# Correlation between speed of the stepped leader and peak current of the return stroke of lightning flashes

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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 (NLDN). The results show that the stepped leader speed right before the ground contact (final speed) has a very strong correlation (R = 0.85) with the peak current of the initiated return stroke. It also shows that the correlation between the average speed and the peak current of the return stroke is strong (R = 0.73). The same analysis for dart leaders did not show any significant correlation with the peak current of the prospective return stroke (R = 0.41 to average speed and R = 0.29 to final speed). This paper discusses why stepped leaders exhibit a significant correlation, while dart leaders do not. In addition, why final speed is better correlated with peak current than average speed.

# Correlation between speed of the stepped leader and peak current of the return stroke of lightning flashes

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## Key Points:

- Analysis of the correlation between the speed of the stepped leaders and the following return stroke.
- A significant correlation was found between the final speed of the stepped leader and the stroke peak current.
- No significant correlation was found between dart leaders speed and stroke peak current.

## 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 (NLDN). The results show that the stepped leader speed right before the ground contact (final speed) has a very strong correlation (R = 0.85) with the peak current of the initiated return stroke. It also shows that the correlation between the average speed and the peak current of the return stroke is strong (R = 0.73). The same analysis for dart leaders did not show any significant correlation with the peak current of the prospective return stroke (R = 0.41 to average speed and R = 0.29 to final speed). This paper discusses why stepped leaders exhibit a significant correlation, while dart leaders do not. In addition, why final speed is better correlated with peak current than average speed.

## Plain Language Summary

Stepped leaders and dart leaders propagate differently, exhibiting characteristic speeds during their development. On average, the speed of dart leaders is 100 times higher than that of stepped leaders. The speeds of darts and stepped leaders may vary during their propagation (increase or decrease). Some leaders can present speed differences of up to 10 times compared to other strokes. The present work shows that differences in the speeds of the stepped leaders are associated with differences in the intensity of the discharges (peak current). This work shows that lightning flashes with high peak currents tend to have higher final speeds, and lightning flashes with lower peak currents have lower final speeds.

## 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 towards 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 0.8 and 39 x $10^5$ 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; 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 x $10^6$ m/s (Jensen et al., 2021; Jordan et al., 1992; Loeb, 1966; Schonland et al., 1935; Shao et al., 1995; Stock et al., 2014). Dart-stepped leaders exhibit two behaviors: fast development as a dart leader, since they develop through a previously ionized medium, and stepped development, as it propagates through a non-ionized medium (Petersen & Beasley, 2013; Wang et al., 2016; Ding et al., 2024).

The amount of charge at the tip of the leader is believed to be correlated with propagation speed of the leader as well as with the intensity of the prospective return stroke (Proctor et al., 1988). Campos et. al (2014) compared the average speed of stepped leaders and dart leaders with their respective peak currents. However, in both analyses there was no correlation. The present work shows that the final speed of the stepped leaders has a significant correlation with the peak current of the return stroke and offers an explanation why Campos et. al (2014) did not obtain a correlation in their results.

## 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 network information, see Biagi et al. (2007), Cummins & 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 & Murphy (2009). This has been shown (mostly through rocket triggered lightning studies) to estimate the peak current well (errors within 10% to 15%) for negative subsequent strokes, although there is still little experimental data for first return strokes and positive strokes (Rakov, 2005).

### 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, towards 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 x 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), Saba et al. (2017), Saba et al. (2022) and Saba et al. (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).

## 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 towards 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 ($H_{F-1}$) located between 200 and 450 m above the ground. See the Figure S1 provided in the supplementary information 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 x $10^5$ 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 ($\delta_{LLS}$ = ±500 m, see Cummins et al.; 1998), camera tilt errors ($\delta_\theta$ = ±0.017 rad) and pixel location in high-speed camera videos ($\delta_{px}$ = ±1 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 open research). 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

$3.7 \pm 0.58 \times 10^5$ 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.

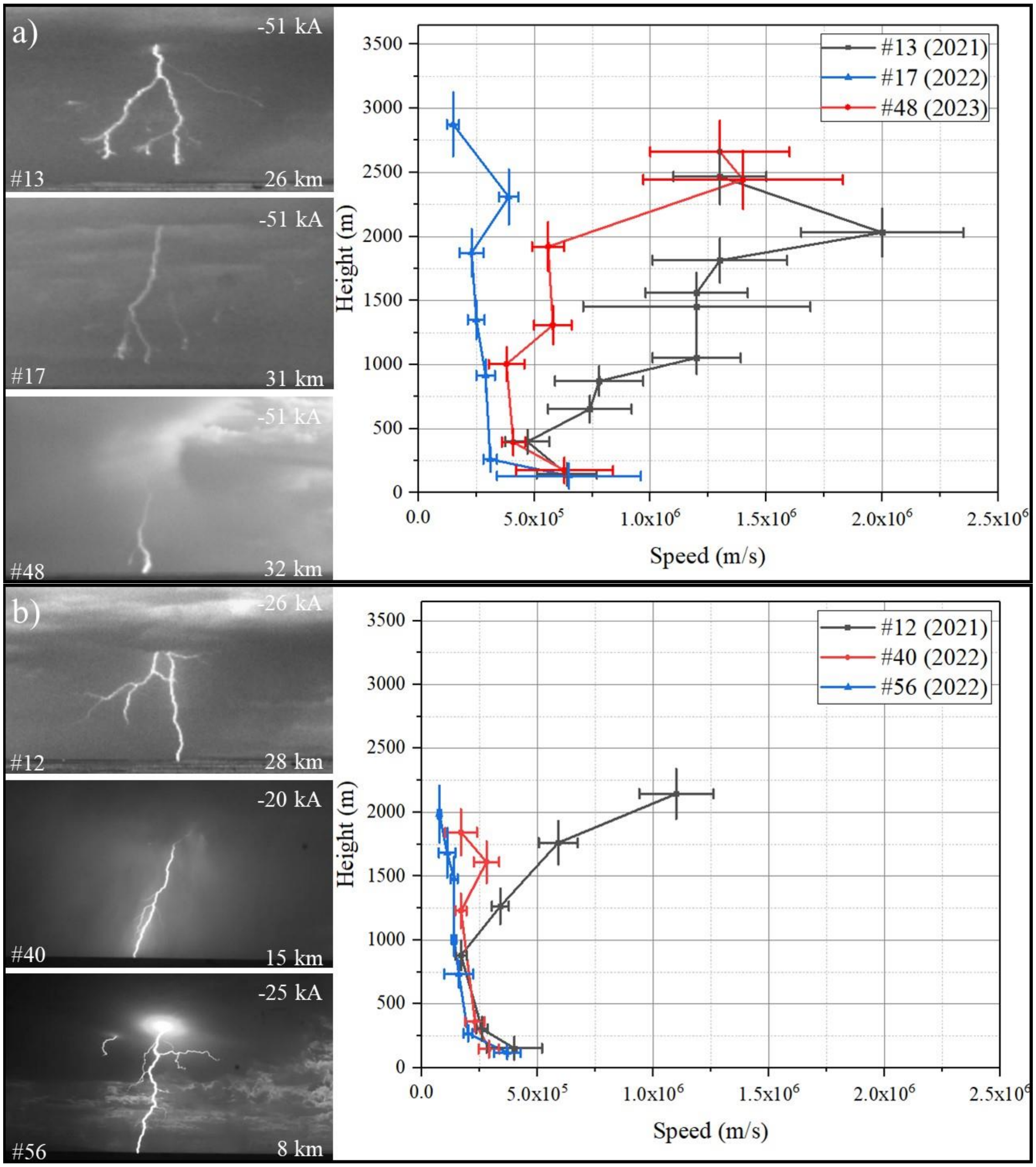


**Figure 1.** The 2D speeds of the stepped leaders vs height. On the left part of figures a) and b), the images of the stepped leaders are shown, together with peak current and distance from camera. On the right of the figures, the 2-D speed profiles of the stepped leaders as a function of height are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

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.

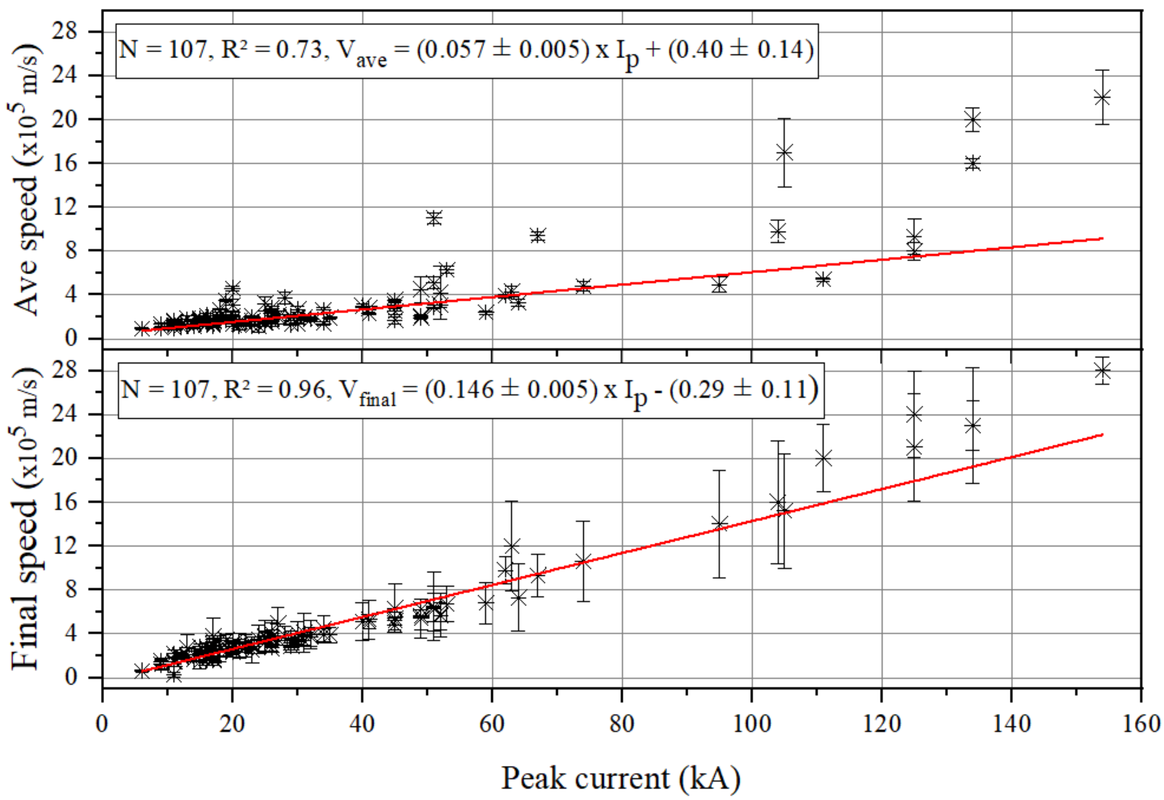


**Figure 2.** The image shows the average and final speed of the stepped leaders as a function of prospective return stroke peak current. $R^2$ represents the coefficient of determination and N indicates the number of analyzed stepped leaders. In the graphs, the negative sign of the current peaks are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

### 4.2 Dart leaders

Figure 3 shows the 2-D speed profiles of three dart leaders (2$^{nd}$ return stroke of lightning flash #9, 10$^{th}$ return stroke of lightning flash #5 and 8$^{th}$ return stroke of lightning flash #31), all with the same prospective return 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 $6.1 \pm 1.6$, $23 \pm 2.2$, and $9.3 \pm 2.5 \times 10^6$ m/s in this case for heights of $140 \pm 23$, $342 \pm 59$, and $330 \pm 42$. The lightning flashes occurred 10, 27, and 17 km away from the high-speed camera, respectively.

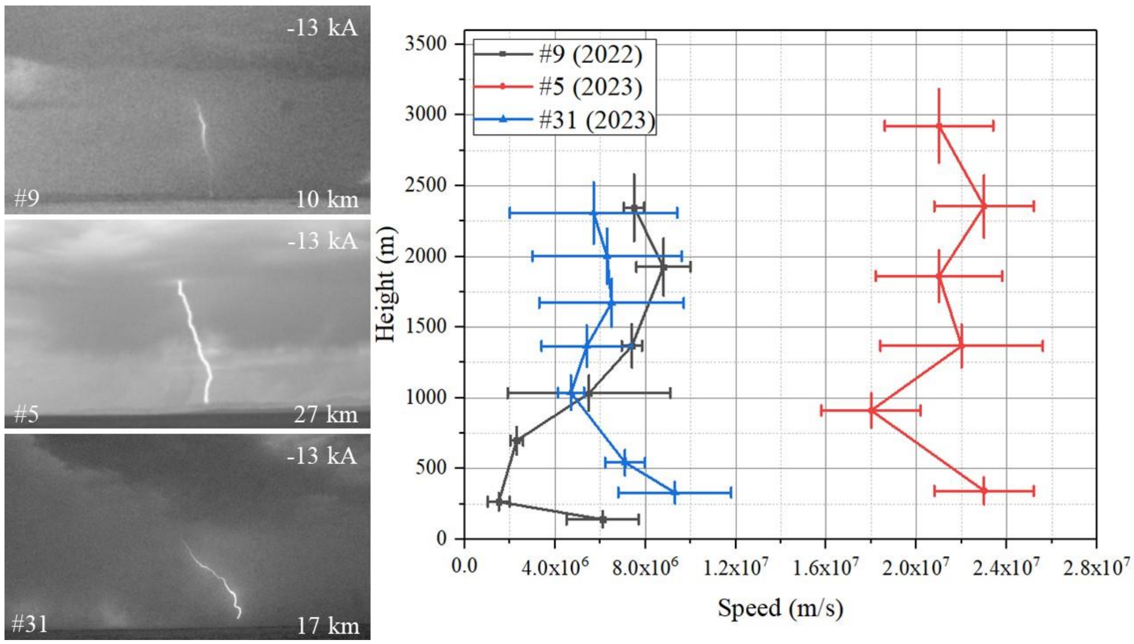


**Figure 3.** On the left, the video images of the three dart leaders right before the occurrence of the return stroke are shown. Their estimated peak currents are the same (-13 kA). On the right, height profiles of the speeds are shown. The horizontal and vertical bars show the values of the speed and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

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 speed of the dart leaders were calculated with one frame difference, i.e. 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 $\leq H_{F-1} \leq$ 1440 m. See Figure S2 of the supplementary information 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.

| | Ip (kA) | | | Average Speed ($x10^5$ m/s) | | Final Speed ($x10^5$ m/s) | |
|---|---|---|---|---|---|---|---|
| | AM | Min. | Max. | Min. | Max. | Min. | Max. |
| Stepped leader (N = 107) | -33 | -6 | -154 | 0.87 | 22 | 0.28 | 28 |
| Dart leader (N = 93) | -17 | -4 | -57 | 13 | 340 | 6.2 | 350 |

**Table 1.** Return stroke peak current and average and final speed values for stepped and dart leaders. N is the number of stepped and dart leaders analyzed.

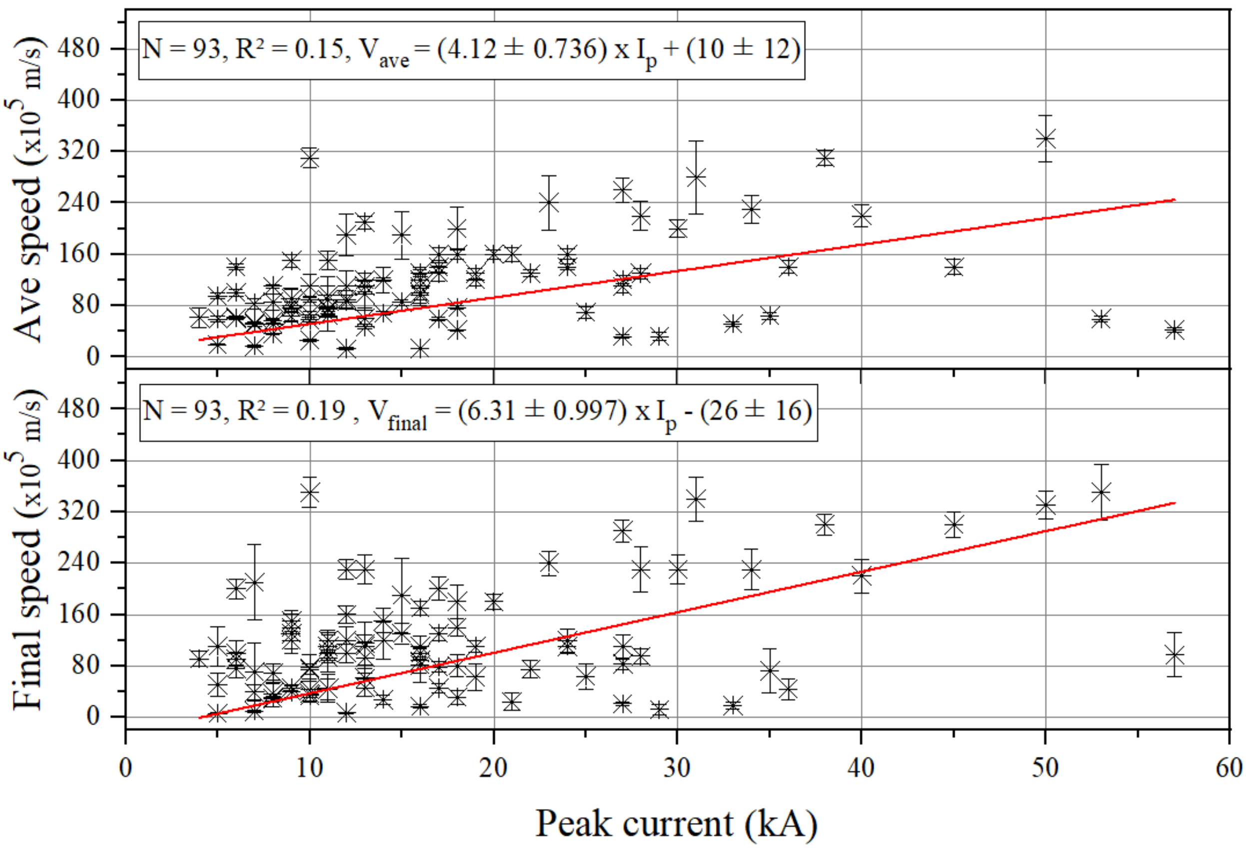


**Figure 4.** Average and final speed of the darts leaders as a function of the peak current. $R^2$ represents the coefficient of determination and N indicates the number of stepped leaders analyzed. In the graphs, the negative sign of the current peaks are disregarded for better visualization.

## 5 Discussion and conclusion

Considering that the speed of leaders is expected to be faster if the amount of charge at their tips is higher (Proctor et al., 1988), and that peak current of the following return stroke is higher if the amount of charge at the bottom part of the leader is higher (Khounate et al., 2021), Campos et al. (2014) tried to find some correlation between the speed of the leader and the peak current of the return stroke. However, they showed that the average speed of positive leaders, negative stepped and dart leaders have apparently no correlation with the peak currents of the return strokes following these leaders. The present work reviews that study, using new data to examine the relationship of the final and average speed of stepped and dart leaders with the stroke peak current initiated by them. The larger sample size and peak current range unveiled a relationship that has never been observed before.

The present work shows that there is a correlation between leader speed and the resulting return stroke peak current for stepped leaders but not for dart leaders. It also 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.

As observed by Campos et al. (2014), the average speed of negative leaders during their downward propagation has a wide variation. This could be related to atmospheric conditions and to the number of branches formed along their propagation. Therefore, the correlation (R = 0.73) of the average speed of a leader with the peak current is weaker than that of the final speed (R = 0.85). Considering that both the peak current and leader speed distributions are not normal, the Spearman correlation coefficient was used. The Spearman correlation coefficients obtained in this research were calculated considering the uncertainties in the speeds. For this, 100,000 Monte Carlo simulations were carried out. The values found represent the average correlation coefficient.

This work shows that the speed of stepped leaders converges to approximate equal final values when the initiated return strokes have similar peak currents. The significant correlation between the final speed and the following stroke peak current 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 downward leader and not by the charges that populate the whole channel. This is also important considering that LLSs are not well validated for the first return and that, while there are possible errors present in the LLS peak current estimation, this is not relevant as the relationship between final speed and peak current clearly holds here.

The correlations between dart leader speed and return stroke peak current were moderate and weak. The dart leaders presented a correlation coefficient R = 0.41 when the average speed was considered, and R = 0.29 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 leader tip, resulting in a moderate (average speed) and weak (final speed) correlation with the peak current.

The fact that the final speed of negative leaders (for 50 m $\leq H_F \leq$ 200 m and 200 m $\leq H_{F-1} \leq$ 450 m) has a very strong correlation with the following return strokes not only shed 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 (Warner, 2010) 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).

## Acknowledgments

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## Open Research

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

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*Geophysical Research Letters*

Supporting Information for

**Correlation between final speed of the stepped leader and the return stroke peak current of lightning flashes**

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## Contents of this file

Figures S1 to S2

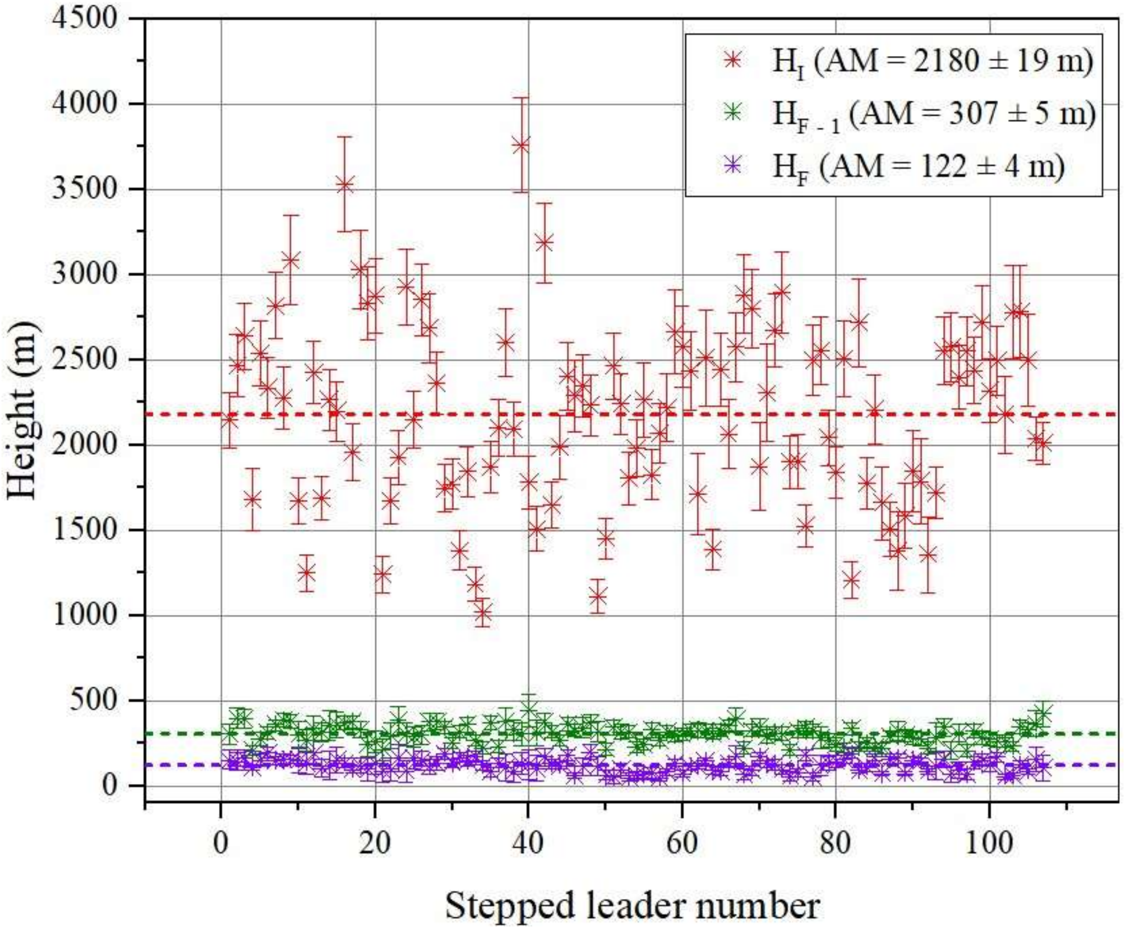


**Figure S1.** The image shows the distributions of the 107 stepped leaders for height close to the cloud base (initial height – $H_I$), final height ($H_F$), and for the penultimate height ($H_{F-1}$). Vertical bars represent height uncertainties. The red, green, and purple dotted lines display the average height of $H_I$, $H_{F-1}$, and $H_F$.

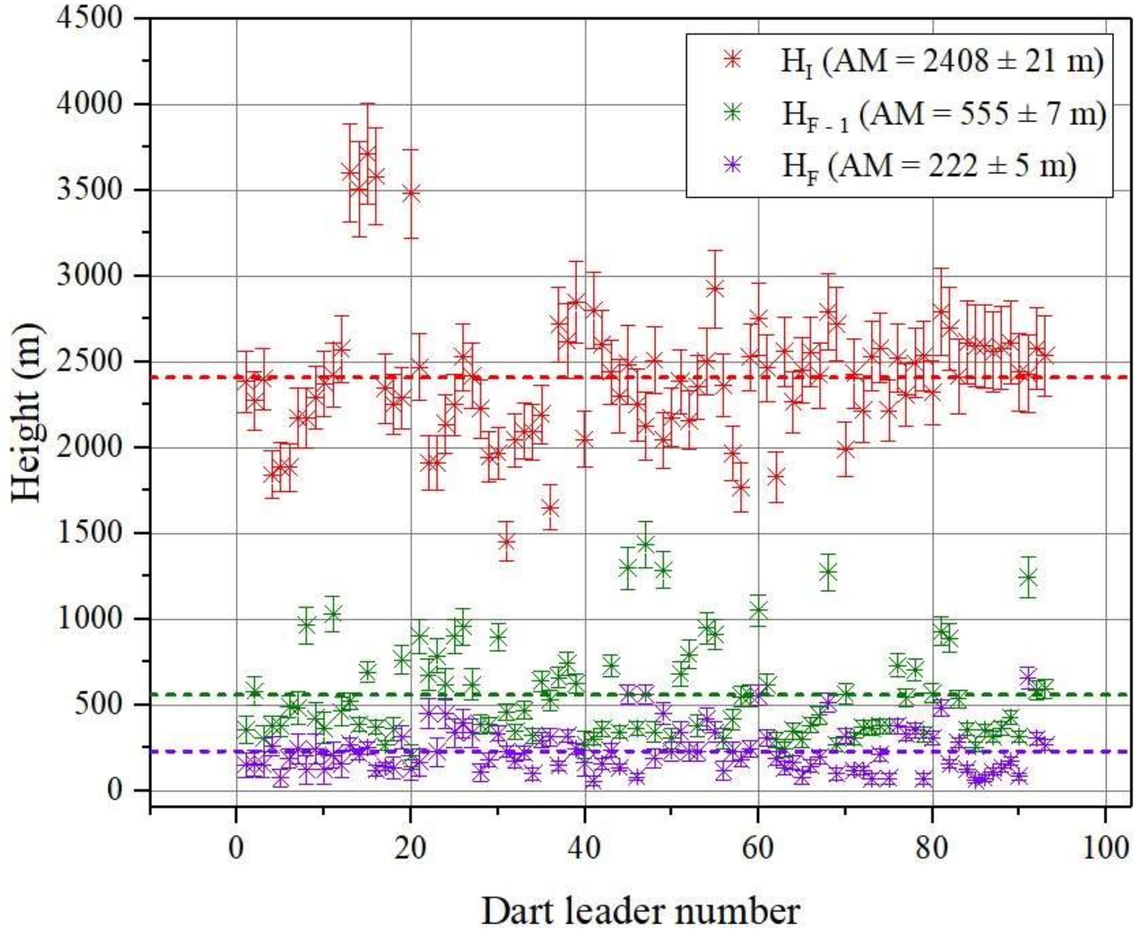


**Figure S2.** The image shows the distributions of the 93 dart leaders for height close to the cloud base (initial height – $H_I$), final height ($H_F$), and for the penultimate height ($H_{F-1}$). Vertical bars represent height uncertainties. The red, green, and purple dotted lines display the average height of $H_I$, $H_{F-1}$, and $H_F$.