Observed one-dimensional return stroke propagation speeds in the bottom 170 m of a rocket-triggered lightning channel

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[1] The return-stroke propagation speeds of five strokes from a seven-stroke triggered lightning flash are measured, with a 2 ns sampling interval, using a vertical array of photodiodes. Various methods for determining the reference point to be tracked are explored, and the speed is seen to vary over nearly an order of magnitude depending upon which method is chosen. The speeds are generally in agreement with the values found in the literature. The return-stroke speed appears to increase with height and then decrease with height in four of the five strokes examined. *INDEX TERMS:* 3324 Meteorology and Atmospheric Dynamics: Lightning; 3394 Meteorology and Atmospheric Dynamics: Instruments and techniques; 3337 Meteorology and Atmospheric Dynamics: Numerical modeling and data assimilation. **Citation:** Olsen, R. C., III, D. M. Jordan, V. A. Rakov, M. A. Uman, and N. Grimes (2004), Observed one-dimensional return stroke propagation speeds in the bottom 170 m of a rocket-triggered lightning channel, *Geophys. Res. Lett.*, *31*, L16107, doi:10.1029/2004GL020187.

1. Introduction

[2] The characteristics of lightning return stroke propagation have most often been studied using time-resolved optical records. Researchers using the Boys drum film camera and linear streak film camera [e.g., *Malan and Collens*, 1937; *McEachron*, 1939; *Schonland*, 1956; *Idone and Orville*, 1982; *Jordan*, 1990] have made significant contributions to the basic understanding of the lightning processes. The use of film as a recording medium has some drawbacks, including limited resolution (both temporal and spatial) and non-linear response to incident light intensity. The recent advent of digital sampling and recording methods, along with the development of solid-state photodetectors, has allowed researchers to achieve finer resolution and increased linearity of data collection, typified by the work of *Mach and Rust* [1997, 1989a, 1989b] and by the ALPS system employed by, among others, *Wang et al.* [1999a, 1999b, 2004]. The use of rocket-triggered lightning allows researchers to predict and determine more accurately the time and location of the termination of the lightning channel, and to prepare data collection instruments prior to the event. A summary of rocket-triggering techniques and history was presented by *Rakov* [1999]. In this paper, we present results obtained from rocket-triggered lightning experiments using a vertical array of four PIN photodiodes. The viewed height of the array elements ranged between 7 m and 170 m above the lightning termination point. The output of the array was digitized using a four-channel Digital Storage Oscilloscope (DSO) operating at a sampling rate of 500 MHz, or a 2 ns sampling interval. The oscilloscope sampled at an 8-bit amplitude resolution, resulting in nearly 50 dB of dynamic range. The seven-stroke lightning flash analyzed here was triggered at Camp Blanding, Florida during the summer of 2003. Using the photodiode array, the one-dimensional speeds of propagation in the lowest 170 m of the lightning channel for five out of the seven return strokes were measured. All of the strokes transported negative charge to ground.

2. Instrumentation and Data

[3] Four discrete PIN photodiodes were arranged in a vertical array. All diodes were EG&G C30807, rated at 5 ns risetime and 10 ns fall time. Each diode's amplifying circuit had a 10%–90% risetime of about 220 ns. Each diode was placed inside of a $7 \times 1.9 \times 30$ cm^3 rectangular aluminum enclosure whose interior was painted matte black and whose orientation placed the longer side of its cross-section horizontally. Figure 1 illustrates the arrangement of a single photodiode in an enclosure. The diode was located near one end of the enclosure, with the sensor surface oriented toward the opposite end of the enclosure. The slit at the opposite end of the enclosure was 1 mm wide vertically and extended horizontally from one edge of the enclosure to the opposite edge. The distance from the photodiode's active area to the slit was approximately 30 cm. The vertical field of view of the diode was thus restricted to an angle defined by the 1 mm slit at a distance of 30 cm. The horizontal field of view was restricted by the internal width of the enclosure, approximately 7 cm. In this configuration, each diode recorded the optical intensity versus time of a lightning channel over a short vertical distance, but was fairly insensitive to horizontal variations in the location of the channel. Four diode assemblies were placed in a vertical array, with the angle of the enclosure varying for each diode as seen in Figure 2. This means that the vertical segment of lightning channel viewed by each diode is at a different height. Comparison of the time at which a luminosity signal was observed by each photodiode with the height viewed by that photodiode allows for the measurement of the propagation speed in the vertical direction of the associated lightning process.

[4] The lightning flash designated F0336 was triggered at Camp Blanding, Florida, on August 2, 2003, at 19:30 UTC. The triggering rocket was launched from a mobile launcher located approximately 300 m from the photodiode array. At this distance, each diode was able to view a vertical section of lightning channel approximately 1 m in length. Seven

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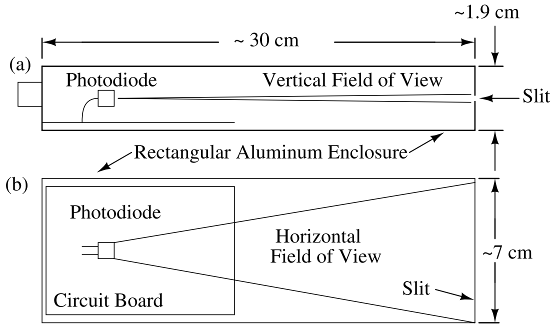

Figure 1. Photodiode assembly diagram. (a) Side view. (b) Top view.

strokes were observed following the initial stage. Of these seven strokes, one was insufficiently bright to trigger the recording oscilloscope, and one occurred after the maximum number of recorded segments had been reached in the oscilloscope memory. The segments which were recorded correspond to strokes 1, 2, 4, 5, and 6. The currents measured at the termination point had peaks of about 28, 15, 13, 18, and 18 kA, respectively. The optical record of stroke 1 is shown in Figure 3, with the height viewed by each photodiode noted. The variations in light intensity associated with the passage of the dart leader and return stroke are clearly visible. The records for the other strokes in this flash are similar in character.

3. Results

[5] Data for all 5 strokes were read from the oscilloscope as raw data files and plotted using MATLAB. The noise in the optical waveforms makes estimation of the time at which the return stroke starts in the waveform somewhat uncertain. Accordingly, each waveform was filtered with a low-pass filter whose −3 dB point was approximately 3.75 MHz and whose response was down 98 dB at about 12 MHz. The step response of the filter was characterized by a 10−90% risetime of 100 ns. Comparison of the filtered and unfiltered versions of the lowermost (h = 7 m) profile for stroke 1 showed that the risetime of the waveform was

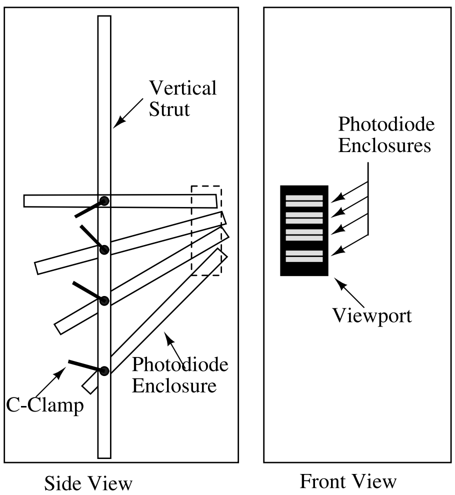

Figure 2. Photodiode array diagram.

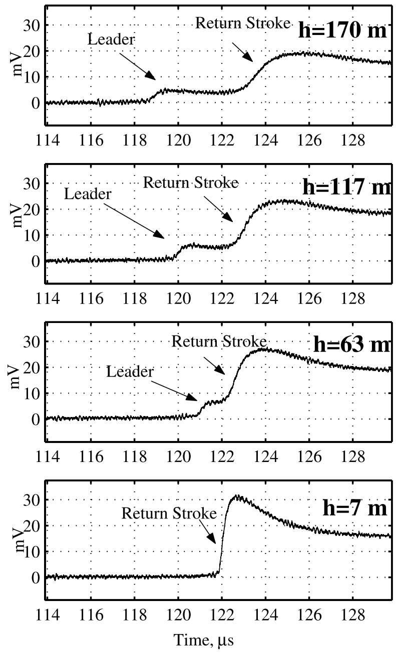

Figure 3. Flash F0336 Stroke 1 optical intensity, in mV at the input of the oscilloscope, versus time at four different heights; 7, 63, 117, and 170 m above the lightning channel termination point. These data are unfiltered.

essentially unchanged by the filter. The filter was found to induce an equal delay in all waveforms, which was acceptable because the primary concern was the time differential between waveforms. This filtering effectively reduced the noise due to electronics and quantization without materially affecting the amplitude and shape of the optical waveforms. Still photographs taken during the event indicated that the lightning channel was essentially straight over the section of channel viewed by the photodiode array, apparently due to the fact that the return-stroke channel was formed along the path previously conditioned by the initial-stage current [e.g., *Rakov*, 1999]. The angle of the lightning channel relative to the vertical was determined, again through inspection of still photographs, to be relatively small, about 10 to 15 degrees. The channel inclined away from and to the right (as viewed from the observation point) of the line joining the observation point to the channel termination point. Trigonometric analysis of the configuration, assuming a perfectly vertical channel, indicated that the light signal propagation path from the uppermost segment of channel observed was some 47 m longer than the propagation path from the lowermost segment. This indicates that the propagation time from that uppermost segment was some 155 ns longer than that from the lowermost segment, again assuming a vertical channel; accounting for the angle away from the observation point would increase the offset further. When measuring the time of arrival of the waveform, this difference in propagation times, $\Delta t(h)$, must be accounted for (see equation (1)). In the literature, the reference points to be tracked on the observed return-stroke waveforms are typically chosen to represent as closely as possible the time at which the wavefront first passes the viewed area. It is clear that the choice of reference points will affect the measured speed, as the shape and amplitude of the waveform change as it propagates up the channel; furthermore, the reference point must be chosen such that it is identifiable in all waveforms despite these variations. One reasonable method of determining a reference point is to find the time at which the waveform reaches 10% of its peak intensity, since the point of initial deflection from zero level is usually masked by noise. Similar operations can easily be performed at any relative intensity level. Another possible reference point would be the time at which the waveform reaches its maximum rate of rise. Some researchers [e.g., *Mach and Rust*, 1989a] have estimated the starting point by examination of their light waveform. Our slope-intercept method, intended to determine a reference point for the return stroke repeatably in the presence of noise, is illustrated in Figure 4 and described below. A straight, horizontal line was drawn on the waveform. The vertical level of this line is chosen to pass through the center of the noise amplitude in the region of minimum signal intensity just prior to the return-stroke waveform. In waveforms which exhibit leader signatures, the region of minimum signal intensity between the leader peak and return stroke peak (not seen in Figure 4) is chosen to be the region of minimum return stroke intensity. This line is labeled "Reference Level Line" in Figure 4. Next, a slanted line was drawn parallel to and congruent with the slope of the return stroke rising portion, approximating as closely as possible the mean of the waveform front over as long a time interval as possible. This line is labelled "Average Slope Line" in Figure 4. The intersection of these two lines, marked "R.S. Beginning" in Figure 4, was taken to be the beginning point of the return stroke waveform for each segment of channel.

[6] The slope-intercept method described above is fairly time-intensive to implement and could be described as being somewhat subjective. Also, the intersection point is apparently influenced by the average steepness of the wavefront, which changes with height. Accordingly, an additional automated process of determining relative intensity levels (for finding reference points to be tracked) was implemented using MATLAB. A moving-window average whose window width was 202 ns was first applied to the waveform in order to further reduce variations due to noise. The window width was chosen such that noise was further reduced without materially affecting the amplitude or shape of the waveform, and the filtered version was overlaid over the original for verification purposes. The region of waveform to be examined was selected to extend from immediately prior to the minimum signal intensity between the leader peak (if any) to immediately after the peak return stroke intensity. This ensured that the minimum level found by the software corresponded to the minimum level between the leader and return stroke peaks. The software reported the times at which the moving-window-averaged waveform reached different "percentage of peak", 10%, 20%, 90%, and 100% levels, and the time of maximum positive derivative. For each set of times the speeds, v, were calculated by dividing the vertical distance between adjacent viewed heights, $h_2 - h_1$, by the time interval, $t_2 - t_1$, measured using all of the aforementioned approaches, accounting for the propagation time difference $\Delta t(h)$:

$$v = \frac{h_2 - h_1}{t_2 - t_1 - \Delta t(h)} \tag{1}$$

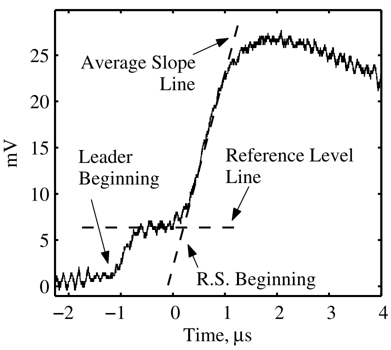

Figure 4. Illustration of the "slope-intercept" method. The optical waveform of Flash F0336 Stroke 1 at a height of approximately 63 m above the termination point is shown on an expanded timescale. The beginning of the return stroke waveform is taken to be the intersection of the two dashed lines. This intersection point was tracked in estimating the return-stroke speed by the "slope-intercept" method (see Tables 1 and 2). These data are unfiltered.

The overall speed from the lowermost viewed segment, 7 m above the termination point, to the uppermost viewed segment, approximately 170 m above the termination point, was calculated for each stroke. These results are presented in Table 1. The slope-intercept method results in the highest speed values, with the various 'percentage of peak' methods yielding speeds which get slower as the percentage increases. This is as expected, since the waveforms recorded at greater heights exhibit slower rises to peak intensity. It is notable that the measurements at 10% of maximum value were subject to error due to noise because in some waveforms the noise amplitude was close to 10% of the maximum signal intensity. As a result, some values of speed were higher than the speed of light. Similarly, the point of maximum positive derivative was occasionally misrepresented by selecting the derivative of the noise rather than the derivative of the underlying signal. In the slope-intercept method, the starting point will be reported earlier in time as the risetime of the waveform gets slower. For this reason, it is believed that the speeds measured using the slope-intercept method overestimate the actual 1-D speed. On the other hand, the 20% of peak method is believed to underestimate the actual 1-D speed. The angle of the lightning channel, as found from various still photographs, is estimated to result in 3-D speeds no more than about 3% higher than these measured 1-D speeds. It is also notable that stroke 4 was characterized by the poorest signal-to-noise ratio in this data set, resulting in speed measurements which may be considered to be less accurate than for other strokes.

[7] There are three primary sources of measurement error: angle error, distance error, and timing error. The angle error is due primarily to potential inaccuracy in the measurement of the angle of the photodiode assembly relative to ground, and is expected to be less than 0.35°. This results in height interval error of ±5% between 7 and 63 m, ±12% between 63 and 117 m, and ±19% between 117 and 170 m. The error between 7 and 170 m was estimated to be ±8.5%. The distance error is a function of the accuracy of the GPS measurements made at the observation point and

the lightning channel termination point, and is estimated to be no greater than ±10 m, or about 3%. Finally, the error in the time intervals due to inaccuracy of the reference point, whether using the slope-intercept method or the "percentage of peak" method, is estimated to be about 25 ns, which corresponds to about 8%. As these errors are uncorrelated, the total speed error for each segment may be taken as the square root of the sum of the squares of the three individual error components. This results in about ±10% for the lowest segment, about ±15% for the middle segment, and about ±21% for the upper segment. The speed error between 7 and 170 m was estimated to be ±10%.

Table 2. Flash F0336 Return Stroke Speed Versus Height

Stroke Order	Reference Point	Return Stroke Speed $\times 10^8$ m s^{-1} 7 m–63 m	63 m–117 m	117 m–170 m
1	20%	1.34	1.62	1.70
	slope-intercept	1.81	1.99	2.33
2	20%	1.19	1.81	1.22
	slope-intercept	1.94	2.59	1.32
4	20%	1.19	1.83	1.50
	slope-intercept	2.04	2.74	2.13
5	20%	1.24	1.78	1.61
	slope-intercept	2.00	2.36	1.74
6	20%	1.24	1.58	1.47
	slope-intercept	1.94	2.09	1.44

4. Discussion

[8] An interesting trend within this data set concerns the variation in measured speed in the three channel segments between 7 m and 170 m, as summarized for the 20% and slope-intercept reference points in Table 2. In 4 of the 5 strokes, the speed profile was non-monotonic with height. Specifically, for strokes 2, 4, 5, and 6, it was observed that the measured speed was greatest in the segment between 63 m and 117 m, slightly lower in the segment between 117 m and 170 m, and lowest in the segment between 7 m and 63 m. This suggests that the speed reaches a maximum value at a height between 63 m and 117 m in these four strokes. In the first stroke the speed appears to increase monotonously with height. However, it is implausible to suggest that the speed will continue to increase with height indefinitely, and so it must be assumed that the height at which the speed of Return Stroke 1 reaches a maximum is higher than the maximum viewed height of the measurement apparatus employed. *Srivastava* [1966] proposed, for the first stroke in natural lighting, a bi-exponential expression for return stroke speed, based on experimental work by *Schonland* [1956], in which the speed reaches a maximum at a height some hundreds of meters above the termination point. Gorin (as cited by *Rakov and Uman* [1998]) proposed a distributed-circuit model of the first stroke, which also predicts that the return stroke speed will reach a maximum at some hundreds of meters above the termination point.

[9] It is notable that the speed estimated using the 10% (although some values were higher than the speed of light) and slope-intercept methods for all five strokes tended to be higher, over the segment between 7 m and 63 m, by about 40% than the 1.3×10^8 m s^{-1} and 1.5×10^8 m s^{-1} reported by *Wang et al.* [1999b] for two strokes over a similar height range and higher, by about a factor of two, over the channel segment from 7 m to 117 m than those reported by *Weidman* [1998] for the lowest 100 m or so of the lightning channel. The basis upon which the validity of any of the presented measurement methods can be evaluated must, ultimately, be the underlying physical processes which cause the optical radiation. Discussion of these processes is beyond the scope of this paper.

Table 1. Flash F0336 Return Stroke Propagation Speeds, 7 m to 170 m

Reference Point	Stroke Order 1	2	4	5	6
	Speed, $\times 10^8$ m s^{-1}				
10%[a]	1.98	1.73	1.81	2.21	1.81
20%	1.53	1.36	1.46	1.50	1.41
90%	0.774	0.621	0.653	0.628	0.630
100%	0.579	0.462	0.368	0.449	0.493
Max dL/dt[b]	1.29	1.27	0.609	1.32	1.45
Slope-intercept	2.02	1.81	2.26	2.00	1.78

[a]Percentages are relative to the peak of return-stroke luminosity pulse, measured with respect to the minimum average intensity between the leader peak (if any) and return-stroke peak.
[b]L = luminosity intensity.

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