Estimation of Lightning Return Stroke Velocities

Matthew Jay
Genesis Langum
Samantha Tabor

Under the advisement of
Dr. Danyal Petersen

University of Oklahoma
School of Meteorology

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**Abstract**

Previous studies regarding return stroke propagation velocity have resulted in a large range of measurements. This study tested a new measurement technique with the aim of identifying whether it would produce estimated velocities within a reasonable range of those from previous studies. Velocities were calculated for nine lightning flashes from the evening of September 26th 2012 in Norman, Oklahoma. Using footage from a high-speed video camera, still images of the return stroke were captured and analyzed using a Python script. Luminosity curves were created and the movement of a reference point along the curve with time was used to calculate a total pixel distance traveled. A velocity in meters per second was then found using basic trigonometric equations, location data from Earth Networks Total Lightning Network (ENTLN), and the frame rate of the video camera. These computed velocities fell within the range of previous studies, which implies that high-speed video may be a useful tool for further research. Resultant values occurred within a small range of each other, with the exception of one case. Additionally, the temporal resolution of two of our cases enabled us to evaluate whether these results were consistent with the previously identified tendency of the return stroke velocity to decrease with height.

**Introduction**

The return stroke phase of lightning involves a large transfer of charge to ground, which occurs in a front-like manner within the channel 'carved out' by the leader (Rakov and Uman 2003). It is as of yet impossible to directly measure the current of this charge transfer for every lightning flash, but a value can be inferred on the assumption that the peak current is related to the propagation velocity of the return stroke current front (Mach and Rust 1989). Several methods have been employed to estimate the return stroke velocity, all relying on the luminosity of the return stroke to serve as a proxy for the current front position. Based on the aforementioned assumption, better estimates of return stroke propagation
velocity—and more accurate peak current estimates—may enable engineers to design improved lightning protection technologies. Prior experiments have estimated velocities to be a significant fraction of the speed of light, but individual values vary within an order of magnitude (Boyle and Orville 1976; Idone and Orville 1982; Mach and Rust 1989). These estimations are intrinsically slower than the true three-dimensional velocity of the return stroke, because of observational limitations regarding spatiotemporal resolution and the lack of observation in the perpendicular horizontal direction.

New potential observation methods are evolving, among them high-speed video. This experiment was undertaken to assess whether the analysis of high-speed video footage would yield reasonable estimates of return stroke propagation velocity. In this paper, estimates of two- and three-dimensional velocity are provided from nine return stroke cases. Calculated mean velocities ranged from \(4.20 \cdot 10^7\) to \(1.39 \cdot 10^8\) ms\(^{-1}\)—all within the range of values from previous studies. When considering the tortuous nature of the lightning channel, it is reasonable to claim that the channel is at least as tortuous in the normal direction as it is in the visible plane. When a basic tortuosity estimation is factored in to calculate a three-dimensional propagation speed approximation, mean values range from \(6.13 \cdot 10^7\) to \(1.87 \cdot 10^8\) ms\(^{-1}\). For flashes that lasted three or more frames, the velocity for each frame was computed. Interestingly, as the luminous pulse propagated upward, the velocity for each frame interval was approximately halved.

**Motivation**

There have been several prior studies investigating return stroke velocity; many of them acknowledge that because the shape of the return stroke luminous pulse is variable as it propagates, its exact boundary is ambiguous, leading to some uncertainty in velocity estimates (Rakov and Uman 2003). It has been suggested that return stroke speed should increase with increasing peak current (Lundholm 1957; Wagner 1963), but other works refute the existence of such a relationship because of the high variance of velocity values implicated by it (Mach and Rust 1989, Willett 1989). There is also a consensus that return stroke velocity changes along the lightning channel; Nakano, et al. (1988) found that
segment mean return stroke propagation speeds increase with height in the first 180 m, and decrease thereafter. Thus, the velocity value at a particular segment may not be an accurate representation of the entire channel.

While the notion that the velocity of a return stroke varies with height may hold more scientific importance, a mean velocity over the entire length of the channel could serve as an overarching representation of the characteristics of the return stroke such as those calculated using a streak camera. Streak camera-derived estimations from Boyle and Orville (1976) ranged from $2.0 \cdot 10^7$ ms$^{-1}$ to $1.2 \cdot 10^8$ ms$^{-1}$. Another streak camera experiment conducted by Idone and Orville (1982) yielded mean channel velocities between the surface and 1.3 km that ranged from $2.9 \cdot 10^7$ ms$^{-1}$ to $2.4 \cdot 10^8$ ms$^{-1}$. Mach and Rust (1989a), using a device consisting of eight photodetectors mounted behind horizontal slits in a camera lens, found a similar range of velocities, from $2.0 \cdot 10^7$ ms$^{-1}$ to $2.6 \cdot 10^8$ ms$^{-1}$. Nakano, et al. (1988) employed a photodiode array to capture the propagation of a positive return stroke; peak velocity was found to be $2.0 \cdot 10^8$ ms$^{-1}$ at reference level, decreasing to $0.3 \cdot 10^8$ ms$^{-1}$ at 180 m above their reference level. According to Rakov (2007), the speed of a return stroke within the lowest 100 m of the channel was typically between one-third and two-thirds the speed of light.

This information comes into practical importance when lightning protection is considered. More is discussed about this in the Implications subsection.

**Data and Methodology**

To accomplish our goal of determining lightning return stroke velocity, we filtered through 45 lightning flashes captured by the high-speed video camera, choosing nine cases to closely examine based on several criteria such as the number of frames each flash spanned, the amount of channel branching, cloud obfuscation, luminous saturation, and reliability of location data. The nine cases chosen were captured at 90000 frames per second. The camera was situated before a south-facing window in room 5620 of the National Weather Center in Norman, Oklahoma. In addition to the high-speed video
camera footage, observations of electric field, made with a flat plate electric field antenna, indicated the sign (positive or negative) of the lightning flashes, and data from a microwave (GPS) antenna provided accurate timing. Both of these instruments were located on the roof of the National Weather Center. Lastly, strike location data from the Earth Networks Total Lightning Network (ENTLN) were used to estimate the strike distance from our instruments.

Photron Fastcam Viewer 3 (PFV3) was used to view the high-speed camera footage, which allowed modulation of contrast, brightness, gamma, playback speed and bit depth settings for optimal depiction of return stroke propagation. Analysis of the electric field signals was done using a waveform viewer program called DF32. The time stamps on these observations are correct to within 100 ns; such precise time stamps enabled confident synchronizing of camera footage to these signals.

Still images of the return stroke were extracted from video footage of each of the nine flashes. To process the images, a program was written in Python that used the Python Image Library. The Python program scanned through each image, pixel by pixel, and recorded to a spreadsheet the X and Y pixel coordinates and RGB brightness percentage of the brightest pixel in each row. These pixels indicated the return stroke path; the Y pixels were graphed along with brightness percentage to see how the luminosity of the return stroke varies with height in each frame. Once graphs of the brightness were created for each frame, a reference point was chosen to monitor the movement of the curve with time. The point was chosen at the base of the steepest increase of brightness on the curve; this method was chosen as it could be applied to every case without introducing a significant amount of selective bias. These reference points were recorded and the “stretched” distance between each point was computed. This was calculated using the algebraic distance formula

$$D = \sqrt{(x_2-x_1)^2 + (y_2-y_1)^2}$$  \hspace{1cm} (1)

for every two points between the initial reference point coordinates and the final reference point coordinates using the first frame of each flash. Summing these distances yielded a
stretched distance of the lightning channel. This is essential to the velocity calculation as lightning does not propagate linearly.

Next the stretched distance, measured in pixels, was converted to meters. This was completed using basic trigonometric principles. Important values in the initial calculations included the height of the camera above the ground—approximately 27.43 m—and the angle of view \( \alpha \) of the camera:

\[
\alpha = 2 \cdot \tan^{-1}\left(\frac{d}{f}\right) \tag{2}
\]

where \( d \) is the sensor height and \( f \) is the lens focal length (McCollough 1893). For sensor height of 3.2 mm and focal length of 24 mm, the angle of view was calculated to be 15.189°. Using these values, a conversion factor in units of meters per pixel was derived using basic trigonometric principles. This value was multiplied by the stretched distance to find the stretched distance in meters. For cases with three or more frames, this process was also repeated for each interval to calculate segment velocities. Finally, dividing the total distance traveled between two frames over the time between frames—\( \frac{1}{90000} \) s—equates to the velocity of the return stroke in meters per second.

![Image of lightning channel](image1.png)

![Graph of pixel number vs. intensity of lightning](image2.png)
The three-dimensional estimations were found by multiplying the two-dimensional velocity estimations by the arc-chord ratio for the tortuosity coefficient:

$$\tau = \frac{L}{C} \quad (3)$$

where $L$ is the total, “stretched” length of the channel, and $C$ is the vertical-only distance from end to end of the channel. This is a basic, rough estimate based on the notion that since every direction of return stroke propagation was not observed, it is reasonable to suggest that the lightning channel meanders in the perpendicular direction as much as it does parallel to the plane of view—thus implying cylindrical symmetry.

**Results**

All of our nine cases were ground flashes of negative polarity from September 26, 2012, between 4:42 and 4:49 UTC and at 7:51 UTC. Calculated channel-mean two-dimensional velocities ranged from $4.20 \cdot 10^7$ to $1.39 \cdot 10^8 \text{ ms}^{-1}$, shown in Figure 2 and in Table 1 of the appendix.
The highest estimated velocity seems anomalous in comparison to the other flashes, which had velocities on the order of $10^7 \text{ ms}^{-1}$. There is no apparent correlation between total channel length (in Table 1) and mean propagation speed through the channel, nor does one seem apparent between mean speeds and strike distance away from the camera. In considering the tortuous nature of the lightning channel, it can be claimed that the channel is at least as tortuous in the normal direction as it is in the visible plane, in order to allow for a low-end estimate of three-dimensional propagation velocity. When $\tau$ is applied to the two-dimensional estimates, channel-mean three-dimensional velocity values range from $6.13 \cdot 10^7 \text{ ms}^{-1}$ to $1.87 \cdot 10^8 \text{ ms}^{-1}$, shown in Figure 3 and in Table 2 of the appendix.
For flashes that spanned three or more frames, the velocity for each frame was computed. Interestingly, as the luminous pulse propagated upward, the velocity for each frame interval was approximately halved as shown in Figure 4.

Figure 3: Plot of estimates of three-dimensional total-channel mean velocity

Figure 4: The above shows the velocity decreasing with height. The factor of decrease ranged from 1.96 to 2.088.
Case 4, “04:45:44 Flash 2” decreased as follows: from frame intervals “1 to 2” and “2 to 3”, the velocity decreased by a factor of 2.088 and from frame intervals “2 to 3” to “3 to 4” the velocity decreased by a factor of 1.967. Case 5, “04:47:24” had one fewer frame than the previous case; however the results of decrease were quite similar: from interval “1 to 2” to “2 to 3” the return stroke velocity decreased by a factor of 1.961. Table 3 of the appendix also shows these values. The time passed between each frame is approximately $1.11 \cdot 10^{-5}$s so the time between intervals is $2.22 \cdot 10^{-5}$s. For both cases, interval one included the approximate first 1000m of the stretched distance; the second interval included the next approximate 500m; and the third interval, for 04:45:44 Flash 2 only, included the last approximate 200m. These results are of a particular interest as it may point to further study of a factor of decrease of the return stroke velocity with height and time.

**Conclusions**

Computation of mean velocities for each case yielded results that fell within the ranges measured by previous studies. In comparison to the work done by Boyle and Orville (1976), Idone and Orville (1982), and the long channel results from Mach and Rust (1989), our overall two-dimensional mean value of $7.43 \cdot 10^7 \text{ ms}^{-1}$ falls toward the lower end of the collective range of their findings. One interesting result from case numbers 4 (04:45:44, Flash 2) and 5 (04:47:24) was that the velocity of the return stroke decreased by a factor of two as it propagated upward. This presents a prompt for future research to determine if this factor is an anomaly or a calculable correlation between the return stroke and height along the channel.

Our sample size is small when compared to previous studies, due to the criteria used to determine whether cases were viable for analysis, but the consistency among values indicates value in continued exploration high-speed video for observation of return strokes. Further collection of camera footage using high frame rates, different bit depths
and higher image resolution are among factors that may improve future estimates. The most improvement would come from having a second camera positioned perpendicularly to create a cubic field of view.

It is important to note that there were several factors for which control was not possible. To calculate our estimates, it was necessary to make several assumptions that are theoretically sound, but physically unrealistic, such as:

- Treating the micro- and macro-scale channel tortuosity as cylindrically symmetrical;
- Assuming no pressure gradient within the lightning channel;
- Assuming constant temperature—thus, constant luminous intensity—with time as the return stroke propagates upward.

In addition, the following sources of error have more salient effects on estimation accuracy:

- The ambiguous location of the return stroke luminous boundary;
- Non-observation of the true three-dimensional meandering of the lightning channel;
- Under- or overestimation of channel tortuosity;
- Assuming that the ENTLN location data are completely accurate;
- Speed and luminosity changes due to return stroke propagation through channel branches.

It is difficult to quantify the amount of error due to many of these factors. The error due to location data inaccuracy is an appropriate base from which to begin, however; given strong enough signal strength, if sensor signal arrival times are accurate to within 10 μs, location observations should be accurate to within 300 m. Mislocation of that amount for a flash that is 15 km away constitutes an error of 2%. Our method attempted to reconcile the difficulty of locating the luminous pulse boundary through analysis of luminosity change, rather than brightness levels themselves. Still, this technique may require more adjustment to minimize bias and provide the most representative propagation rate possible.

**Implications**

Many different kinds of industries seek ways to prevent or mitigate the damage done by lightning strikes because of costly property and natural resource losses and
disruption of communications networks and power transmission. For example, research currently being done for the Defense Advanced Research Projects Agency (DARPA) involves exploration of various aspects of lightning behavior in the scope of military application. Also, utilities and telecommunications companies wish to protect their transmission systems from damage due to voltage overloads in thunderstorms (Rachidi, et al. 2001). However, there is a shortage of definitive information to share for application, due to standing uncertainties regarding important research questions. Some of these questions include:

- How to characterize the nature of the lightning channel in models of the return stroke (Baba and Rakov 2006);
- The relationship of return stroke velocity change with height to the stroke’s current (Rakov 1998);
- The relationship of lightning characteristics to geographic location (Chowdhuri, et al. 2003).

Lightning detection technology continues to improve, and as it does, it is important to develop a solid informational basis on which empirical relationships can be drawn and explored. It is hoped that, eventually, these empirical relationships will be understood and explained by physical relationships. Our project contributes to this cause by its trial of a novel measurement method, and by bringing forth observations and analysis that may be useful to other researchers in venturing to further improve lightning detection and protection technologies.

**Acknowledgements**

We are grateful for the guidance and assistance of our mentor, Dr. Danyal Petersen, of the University of Oklahoma School of Meteorology. We also appreciate Dr. William Beasley’s help in brainstorming our topic.
**Appendix**

**Table 1: Lightning channel lengths and estimated two-dimensional velocity values**

<table>
<thead>
<tr>
<th>Case Number</th>
<th>Time [UTC]</th>
<th>Visible Channel Length [m]</th>
<th>Velocity [$\cdot 10^8 \text{ ms}^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>04:42:47</td>
<td>1539.354911</td>
<td>1.38541942</td>
</tr>
<tr>
<td>2</td>
<td>04:44:41</td>
<td>896.7414163</td>
<td>0.807067275</td>
</tr>
<tr>
<td>3</td>
<td>04:45:44</td>
<td>833.5307265</td>
<td>0.754177654</td>
</tr>
<tr>
<td>4</td>
<td>04:45:44 Flash 2</td>
<td>1553.188678</td>
<td>0.465956603</td>
</tr>
<tr>
<td>5</td>
<td>04:47:24</td>
<td>1567.691201</td>
<td>0.70546104</td>
</tr>
<tr>
<td>6</td>
<td>04:48:16 Flash 2</td>
<td>466.6975216</td>
<td>0.420027769</td>
</tr>
<tr>
<td>7</td>
<td>04:48:16 Flash 3</td>
<td>662.9742637</td>
<td>0.596676837</td>
</tr>
<tr>
<td>8</td>
<td>07:51:24</td>
<td>769.9899948</td>
<td>0.692990995</td>
</tr>
<tr>
<td>9</td>
<td>07:51:24 Flash 2</td>
<td>956.8192224</td>
<td>0.8611373</td>
</tr>
</tbody>
</table>

**Table 2: Arc-chord ratios and estimated three-dimensional velocity values**

<table>
<thead>
<tr>
<th>Case Number</th>
<th>Time [UTC]</th>
<th>Arc-Chord Ratio</th>
<th>Velocity [$\cdot 10^8 \text{ ms}^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>04:42:47</td>
<td>0.775722069</td>
<td>1.785973966</td>
</tr>
<tr>
<td>2</td>
<td>04:44:41</td>
<td>0.432438403</td>
<td>1.866317305</td>
</tr>
<tr>
<td>3</td>
<td>04:45:44</td>
<td>0.400301389</td>
<td>1.874032103</td>
</tr>
<tr>
<td>4</td>
<td>04:45:44 Flash 2</td>
<td>0.75972028</td>
<td>0.613326531</td>
</tr>
<tr>
<td>5</td>
<td>04:47:24</td>
<td>0.752331767</td>
<td>0.937699392</td>
</tr>
<tr>
<td>6</td>
<td>04:48:16 Flash 2</td>
<td>0.271772587</td>
<td>1.545511906</td>
</tr>
<tr>
<td>7</td>
<td>04:48:16 Flash 3</td>
<td>0.392778333</td>
<td>1.519118512</td>
</tr>
<tr>
<td>8</td>
<td>07:51:24</td>
<td>0.479242069</td>
<td>1.44601453</td>
</tr>
<tr>
<td>9</td>
<td>07:51:24 Flash 2</td>
<td>0.491734722</td>
<td>1.751223294</td>
</tr>
</tbody>
</table>

**Table 3: Incremental rates of change of velocity with height for two cases with three or more return stroke frames**

<table>
<thead>
<tr>
<th>Case Number</th>
<th>Frame Interval</th>
<th>Factor of Decrease</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>1 to 3</td>
<td>2.088072209</td>
</tr>
<tr>
<td></td>
<td>2 to 4</td>
<td>1.966590889</td>
</tr>
<tr>
<td>5</td>
<td>1 to 3</td>
<td>1.961131366</td>
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References


