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Observed leader and return-stroke propagation characteristics in the bottom 400 m of a rocket-triggered lightning channel

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Abstract. Using a high-speed digital optical system, we determined the propagation characteristics of two leader/return-stroke sequences in the bottom 400 m of the channel of two lightning flashes triggered at Camp Blanding, Florida. One sequence involved a dart leader and the other a dart-stepped leader. The time resolution of the measuring system was 100 ns, and the spatial resolution was about 30 m. The leaders exhibit an increasing speed in propagating downward over the bottom some hundreds of meters, while the return strokes show a decreasing speed when propagating upward over the same distance. Twelve dart-stepped leader luminosity pulses observed in the bottom 200 m of the channel have been analyzed in detail. The luminosity pulses associated with steps have a 10-90% risetime ranging from 0.3 to 0.8 μs with a mean value of 0.5 μs and a half-peak width ranging from 0.9 to 1.9 μs with a mean of 1.3 μs. The interpulse interval ranges from 1.7 to 7.2 μs with a mean value of 4.6 μs. The step luminosity pulses apparently originate in the process of step formation, which is unresolved with our limited spatial resolution of 30 m, and propagate upward over distances from several tens of meters to more than 200 m, beyond which they are undetectable. This finding represents the first experimental evidence that the luminosity pulses associated with the steps of a downward moving leader propagate upward. The upward propagation speeds of the step luminosity pulses range from 1.9×10^7 to 1.0×10^8 m/s with a mean value of 6.7×10^7 m/s. In particular, the last seven pronounced light pulses immediately prior to the return stroke pulse exhibit more or less similar upward speeds, near 8×10^7 m/s, very close to the return-stroke speed over the same portion of the channel. On the basis of this result, we infer that the propagation speed of a pulse traveling along the leader-conditioned channel is primarily determined by the channel characteristics rather than the pulse magnitude. An inspection of four selected step luminosity pulses shows that the pulse peak decreases significantly as the pulse propagates in the upward direction, to about 10% of the original value within the first 50 m. The return-stroke speeds within the bottom 60 m or so of the channel are 1.3×10^8 and 1.5×10^8 m/s for the two events analyzed, with a potential error of less than 20%.

1. Introduction

A knowledge of the propagation characteristics of leaders and return strokes within some hundreds of meters of ground is very important for understanding the physics of the lightning discharge. However, since some of these processes occur on a submicrosecond scale, they could not be sufficiently resolved by previously used Boys-camera and streak-camera techniques [*Schonland et al.*, 1935; *Berger*, 1967; *Orville and Idone*, 1982; *Idone and Orville*, 1982]. In this paper, we present observations of the bottom 400 m of the rocket-triggered lightning channel using the 100-ns time resolution optical imaging system, Automatic Lightning Progressing Feature Observation System (ALPS). The observations were conducted during the summer of 1997 at the International Center for Lightning Research and Testing at Camp Blanding, Florida. The spatial resolution of ALPS for this experiment was about 30 m. The temporal resolution of our measurements is superior to that in previous studies and, as a result, we are able to shed additional light on lightning mechanisms. Among the new findings, we detected and characterized upward propagating luminosity pulses associated with individual steps of a dart-stepped leader and measured return-stroke speeds of 1/3 to 1/2 the speed of light in the bottom 60 m of the lightning channel.

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2. Instrumentation and Data

The optical data presented in this paper were acquired using the digital optical imaging system ALPS that was specifically designed for recording the luminous progression of lightning discharges [*Yokoyama et al.*, 1990]. The version of ALPS used in the present experiment has been described by *Wang et al.* [1999a]. It consists of a conventional camera lens, a photodiode array module, large dynamic range amplifiers, a multichannel digitizer, and a personal computer system. The photodiode array module consists of 256 (16×16) pin photodiodes, each 1.3×1.3 mm^2 in size, with a separation of 1.5 mm between the centers of individual diodes. A lightning channel imaged onto the sensor surface falls mostly (nearly 90%) onto the active sensing surface. Each of the diodes operates at wavelengths from 400 to 1000 nm with a response time of less than 3 ns. The ALPS can operate at a time resolution (interframe interval) from 100 ns to 50 ms with either an internal or external trigger and can record up to 16,000 frames for each event with up to 16,000 frames of pretrigger. The interframe interval used in the present study was 100 ns, and thus the resulting total recording time per event was 1.6 ms. ALPS was installed in the office building of the International Center for Lightning Research and Testing at Camp Blanding, Florida [see Uman et al., 1997, Figure 1]. From there, lightning flashes triggered from all three rocket launchers used in the 1997 experiments could be viewed. Two of the recorded leader/return stroke sequences are suitable for the present study. These two sequences occurred in two different flashes triggered from the University of Florida (UF) runway launcher at a distance of 530 m on August 2, 1997, at 2117:15 and 2127:54 UTC. A lens with a focal length of 28 mm was used with the resultant spatial resolution at a distance of 530 m being about 30 m. Both flashes lowered negative charge to ground. Their still photos are shown in Figures 1a and 1b. As evident in Figures 1a and 1b, the 2117:15 flash had a straight channel section of 260 m, while the 2127:54 flash had a straight channel section of 200 m. The straight channel sections follow the traces of the triggering wires, which are melted and evaporated during the initial stage of the triggered-lightning discharges [*Wang et al.*, 1999b], well before the leader/return-stroke sequences studied here. The channel-base current was recorded only for the second event (2127:54 UTC). The peak value of that current was about 17 kA.

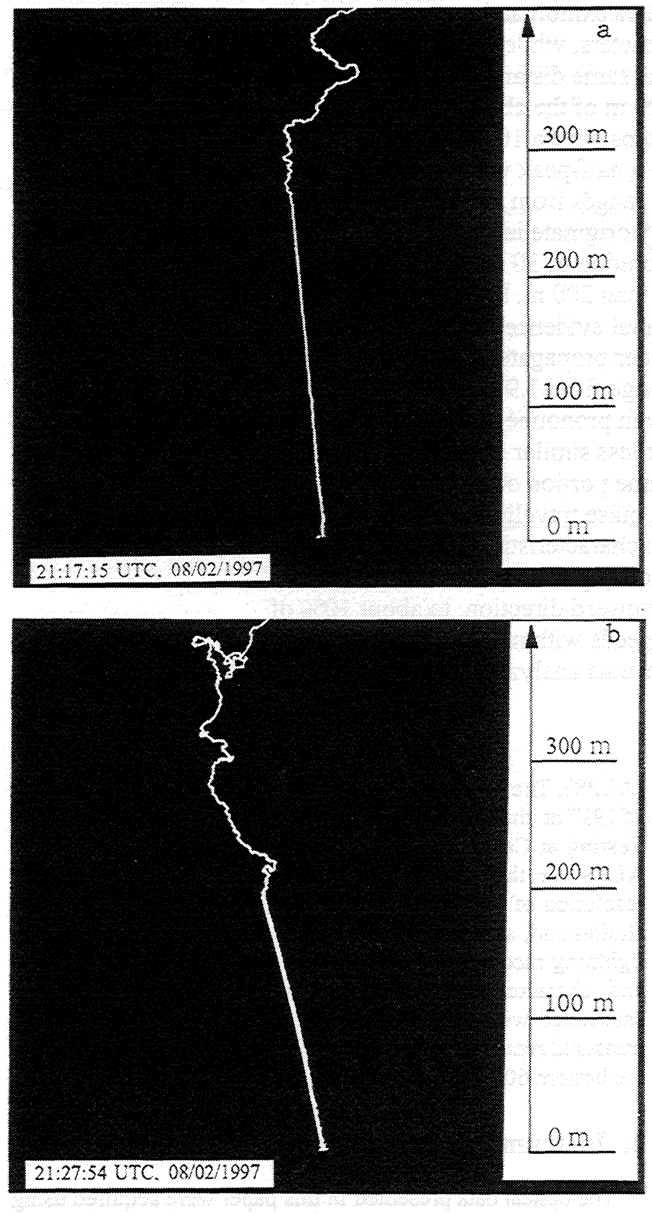

Figure 1. Still photographs of two flashes triggered on August 2, 1997, at Camp Blanding, Florida, at (a) 2117:15 UTC and (b) 2127:54 UTC. The straight channel sections follow the triggering wire trace.

3. Results

3.1. Leader Speed Profile

Figures 2a and 2b show the leader light waveforms as a function of time at various heights for the 2117:15 and 2127:54 events, respectively. The various channel sections viewed by different rows of photodiodes are numbered sequentially from ground (S1 through S13) as shown on the left of Figures 2a and 2b, and the straight distances along the discharge channels (inclined) to their centers, measured from the ground, appear in parentheses. For convenience, these distances are simply termed heights in this paper. Note that the heights are slightly different for the 2117:15 and 2127:54 events owing to the different channel inclinations, as can also be seen in Figure 1. Leader light signals at the lower heights occur later in time, hence these leaders propagate in the downward direction. As is evident from Figure 2a, the leader in the 2117:15 event does not exhibit any pronounced pulses superimposed on its light signals, and hence it is identified as a dart leader. Note that dart-leader light signals have been reported by *Jordan et al.* [1997] for natural lightning to begin with a sharp pulse (a feature not seen in Figure 2a) followed by a plateau. However, *Mach and Rust* [1997] found that some dart leaders exhibit a rather gradual rise to a relatively constant light level without the initial pulses for both natural and triggered lightning, and these are similar to the waveforms seen in Figure 2a. As evident in Figure 2b, the luminous signals of the leader in the 2127:54 event contain many sharp pulses at least within 300 m of the ground, and thus this leader is identified as a dart-stepped leader. The measurement of the time difference between the onset points of the light signals at any two channel sections in conjunction with the distance between the two sections allows one to estimate the average two-dimensional leader speed over that distance. Figure 3 shows the propagation speed profiles of the two leaders. In this study, the leader speed at a given height (for example, at S3) was obtained over the distance between its two neighboring channel sections (i.e., S2 and S4 for this example). The resulting error in downward speed estimation for the dart leader with continuous propagation is expected to be less than 10%, while for the dart-stepped leader, owing to the uncertainty in the determination for the exact location of the formation point of the step pulses within channel sections viewed by individual photodiodes, it

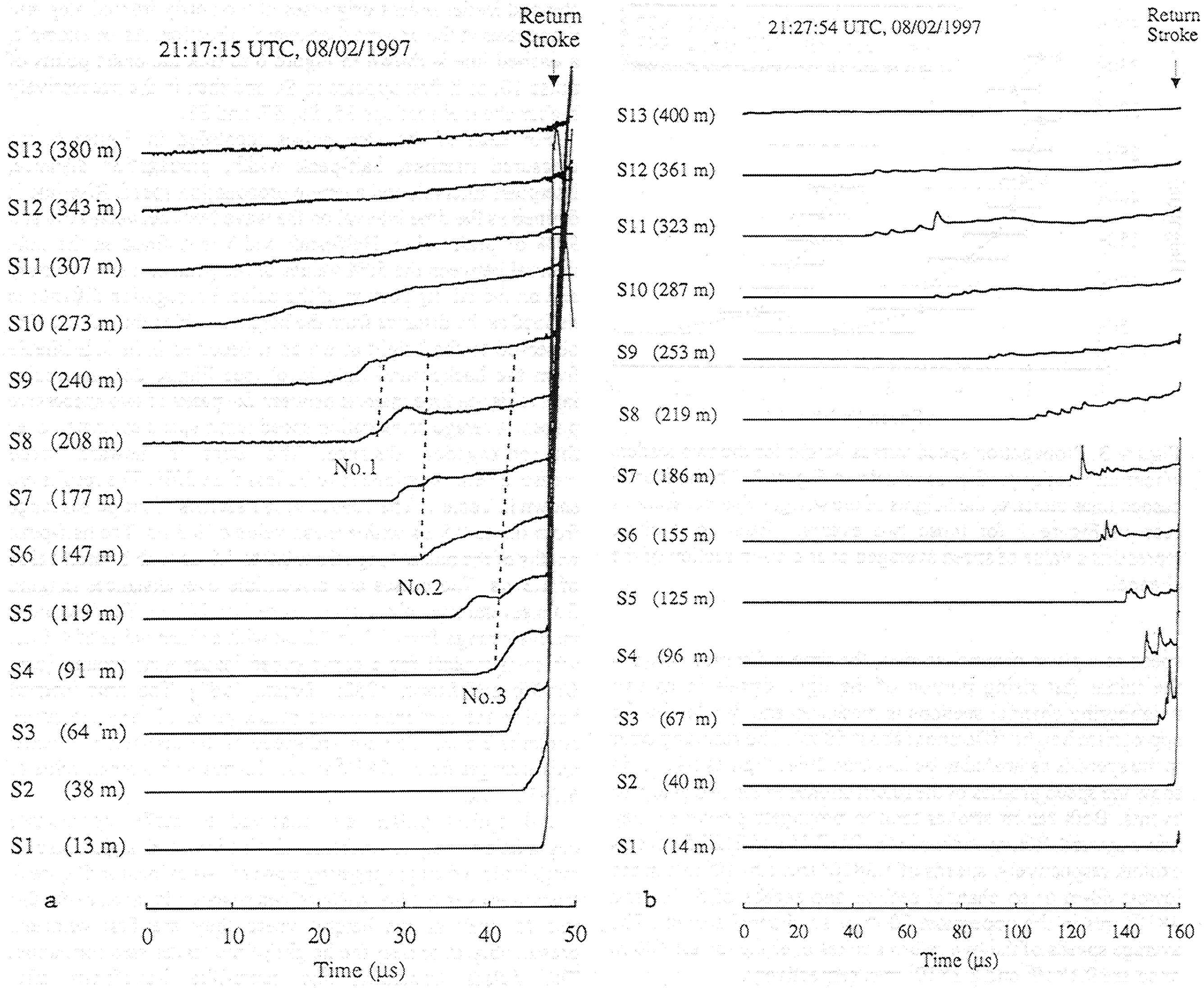

Figure 2. Leader light versus time waveforms at different heights above ground for events triggered on August 2, 1997 at (a) 2117:15 UTC and (b) 2127:54 UTC. Note that the three humps numbered 1, 2, and 3 in Figure 2a appear to propagate in the upward direction. See also Figure 6 which is an expansion of Figure 2b.

could be as much as 30%. As seen in Figure 3, both leaders tend to propagate faster as they approach ground. In the case of the 2117:15 event, the leader speed increases from 8×10^6 to 13×10^6 m/s during its downward propagation from 350 to 40 m, with an average speed of about 8.9×10^6 m/s. In the case of the 2127:54 event, the leader speed increases from 2×10^6 to 8×10^6 m/s during its propagation from 200 to 40 m, with an average speed of about 2.5×10^6 m/s. Both leaders exhibit a relatively sharp increase in speed over the lowest several tens of meters. On average, the dart leader propagates much faster than the dart-stepped leader, this observation being consistent with previous reports [e.g., *Uman*, 1987; *Jordan et al.*, 1992].

The leader luminosity waveforms in Figure 2a exhibit humps best seen at heights from S5 to S9. The onset points of three of such waves at different heights are connected by dashed lines, with the positive slope of the lines, indicating that these three waves move in the upward (backward) direction. The speed of the upward moving wave labeled 3 is estimated to be 4.5×10^7 m/s. This finding is in support of the prediction of *Rakov* [1998] that the relatively low frequency components associated with the dart-leader light plateau should propagate from the leader tip in the upward direction at characteristic dart-leader speeds. The leader tip is defined here as the leading edge of the extending leader channel, at which the leader current is assumed to be generated via breakdown processes. In this view, the dart-leader tip is a continuously moving current source, launching current and luminosity waves in the backward direction [e.g., *Rakov*, 1998]. Note that with 30-m resolution we are unable to resolve the leader tip itself since its length is probably of the order of 10 m [*Jordan et al.*, 1997].

3.2. Return-Stroke Speed Profile

Figures 4a and 4b show the rising portions of return-stroke light signals as a function of time at different heights for the 2117:15 and 2127:54 events, respectively. The light signals in rows S2 to S6 for the return stroke in the 2117:15 event and in rows S1 to S10 for the return stroke in the 2127:54 event are clipped owing to their exceeding the upper measurement limit. As seen in Figure 4, the light signals occur later in time at progressively higher altitudes, and hence they are propagating upward. To determine an average two-dimensional return-stroke

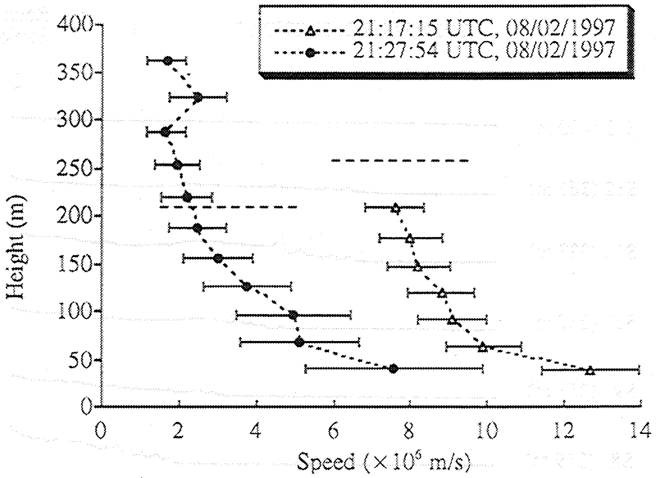

Figure 3. Propagation speed versus height for the two leaders whose luminosity profiles are shown in Figure 2. The horizontal dashed lines indicate, the heights of the straight channel sections seen in Figure 1 for those two events. Each solid circle represents a value of speed averaged over a 60-m section of the channel.

speed at a given channel section, the time difference between the initial fast rising portion of the light signals in its two neighboring channel sections is measured and divided by the appropriate height difference (about 60 m). The resulting error in the speed is estimated to be less than 20%. Figures 5a and 5b show the speed profiles of the return strokes in the two analyzed events. Both return strokes tend to propagate slower as they move upward. Return strokes in the 2117:15 and 2127:54 events exhibit, respectively, speeds of 1.3×10^8 and 1.5×10^8 m/s in the lowest 60-m or so channel section and speeds of 5×10^7 and 4×10^7 m/s in the uppermost 70-m or so channel section. The average speeds of the two return strokes over the lowest 400 m or so are 9.1×10^7 and 8.3×10^7 m/s, respectively.

From the nonclipped signals in Figure 4a, the return stroke shows an appreciable increase in risetime and a decrease in peak value when propagating from ground upward to a height of some hundreds of meters.

3.3. Characteristics of Dart-Stepped Leader Pulses

Figure 6 is an expansion of Figure 2b, showing more clearly the dart-stepped leader pulses. We identified a total of 12 pulses, numbered from 1 to 12, that occurred in the lowest 200 m of the channel during the 60 μs just prior to the return stroke. Each pulse is inferred to correspond to one luminous step of the dart-stepped leader as seen in streak photographs [e.g., *Berger*, 1967; *Orville and Idone*, 1982]. In some channel sections, such as S4, only one new pronounced pulse apparently occurs, while in other channel sections the number of new pulses is more than one, for example, three in S6 and S8. The occurrence of multiple pulses is apparently due to a combination of (1) the 30-m height resolution (each row of photodiodes "views" about 30 m of the channel and "reports" all processes occurring in this channel section) and (2) the formation of more than one step within 30 m.

As evident in Figure 6, the pulses numbered 4 through 12 can each be traced from the lowest level where each of them is first detected to one to five levels higher. The positions, shapes, and amplitudes of the pulses suggest that each of the optical dart-stepped leader pulses originates at the newly formed step and propagates in the upward (backward) direction. As an example, a dashed line is drawn in Figure 6 to link the onset points of pulse 10, as it first appears in S4 and then in the successively higher channel sections S5, S6, S7, and S8.

For each of the step pulses identified in Figure 6, we measured risetime, half-peak width, propagation distance, interpulse interval, and average propagation speed. Risetime is defined as the time interval on the wave front between 10% and 90% of peak value. Half-peak width is defined as the time interval between the 50% values of the peak on the wave front and on the falling portion of the pulse. Propagation distance is defined as the distance from the height at which the pulse is first observed to the height at which it becomes indistinguishable from the background light level (see Figure 2b). Interpulse interval is the time interval between the peaks of two successive pulses. Average propagation speed is the speed estimated over the propagation distance. The error in upward speed measurement is estimated to be less than 20%. The results are shown in Table 1. The 10% to 90% risetimes of the pulses range from 0.3 to 0.8 μs with a mean value of 0.5 μs. The half-peak widths of the pulses range from 0.9 to 1.9 μs with a mean value of 1.3 μs. The pulses are discernible over distances ranging from several tens of meters to more than 200 m. The interpulse intervals range from 1.7 to 7.2 μs with a mean value of 4.6 μs, which is typical for a dart-stepped leader near ground [e.g., *Orville and Idone*, 1982; *Uman*, 1987]. The time interval between the last pronounced pulse, pulse 12, and the return stroke is 2.5 μs. The upward speed of the dart-stepped leader pulses ranges from 1.9×10^7 to 1.0×10^8 m/s with a mean value of 6.7×10^7 m/s.

All optical pulses are observed to suffer appreciable degradation, i.e., an increase in risetime and a decrease in magnitude, when propagating upward. As evident in Figure 6, the pulses usually have well-defined shapes with a relatively fast rise to peak at the height where they are first detected, presumably at or near the height of the leader step formation. The pulses transform into ramp-like waveforms after propagating several tens of meters. Each pulse is a manifestation of a transient increase in channel luminosity and, by inference, in channel current. To perform a detailed study of pulse peak attenuation characteristics, pulses 5, 10, 11, and 12 were selected for analysis because their waveforms allow an adequate measurement of pulse peaks at least over five height levels (except for pulse 5 which appears at three height levels, S9, S10, and S11, the latter one being not shown in Figure 6). The measured light pulse peak as a function of propagation distance for each of the four pulses is plotted in Figure 7. All four pulses exhibit significant attenuation with distance. Specifically, as seen in Figure 7, over the first 50 m the pulse peaks decreased to about 10% of their original values.

4. Discussion and Concluding Remarks

Dart-leader speed variation between the cloud base and ground in natural lightning has been previously studied using high-speed photography. *Schonland et al.* [1935] reported that dart leaders have an essentially constant luminosity propagation speed, with some leaders slowing down as ground is approached. In none of the cases observed by *Schonland et al.* [1935] did the speed of propagation increase near ground. *Orville and Idone* [1982] reported that several dart leaders they observed exhibited a decrease in propagation speed, while four

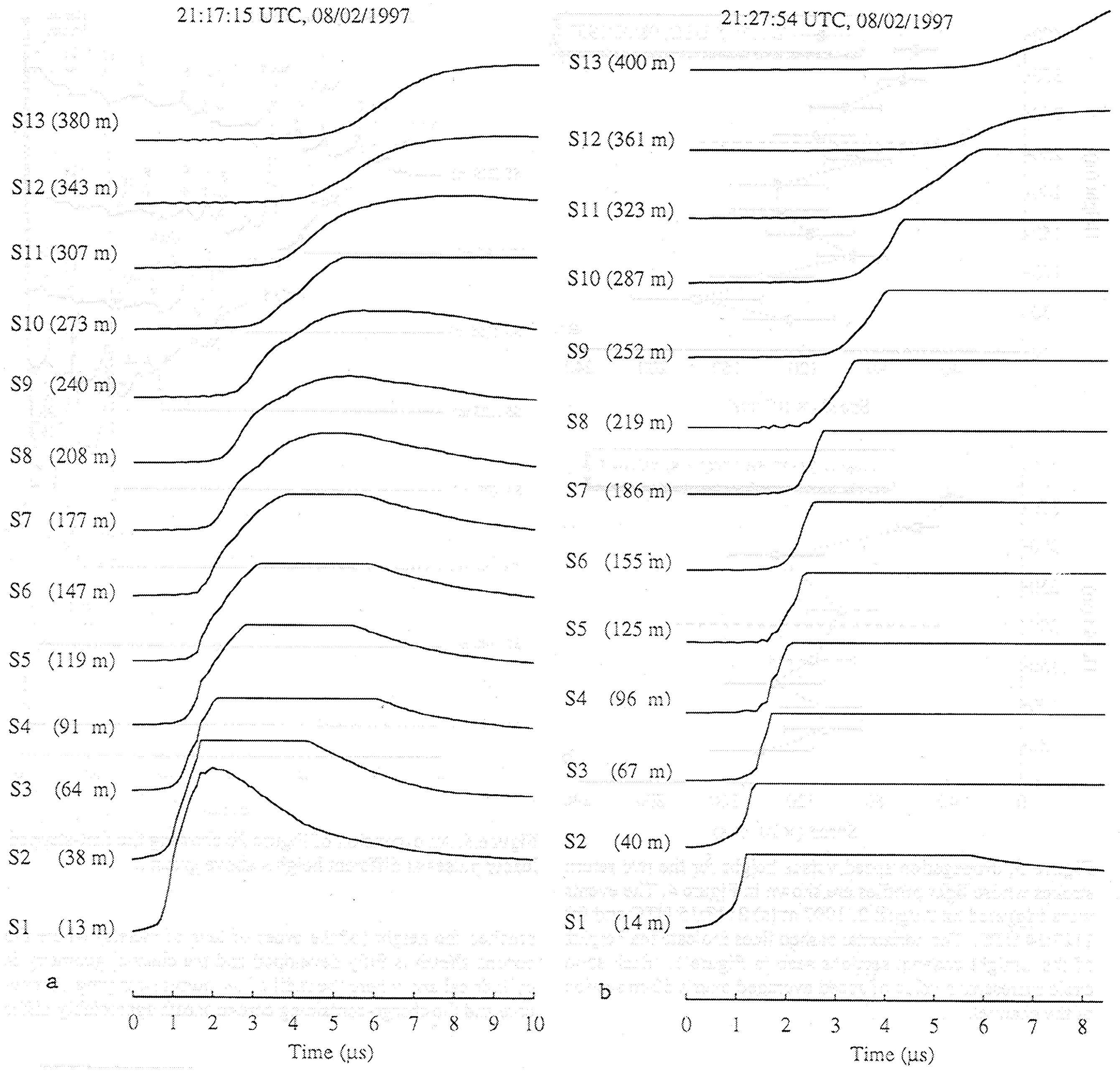

Figure 4. Return-stroke light versus time waveforms at different heights above ground for events triggered on August 2, 1997, at (a) 2117:15 UTC and (b) 2127:54 UTC. The flat portions of the waveforms are due to the saturation of the automatic lightning progressing feature observation system (ALPS).

dart leaders out of a sample of 16 in two separate flashes showed the opposite tendency when propagating downward over a distance of about 1 km. This paper reports detailed dart-leader speed variation over the lowest few hundreds of meters of the channel with a tens of meters spatial resolution. Both leaders observed show an increase in speed when approaching ground, the rate of increase being highest in the lowest several tens of meters of the channel.

Return-stroke speed variation with height has previously been reported by *Schonland et al.* [1935] and *Idone and Orville* [1982]. Their results show that return-stroke speed tends to decrease with increasing height. The spatial resolution of these measurements was of the order of hundreds of meters. *Nagano et al.* [1987] reported a speed profile over a height of 180 m for a positive return stroke. The positive return-stroke speed decreased from a value of 2×10^8 to 0.3×10^8 m/s after propagating over a distance of only 180 m. *Mach and Rust* [1989] found that the return-stroke speed is statistically larger over channel segments of about 330 m starting near the ground (short-segment speeds) than over channel segments of about 900 m starting near ground (long-segment speeds) for triggered, natural first, and natural subsequent return strokes. The present paper is the first report on the speed profile for a negative subsequent return stroke over the lowest some hundreds of

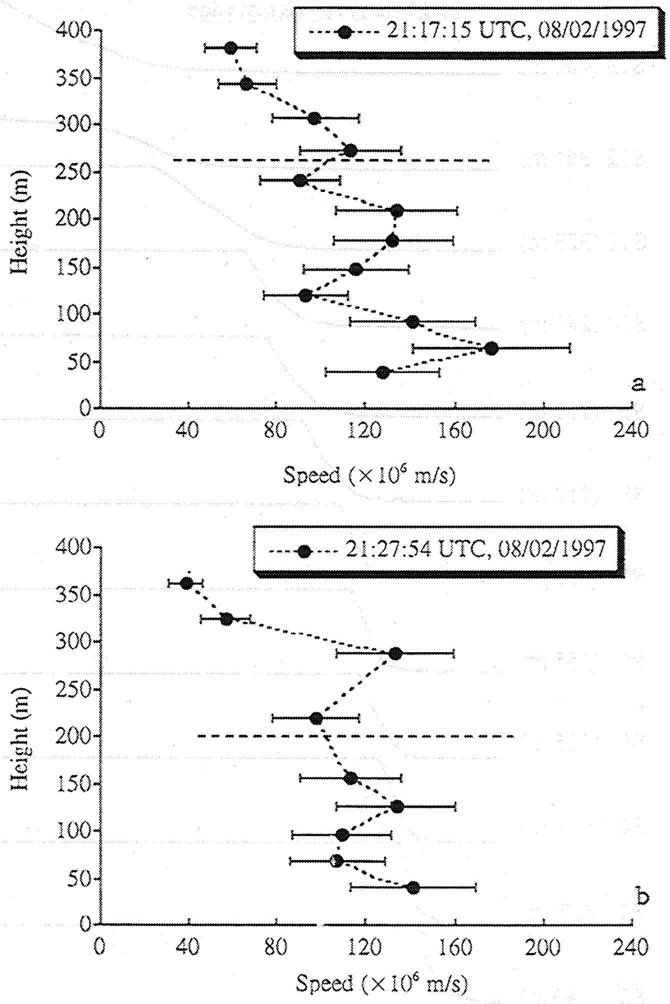

Figure 5. Propagation speed versus height for the two return strokes whose light profiles are shown in Figure 4. The events were triggered on August 2, 1997 at (a) 2117:15 UTC and (b) 2127:54 UTC. The horizontal dashed lines indicate the heights of the straight channel sections seen in Figure 1. Each solid circle represents a value of speed averaged over a 60-m section of the channel.

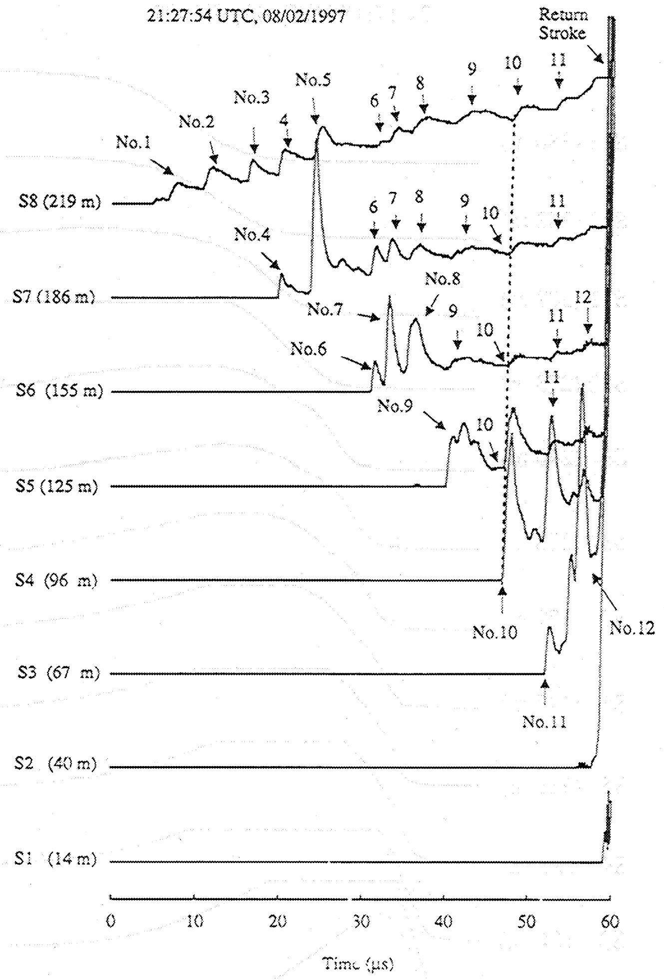

Figure 6. An expansion of Figure 2b showing the dart-stepped leader pulses at different heights above ground.

meters of the channel with a tens of meters spatial resolution. Both return strokes studied here exhibit a speed decrease as they move upward, which is consistent with the results reported previously. Further, we note that the speed variations shown in Figure 5 over the bottom straight channel section (below the dashed lines in Figure 5) appear smaller (speed is more or less constant) compared to the variations over higher channel sections (above the dashed lines). It is possible that the greater speed decrease in the higher channel sections may be related to higher channel tortuosity as seen in Figure 1, which could cause an underestimation of the actual speed.

Mach and Rust [1989] suggest that return-stroke speed for natural strokes may be very close to *c*, the speed of light, within 100 m of ground. *Baum* [1990], using a conical charge distribution model for the bottom part of the channel, predicted an initial return-stroke speed of nearly c, because both the longitudinal channel current and channel charge near ground are confined in a volume of approximately the same radial dimension [see also *Rakov and Uman*, 1998]. The speed is predicted by Baum to decrease when the return-stroke front reaches the height (of the order of tens of meters) where the corona sheath is fully developed and the channel geometry is cylindrical and where the radii of the current-carrying channel core and the charge-containing corona sheath appreciably differ

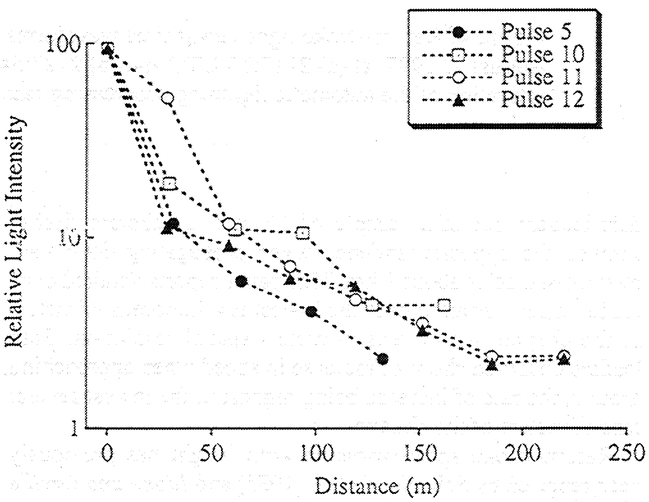

Figure 7. Variation in luminosity pulse peak with the distance traveled by the pulse for four selected pulses out of 12 identified in Figure 6.

Table 1. Characteristics of Luminosity Pulses Produced by Dart-Stepped Leader

	Pulse Number											
	1	2	3	4	5	6	7	8	9	10	11	12
Risetime, µs	0.6	0.8	0.4	0.3	0.3	0.4	0.4	0.7		0.7	0.5	0.4
Half-peak width, µs		1.9	1.7	1.0	1.0	0.9	1.0	1.9		1.4	1.6	0.9
Propagation distance, m	>66	>66		98	>168	94	127	127	149	256	247	260
Interpulse interval, µs		5.9	4.0	3.9	4.3	7.2	1.7	3.8	5.8	5.7	4.7	3.6
Average speed, × 10^7 m/s	1.9	3.5		6.7	5.8	8.4	7.6	6.5	7.4	7.2	8.4	10.3

from each other. Experimental data presented here do not support such an assertion. The return strokes reported here exhibit speeds of 1.3×10^8 and 1.5×10^8 m/s within 60 m or so above ground. Nevertheless, in a previous paper [*Wang et al.*, 1999a], we reported one case in which the return stroke speed appeared to be close to *c* near ground.

Finally, we discuss the characteristics of the dart-stepped leader pulses. The mean 10-90% risetime and the half-peak width of the individual luminosity pulses associated with steps of the dart-stepped leader are 0.5 and 1.3 μs, respectively. Both values are similar to their counterparts obtained by *Krider et al.* [1977] for electric field pulses produced by individual steps of dart-stepped leaders. The mean interpulse interval found in our study is 4.6 μs, which is also quite similar to the 6 to 8 μs reported by *Krider et al.* [1977] for dart-stepped leader electric field pulses. The optical step pulses apparently originate from the newly formed leader step and propagate upward over a distance from several tens of meters to more than 200 m, where they become indistinguishable from the background light level, with a propagation speed ranging from 1.9×10^7 to 1.0×10^8 m/s. *Rakov et al.* [1998] estimated that the formation of each step in one dart-stepped leader in triggered lightning was associated with a charge of a few millicoulombs and a current of a few kiloamperes. The step formation process apparently involves a channel section whose length can be a fraction of the 30-m height resolution in this study. *Idone* [1992] reported on downward propagating luminosity pulses in an upward positive leader in triggered lightning.

The last seven pronounced light pulses produced by the dart-stepped leader have more or less similar upward speeds, near 8×10^7 m/s as seen in Table 1, which is very close to the speed, 8.3×10^7 m/s, of the following return stroke averaged over the lowest 400 m or so of the channel. Note, however, that the luminosity of step pulses is at least 1 order of magnitude lower than that of the following return strokes. This observation is in support of the view [*Rakov*, 1998] that the propagation speed of a pulse traveling along the leader-conditioned channel is primarily determined by the channel characteristics, as opposed to being determined by the pulse magnitude.

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