign of the current peaks is disregarded for better visualization. The horizontal and vertical bars show the peak current and speed errors.

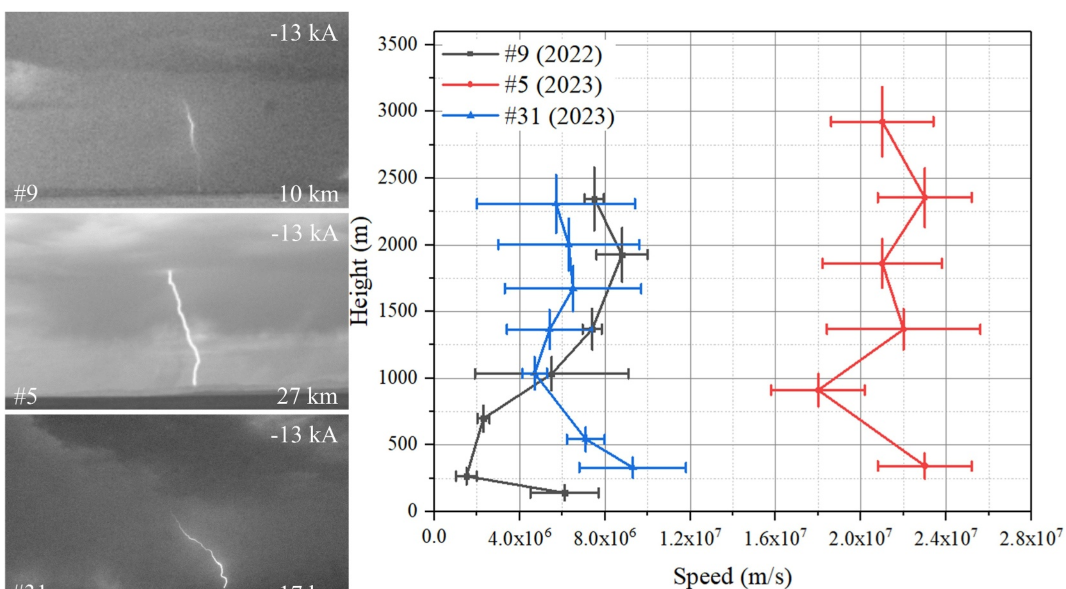

Figure 3. The 2D speeds of the dart leaders versus height. On the left, the video images of the three dart leaders right before the occurrence of the return stroke are shown. Their estimated peak currents are the same (−13 kA). On the right, height profiles of the speeds are shown. The horizontal and vertical bars show the values of the speed and height errors.

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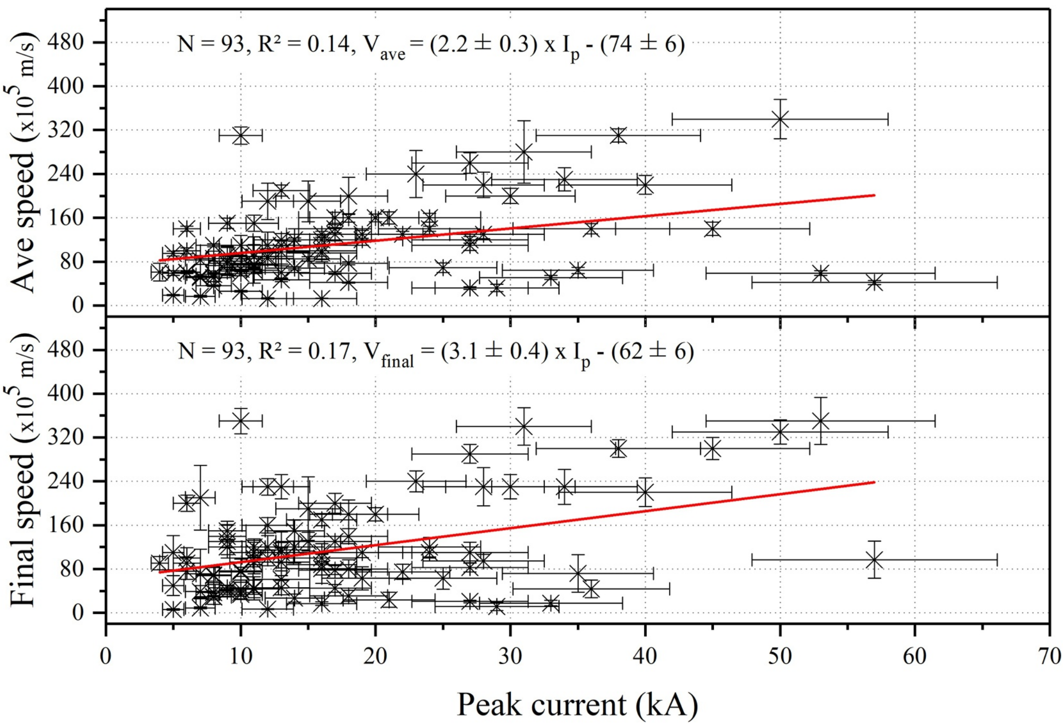

Figure 4. Average and final speed of the darts leaders as a function of the peak current. R^2 represents the coefficient of determination and N indicates the number of stepped leaders analyzed. In the graphs, the negative signs of the current peaks are disregarded for better visualization. The horizontal and vertical bars show the peak current and speed errors.

In this case, the final speeds have no significant correlation with the peak current. In order to better investigate the relation between the dart leader speed and prospective return stroke peak current, the average and final speeds of 93 dart leaders were analyzed (Figure 4). It was only possible to obtain 39 cases in the same height range of that considered for stepped leaders (50 m $\leq H_F \leq$ 200 m and 200 m $\leq H_{F-1} \leq$ 450 m), as the speed of dart leaders is higher, some cases having their final steps at a height greater than 300 m. The remaining cases (54 cases), the speeds of the dart leaders were calculated with one frame difference, that is, a fixed difference of 25 μs. For the dart leaders, the heights varied from 50 m $\leq H_F \leq$ 760 m and 200 m $\leq H_{F-1} \leq$ 1,440 m. See Figure S2 in Supporting Information S1 and "data.xlsx" available in open research (the videos of these three dart leaders in. cine format are also available at open research). Statistics on return stroke peak current and speed values are shown in Table 1.

5. Discussion and Conclusion

The present work shows that the final speed of the leader has a better correlation with the final return stroke peak current than the average speed of the leader values measured along their propagation. It also shows that there is a correlation between leader speed and the resulting return stroke peak current for stepped leaders but not for dart leaders.

The linear fit for the relationship between the stepped leader final speed and the peak current of the following return stroke was obtained for peak current values ranging from −6 to −154 kA. However, the fit is also consistent with a value way outside this range, as in the case reported by Wu et al. (2021) for a leader followed by a very high peak current return stroke (−335 kA) that occurred in winter thunderstorm in Japan.

The significantly better correlation between the final speed and the following stroke peak current ($R = 0.82$ rather than $R = 0.71$ for the average speed) can be understood if one considers that the return stroke current is composed by the flow of charges that are concentrated in the final portion (few hundreds of meters) of the leader channel (e.g., Cooray & Lundquist, 1985; Khounate et al., 2021; Proctor et al., 1988). Krider et al. (1976) state that, since the return stroke velocity is of the order of 10^7 and 2×10^8 m/s and its rise time is of the order of 1–5 μs, the peak return stroke current must be related to the charge distribution in a length of the channel of some tens to hundreds of meters from ground. Cooray et al. (2007), through a theoretical model, assume that the charge that is most important in the formation of the peak current is located a few hundred meters above the ground. Nag and Rakov (2016) also make this assumption in their conceptual model and it shows good correspondence with electric field measured waveforms of the negative cloud-to-ground lightning flash.

As observed by Campos et al. (2014), the speed of negative leaders during their downward propagation has a wide variation. Therefore, the average speed may not reflect the many varying processes involved in the leader propagation (charge distribution, leader branching, etc.). In fact, Figure 1a shows that, although lightning flashes #13, #17, and #48 have different average speeds (11, 5.1, and 2.9×10^5 m/s respectively), and varying speeds at higher altitudes, they all converge to the same final speed and are all followed by return stroke with same peak current. The same is observed in Figure 1b. Furthermore, this work also shows that almost all stepped leaders increase their speed close to the ground (altitudes lower than 500 m). The data presented are in agreement with the theoretical models presented by Nag and Rakov (2016) and Cooray and Arevalo (2017).

The correlations between dart leader speed and return stroke peak current were weak. The dart leaders presented a correlation coefficient $R = 0.39$ when the average speed was considered, and $R = 0.28$ when the final speed was used. As they propagate in a previously ionized heated channel, the speed of the dart leaders will depend not only on the charge at their tip (as supposed for stepped leaders) but also on other factors like the presence of continuing current (CC), duration of previous interstroke time intervals, and other characteristics that influence the conductivity of the decaying channel. Therefore, the leader speed is not solely related to the quantity of charge stored at the final portion of the leader, resulting in a weak (for final and average speed) correlation with the peak current.

The fact that the final speed of negative leaders has a very strong correlation with the following return strokes not only sheds light on the physics of leader propagation and return strokes but also can be of practical use for models dealing with upward leader from structures (Becerra & Cooray, 2006) and for attachment to transmission lines in general (Rizk, 2010a, 2010b, 2024). It is during the final propagation of the downward leader that the upward leaders are induced, incepted and propagate upwards (Saba et al., 2017, 2022, 2023; Warner, 2010).

Data Availability Statement

The data analyzed in this work are available at Cruz (2024).

Acknowledgments

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