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High-speed video observations of a lightning stepped leader

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[1] High-speed video images of eight branches of a lightning stepped leader recorded at a frame rate of 300 kiloframes per second (kfps) (3.33 μs exposure) are analyzed, representing the fastest published frame rate measurements of stepped leader stepping by about 1 order of magnitude and the first observations of space stems/leaders associated with stepped leaders. Sixteen occurrences of space stems/leaders were imaged in 14 different frames at various distances in front of the descending leader tip. A total of 225 frames (about 0.75 ms) involving 82 steps of the downward moving, negatively charged stepped leader were captured, followed by 45 frames of leader channel illumination by the return stroke after the ground attachment of the primary leader channel. The stepped leader exhibited characteristics similar to those observed in both dart-stepped leaders in triggered lightning and in long laboratory sparks. In most cases, the space stem/leader in one frame connects to the leader tip above in the subsequent frame, extending the leader channel. Most connections are associated with significant isolated brightening of the space stem/leader and the connection region, followed by frames of upward propagating reillumination of the existing leader channel. Assuming the leader to be 1 km distant, we measure the 16 space stems/leaders to be on average 3.9 m in length and separated from the previous leader channel tip by an average of 2.1 m. For the 82 steps, interstep intervals are on average 16.4 μs and step lengths are on average 5.2 m.

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1. Introduction

[2] Properties of stepped leaders preceding negative natural lightning first strokes have been studied optically via streak photography [e.g., *Schonland et al.*, 1935; *Berger*, 1967; *Orville and Idone*, 1982], through the use of photodiode array photographic systems [e.g., *Chen et al.*, 1999; *Krider*, 1974; *Lu et al.*, 2008], and through electric field measurements [e.g., *Kitigawa*, 1957; *Krider and Radda*, 1975; *Krider et al.*, 1977; *Thomson*, 1980; *Beasley et al.*, 1982; *Cooray and Lundquist*, 1985]. Using a Boys continuous moving film camera with time resolution of approximately 600 ns, *Schonland et al.* [1935] measured individual step lengths from 10 to 200 m, interstep intervals ranging from 40 to 100 μs, and average 2D stepped leader speeds of 3.8 × 10^5 m/s. *Berger* [1967] used a similar streak camera to photograph four downward negative stepped leaders to the lightning research towers atop Mount San Salvatore. They also photographed 14 negative stepped leaders that terminated on ground. The step lengths for negative stepped leaders to the towers were 8 to 10 m with interstep intervals from 40 to 52 μs, and the step lengths for negative stepped leaders to ground were 3 to 17 m with interstep intervals from 29 to 47 μs. Stepped leader speeds ranged from 0.9 to 4.4 × 10^5 m/s. *Orville and Idone* [1982] imaged three stepped leaders using a streak camera, but only the overall propagation speeds for the three leaders could be determined due to the weak optical intensity of the steps. Their measured leader speeds ranged from 5.9 to 15 × 10^5 m/s. *Chen et al.* [1999] recorded two stepped leaders using the Automatic Lightning Progressing Feature Observation System (ALPS) photodiode array imaging system in both Australia and China. For the event in Australia (time resolution of 500 ns), individual step lengths were measured between 7.9 and 20 m, interstep intervals were from 5 to 50 μs, and leader speeds were from 4.9 to 11 × 10^5 m/s. For the event in China (time resolution of 100 ns), step lengths were reported to be 8.5 m, interstep intervals were from 18 to 21 μs, and leader speeds ranged from 4.9 to 5.8 × 10^5 m/s. Using a photoelectric detector in Arizona, *Krider* [1974] measured interstep intervals from 17 to 32 μs for stepped leader pulses within 70 μs of the return stroke. *Lu et al.* [2008] also used the ALPS optical imaging system to record a downward branched stepped leader in Florida at an estimated distance of about 1.3 km. They measured 60 values for interpulse interval for the main channel ranging from 0.2 to 15.7 μs with geometric mean of 3.3 μs and an average 2D leader propagation speed of 1.5 × 10^6 m/s. Through measurements of the electric field produced by descending negative stepped leaders obtained within a few hundred microseconds of the return stroke, interstep intervals have been estimated to be from 5 to 25 μs [e.g., *Kitigawa*, 1957; *Krider and Radda*, 1975; *Krider et al.*, 1977; *Thomson*, 1980; *Beasley et al.*, 1982; *Cooray and Lundquist*,

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Table 1. Previous Optically Obtained Stepped Leader Statistics

	Interstep Interval (μs)	Step Length (m)	Leader Speed ($\times 10^5$ m/s)
Schonland et al. [1935]	10–200	40–100	3.8
Schonland [1956]	37–124	10–200	0.8–8
Berger [1967]	29–47	3–17	0.9–4.4
Orville and Idone [1982]	-	-	5.9–15
Chen et al. [1999] (Australia)	5–50	7.9–20	4.9–11
Chen et al. [1999] (China)	18–21	8.5	4.9–5.8
Krider [1974]	17–32	-	-
Lu et al. [2008]	0.2–15.7	-	15

1985]. Summary statistics for interstep interval, step length, and stepped leader propagation speed from previous optical studies of stepped leaders are given in Table 1.

[3] While the overall characteristics of negative stepped leaders have been well studied, as noted above, the actual formation process of individual leader steps remains poorly documented and poorly understood. From the photographic and photoelectric work of *Schonland et al.* [1935] and *Orville and Idone* [1982], the step formation appears to occur within about a microsecond, and is unresolved. The formation mechanism of natural negative leader steps has however been inferred from meter-length laboratory spark experiments, although the time and size scales of the two phenomena differ. Long laboratory spark development has been described by *Gorin et al.* [1976], *Bazelyan and Raizer* [1998], *Ortega et al.* [1994], *Reess et al.* [1995], *Gallimberti et al.* [2002], and *Les Renardieres Group* [1978]. Long laboratory spark discharges are initiated by applying megavolts of potential difference between electrodes separated by up to a few meters. Typically, the voltage magnitude across the gap and the rate of voltage rise are adjusted to control the discharge properties. The voltage across the gap and current through the gap are measured and the spark gap is often imaged using image converter cameras in either frame or streak mode. A general sequential description of the negative leader step formation process in long laboratory sparks follows: (1) when the negative voltage impulse is applied to the high-voltage electrode, a burst of branched filamentary corona streamers moves into the gap, heating the air in the immediate proximity to the electrode and establishing the initial leader channel at the electrode, (2) a luminous, apparently isolated space stem forms ahead of the primary negative leader tip with positive streamers propagating back from it toward the negative high-voltage electrode (and initial leader channel) and negative streamers propagating downward from the space stem into the gap, (3) a new section of leader channel is formed when a sufficient number of positive backward propagating streamers reach the negative primary leader channel, then instantly transferring the potential of the high-voltage electrode to the end of the secondary channel established by the space stem, and (4) a burst of negative streamers is emitted from the end of the secondary channel, initiating a current pulse that propagates up the existing channel segment toward the high-voltage electrode, illuminating the full channel. A new space stem forms and the sequence noted above repeats during the formation of each new step. A drawing of the process, modified from *Gorin et al.* [1976], is given by *Biagi et al.* [2010].

[4] While lightning stepped leaders should share some characteristics with long laboratory spark leaders, the larger available gap, different charge source, and higher potential voltage at the tip of a lightning leader likely generates larger leader step currents with higher charge densities and greater propagation speeds [e.g., *Rakov and Uman*, 2003]. The fact that the type of leader channel development shown in laboratory sparks also occurs in lightning was first shown by *Biagi et al.* [2009] who obtained an image of a 2 m long space stem located roughly 4 m below the tip of a dart-stepped leader that preceded the eighth return stroke of a triggered-lightning discharge. The space stem was photographed using a Photron SA1.1 high-speed camera operated at a frame rate of 50 kiloframes per second (kfps), or 20 μs per frame. *Biagi et al.* [2010] show additional instances of space stems and/or space leaders in seven high-speed video frames of a dart-stepped leader that preceded the fifth return stroke of a triggered-lightning discharge. The frames were recorded with the same camera, but at a frame rate of 240 kfps, or 4.17 μs per frame. In each case, the luminous segments were 1 to 4 m in length and separated from (and were below) the primary leader channel by 1 to 10 m. In three frames, there were two clearly separated segments of luminosity vertically below the primary leader channel. In some instances, the luminous intensity of the separated channel segments was comparable to that of the primary leader channel, and in all cases, the luminous intensity of the separated channel segments was greater than that of the surrounding corona streamers.

[5] In this paper we analyze the shortest time exposure (3.33 μs) video observations to date of a natural lightning stepped leader and present accompanying statistics for measured interstep interval, step length, and 2D leader propagation speed. We present the first observations of space stems/leaders associated with stepped leaders. We provide a schematic view of the formation of a natural negative leader step from examination of 82 individual steps imaged during this event. We compare our observations to those obtained in association with dart-stepped leaders in triggered-lightning discharges. Finally, we confirm the observations of *Wang et al.* [1999] and the suggestion of *Chen et al.* [1999] that following the progression of the leader channel due to a new step, a luminosity wave propagates from the leader tip back up the existing channel.

2. Experiment

[6] The high-speed video images acquired of the negative stepped leader presented here were recorded at the International Center for Lightning Research and Testing (ICLRT) located on the Camp Blanding Army National Guard base in north central Florida. The flash occurred at 19:38:29.853946 (UT) on June 18, 2010. The National Lightning Detection Net-

Table 2. Measured Stepped Leader Statistics Assuming a Range of 1 km[a]

Branches[b]	Number of Steps	Average Interstep Interval (μs)	Average Step Length (m)	Average Leader Speed ($\times 10^5$ m/s)
P-1	28	13.7	4.8 (+4.8/−1.4)	4.4 (+4.4/−1.3)
P-2	21	14.9	5.2 (+5.2/−1.6)	4.6 (+4.6/−1.4)
P-3	15	15.1	5.1 (+5.1/−1.5)	4.5 (+4.5/−1.4)
S-1	5	21.3	6.0 (+6.0/−1.8)	2.7 (+2.6/−0.8)
S-2	6	23.9	7.1 (+7.1/−2.1)	NA
S-3	2	40.0	6.0 (+6.0/−1.8)	NA
S-4	3	12.2	5.8 (+5.8/−1.7)	6.2 (+6.2/−1.9)
S-5	2	26.7	5.4 (+5.4/−1.6)	NA

[a]Given in parentheses are range corrections for a maximum range of 2 km and a minimum range of 700 m. NA means not available.
[b]"P-X" represents a primary branch and "S-X" represents a secondary branch.

work's (NLDN) most probable ground strike location of the 10.6 kA negative return stroke associated with the stepped leader we imaged was about 1 km to the northwest of the ICLRT. Our high-definition video records indicate that the stepped leader branches we imaged with the high-speed video traversed a path over and slightly to the southeast of the ICLRT. The stepped leader entered the field of view of our Photron SA1.1 high-speed camera that was configured with a 20 mm Nikon lens set to an aperture of f/4 for imaging rocket-triggered lightning discharges at a distance of 300 m. The Photron SA1.1 recorded the stepped leader at a frame rate of 300 kfps, or 3.33 μs per frame. The resolution was 320 × 32 pixels (vertical × horizontal) with 12 bit gray scale amplitude resolution.

[7] Our best estimate of the distance from the camera to the stepped leader is 1 km, providing a spatial resolution of 1 m per pixel, with a possible range from as far away as 2 km to as close as 700 m. We base our best estimate and distance limits on the following: (1) comparison of the luminous features of streamers and space stems/leaders observed in the present high-speed video with video recorded at the known distance of 430 m of dart-stepped leaders in triggered lightning with the same camera at essentially the same frame rate [e.g., *Biagi et al.*, 2010], (2) the fact that the stepped leader speed computed from our data at a distance between 700 m and 2 km (see section 4 and Table 2) is consistent with speeds found in the literature, (3) knowledge of the ground strike point of the lightning in question from the NLDN, and (4) the spatially smaller and less luminous phenomena evident in our video would have been difficult to resolve at distances too much beyond 1 km in the presence of the light precipitation that was falling at the end of the storm when the video was acquired.

[8] All stepped leader size and velocity measurements scale linearly with the assumed distance to the stepped leader. For all spatial measurements presented, the stepped leader channel is assumed to propagate only within the plane perpendicular to the field of view of the camera. Since each pixel represents 1 m at a range of 1 km, the approximate error in all length measurements is 1 m at 1 km. In addition, all spatial measurements are straight line lengths and are presented to tenths of a meter because of propagation along directions other than the horizontal or vertical of the pixel array.

3. Results

[9] A total of 225 frames (about 750 μs) of downward stepped leader were recorded. After the ground attachment of the primary leader channel out of the field of view of the camera (just another branch until it connected to ground), the branches being observed were illuminated by the return stroke. There were 45 frames (about 150 μs) captured during the return stroke illumination and subsequent decay. The stepped leader channel entered the field of the view of the camera at an altitude of 358 m. The leader propagated downward within the field of view, splitting into two distinct branches about 417 μs later at an altitude of 268 m. The two stepped leader branches continued to propagate downward and to the left in the frame, ultimately exiting the horizontal field of view of the camera at altitudes of 217 m and 202 m, respectively, and 227 μs and 287 μs, respectively, after branching from the original leader channel. In Figure 1, we show a full-frame image of the flash obtained by time integrating the luminosity from four consecutive frames during the return stroke illumination of the leader channel. We have labeled all of the stepped leader branches with the notation "P-X" indicating a primary branch and "S-X" indicating a secondary branch, where "X" is an integer. Differentiation between primary and secondary branches was to some degree subjective. However, primary branches were characterized by more extensive propagation within the field of view (and hence a greater number of measured leader steps) while secondary branches were channels with smaller extent originating from the three primary leader channels. We have analyzed the three primary branches and five secondary branches. In Table 2, we present measured statistics for each individual branch including the number of individual leader steps, the average interstep interval, the average step length, and the average 2D leader propagation speed, all assuming a range of 1km. Located below each value in Table 2 for average step length and average 2D leader speed, we have provided uncertainties in the presented statistics in the form "(+A/−B)," where "A" represents the range correction in measurement for a maximum range of 2 km and "B" represents the correction for a minimum range of 700 m. For the three primary branches, there were a total of 64 individual leader steps analyzed. The average interstep intervals for the three primary branches ranged from 13.7 μs to 15.1 μs, the average step lengths ranged from 4.8 m to 5.2 m, and the average 2D leader speeds ranged from 4.4 to 4.6 × 10^5 m/s. For the five secondary branches, there were a total of 18 individual leader steps analyzed. The average interstep intervals for the five secondary branches ranged from 12.2 μs to 40.0 μs, the average step lengths ranged from 5.4 m to 7.1 m, and the average 2D leader speeds ranged from 2.7 to 6.2 × 10^5 m/s. Average 2D leader speeds could only be calculated for two of the five secondary branches (S-1 and S-4). Leader speeds were calculated by dividing the distance

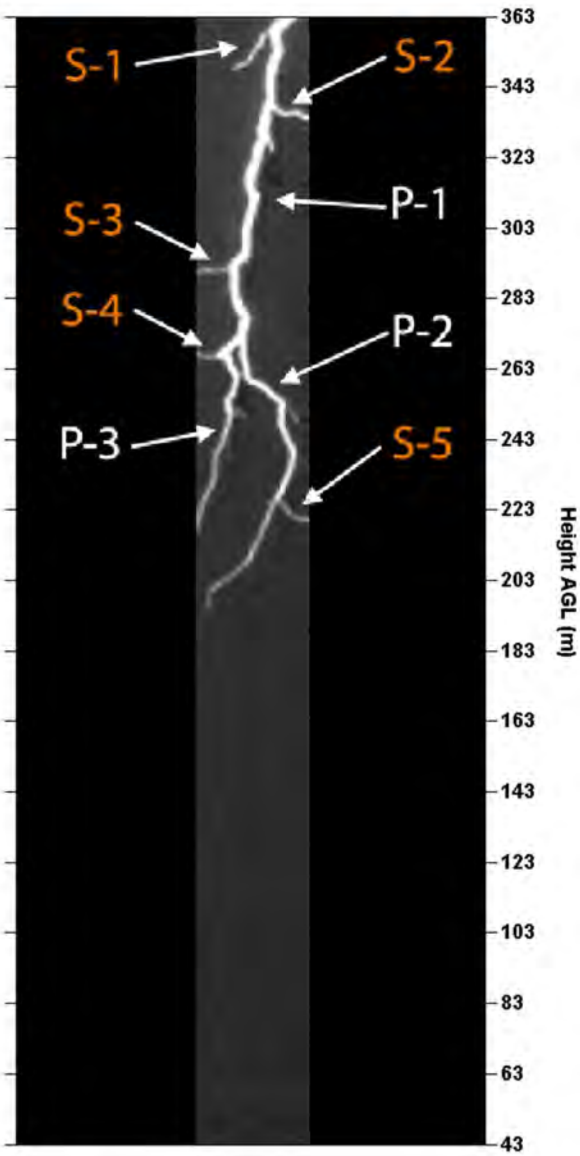

Figure 1. Full frame time-integrated image of flash and identification of all branching structure.

between the ending points in space of two consecutive leader steps in a respective branch by the number of frame integration times of 3.33 μs apiece between the steps. The speeds obtained between each set of two consecutive steps were summed and divided by the total number of steps in the respective branch. It appears that there is not much difference between the step lengths and average leader speeds in the primary and secondary channels, but that the interstep times in the secondary channels are longer.

[10] Before presenting video frames of the stepping mechanism, we provide an artist sketch of our view of the leader step formation process in Figure 2. This sequential process, decomposed into five stages, was derived from analyzing the high-speed video images with frame integrations ending randomly at different times within the leader step formation process. Here, we have drawn a 50 m segment of leader channel. In the first stage, we show a negative stepped leader channel having decayed in luminosity following a prior leader step. In the second stage, we show the formation of a space stem/leader with vertical extent of several meters located several meters below the tip of the leader channel above. It is likely that the space stem/leader actually forms within the negative streamer zone of the leader channel above as illustrated by *Biagi et al.* [2010]. However, due to the increased distance between the channel and camera, estimated at roughly twice that of *Biagi et al.* [2010], and the ambient atmospheric conditions, we had insufficient spatial and luminosity resolution in our high-speed video data to well spatially resolve the streamer zones, though we infer they exist in each case by the observed low-level "glow" surrounding both the leader tip and the space stem/leader. In the third stage, the space stem/leader begins to reconnect to the leader channel above with low-level luminosity, and in the fourth stage, the space stem/leader fully connects to the above leader channel, brightly illuminating the space stem/leader and the connection region. Finally, in the fifth stage, after the new bright segment of stepped leader channel has been formed, a luminosity wave propagates back up the existing channel for some tens of meters, illuminating the channel above with intensity comparable to that of the leader tip. We believe all five stages shown in Figure 2 likely occur within about a microsecond.

[11] We now present the first examples of space stems/leaders shown in association with natural stepped leader steps. In both examples, shown in Figure 3 and Figure 4, we have plotted five consecutive 3.3 μs frames (about 16.7 μs total) which we have inverted and contrast enhanced to show better the more faint luminous characteristics of the step formation process. Time progresses from left to right and the frames span 70 m in altitude. Figure 3 and Figure 4 show consecutive leader steps. The final frame shown in Figure 3 is the first frame shown in Figure 4. In both examples the top of the frames are located about 16 m below the split of primary branch P-1 into primary branches P-2 and P-3 (as shown in Figure 1).

[12] The first example of the leader step formation process is shown in Figure 3. A new leader step is forming in frame A in branch P-2, brightly illuminating the leader tip. An upward propagating luminosity wave in branch P-3 moves out of the frame from a new leader step in the previous frame (not shown). In frame B, the upward propagating luminosity wave from the new leader step in frame A moves up branch P-2 and out of the frame and the luminosity in branch P-2 begins to decay. In frame C, two distinct space stems/leaders are imaged, one below branch P-3 and one to the right of branch P-2, both annotated by arrows. Interestingly, the space stem/leader below branch P-3 is already partially connected to the leader channel above with low-level luminosity, likely a result of the frame integration ending during the third stage of the leader step formation process outlined in Figure 2. The space stem/leader shown to the right of branch P-2 appears to be completely separated from the existing leader channel. In this case, the space stem/leader below branch P-3 is significantly brighter than the leader channel above. However, this could be a result of the existing partial connection. The space stem/leader to the right of branch P-2 is quite faint in comparison to the leader channel which is still decaying in luminosity from the new leader step two frames prior. In frame D (Figure 3), both space stems/leaders fully connect

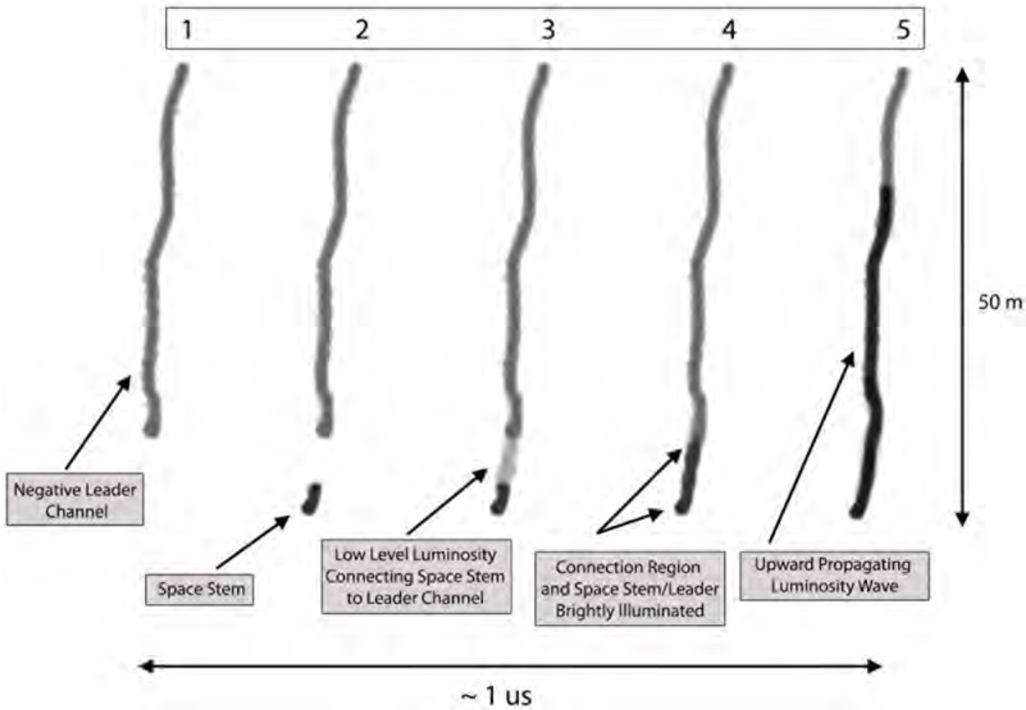

Figure 2. Sketch of the step formation process inferred from the 3.3 μs frame data.

to their respective leader channels, at left forming a new section of branch P-3 and at right forming a new step in branch S-5. Also in frame D, upward propagating luminosity waves have moved up branch P-3 and from branch S-5 into branch P-2. It is interesting to note that the upward propagating luminosity wave originating from the new step in branch S-5 appears to only move into the existing channel section above the junction point of branches S-5 and P-2 and does not appear to influence the new channel section of branch P-2 formed in frame A.

[13] A second example of the leader step formation process in shown in Figure 4. In frame A of Figure 4, three distinct leader channels have already decayed in luminosity from prior leader steps, P-3 on the left, P-2 in the middle, and S-5 on the right. In frame B, all three leader channels decay further in luminosity where P-3 and P-2 are only faintly visible.

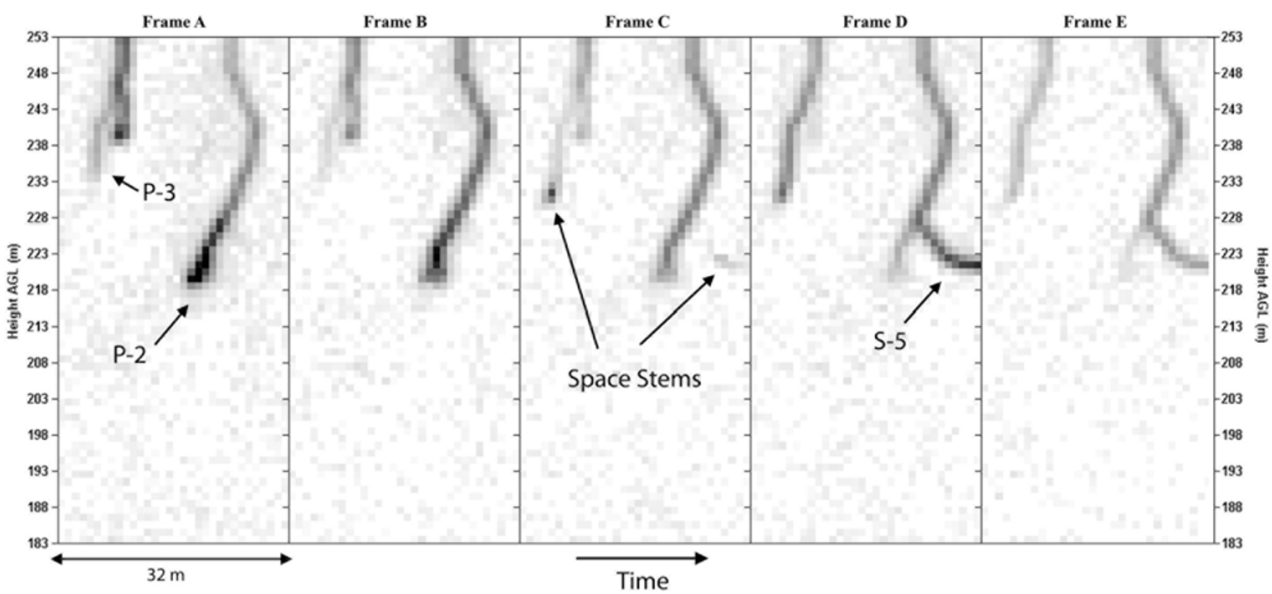

Figure 3. First example of space stem/leaders of a natural negative stepped leader step. Five consecutive 3.33 μs frames are shown.

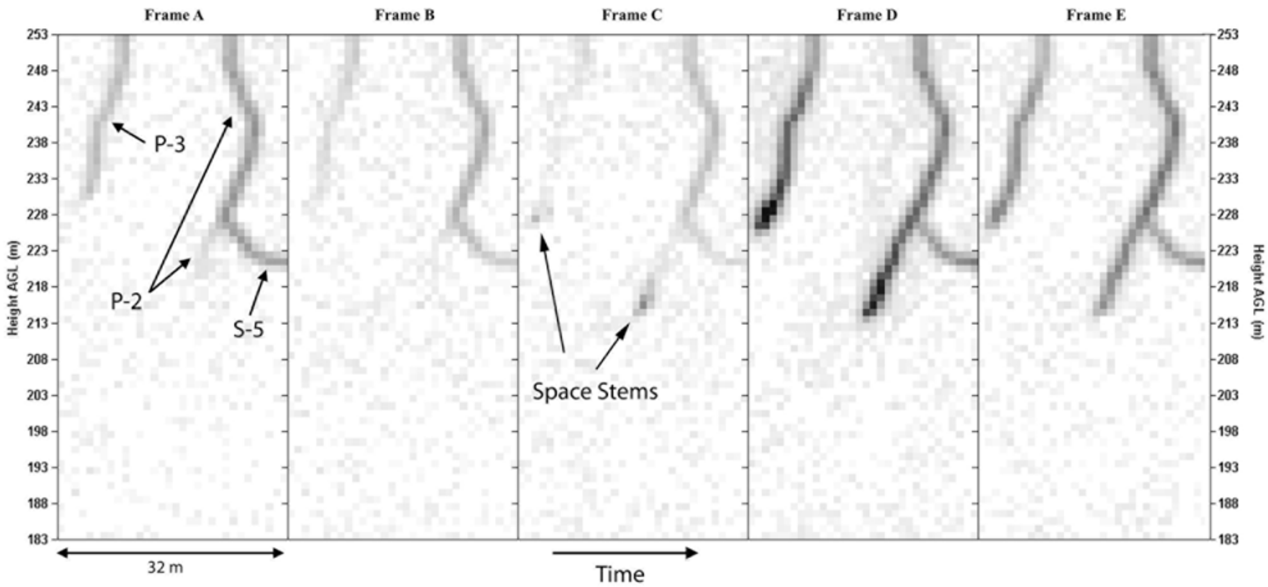

Figure 4. Second example of space stem/leaders of a natural negative stepped leader step. Five consecutive 3.33 μs frames are shown.

In frame C, two distinct space stems/leaders form below leader channels P-3 and P-2 and are annotated with arrows. The luminosity levels of the space stems/leaders are comparable to or somewhat brighter than the leader channels above. In frame D, both leader channels P-3 and P-2 connect with the space stems/leaders formed in frame C, brightly illuminating the connection regions. Also in frame D, the propagation of upward luminosity waves over several tens of meters in both channels P-3 and P-2 is evident. In frame E, the upward propagating luminosity waves move out of the frame and the luminosity of the new steps in channels P-3 and P-2 begin to decay.

[14] We have analyzed a total of 16 instances of space stems/leaders from our high-speed video data. In Table 3, we provide measured statistics for all imaged space stems/leaders including length and separation from the leader channel above assuming a range of 1 km. The separation is measured as the distance between the top of the space stem and the lowest point in space of the prior leader step along the direction of the space stem formation. The average space stem/leader length was 3.9 m and the average separation from the leader channel above was 2.1 m. For all statistics presented in Table 3, we have provided range corrections (shown to the right of each primary value) in the form "(+A/−B)," where "A" represents the range correction in measurement for a maximum range of 2 km and "B" represents the correction for a minimum range of 700 m.

[15] Of the 82 leader steps identified, we successfully measured the lengths of the upward propagating luminosity waves following the step formation in 28 instances. The measurements were restricted by the field of view and dynamic range of the camera and by the relative difference between the background luminosity preceding the formation of each leader step and the luminosity of the upward propagating luminosity wave. Measurements were obtained by subtracting the luminosity one frame prior to a new step from the frame containing the new step and the subsequent three frames. In seven cases, we measured upward propagating luminosity in only one frame, for 20 cases, in two consecutive frames, and for one case, in three consecutive frames. The total lengths of the upward propagating waves ranged from 14 to 85 m with an average value of 43 m. The velocities calculated from these length values ranged from about 4.0×10^6 to 1.3×10^7 m/s with an average value of about 7.5×10^6 m/s. The velocities of the upward propagating waves were calculated by dividing the total length traveled by the elapsed time of either one, two, or three frame integrations

Table 3. Measured Space Stem/Leader Statistics Assuming a Range of 1 km[a]

Space Stem/ Leader Number	Length (m)	Distance From Previous Leader Channel Tip (m)
1	3.0 (+3.0/−0.9)	3.2 (+3.2/−0.9)
2	5.0 (+5.0/−1.5)	1.0 (+1.0/−0.3)
3	3.2 (+3.2/−1.0)	2.2 (+2.2/−0.7)
4	3.0 (+3.0/−0.9)	3.0 (+3.0/−0.9)
5	4.2 (+4.2/−1.2)	0.0[b] (+0.0/−0.0)
6	4.2 (+4.2/−1.2)	2.0 (+2.0/−0.6)
7	3.2 (+3.2/−1.0)	3.2 (+3.2/−0.9)
8	2.4 (+2.4/−0.7)	3.2 (+3.2/−0.9)
9	3.2 (+3.2/−1.0)	3.6 (+3.6/−1.1)
10	3.2 (+3.2/−1.0)	2.2 (+2.2/−0.7)
11	5.0 (+5.0/−1.5)	2.0 (+2.0/−0.6)
12	5.1 (+5.1/−1.5)	1.4 (+1.4/−0.4)
13	5.5 (+5.5/−1.6)	0.0[b] (+0.0/−0.0)
14	4.6 (+4.6/−1.4)	1.4 (+1.4/−0.4)
15	4.6 (+4.6/−1.4)	1.4 (+1.4/−0.4)
16	3.0 (+3.0/−0.9)	3.0 (+3.0/−0.9)
Averages	3.9 (+3.9/−1.2)	2.1 (+2.1/−0.6)
Biagi et al. [2010]	1–4	1–10

[a]Given in parentheses are range corrections for a maximum range of 2 km and a minimum range of 700 m.

[b]The ending point in space of the leader step and the top of the subsequent space stem/leader occurred in the same pixel but after the leader step luminosity became undetectable.

of 3.33 μs apiece. The stated velocity measurements are clearly the minimum possible velocities considering the impossibility of determining what fraction of the 3.33 μs frame integration time imaged the actual motion of the luminosity wave.

4. Discussion

[16] Clearly, the space stem/leader plays an integral role in determining the propagation characteristics of the negative stepped leader. The measured statistics for space stem/leader length and separation from the previous leader channel tip given in Table 3 are in relatively good agreement with those obtained by *Biagi et al.* [2010] for a dart-stepped leader preceding a rocket-triggered lightning return stroke at a range of 430 m. *Biagi et al.* [2010] reported space stem/leader lengths ranging from 1 to 4 m and separations from the above leader channel ranging from 1 to 10 m.

[17] Comparing our measured statistics for the natural stepped leader with previously obtained statistics for interstep interval and step length using continuous moving film (streak) cameras, we find that both our interstep intervals and step lengths are, in general, shorter in duration and length. Our measured statistics for interstep interval and step length are in better agreement with those measured for stepped leaders using photodiode arrays, and also in better agreement with those measured optically and through electric field waveforms for dart-stepped leaders in both natural and triggered lightning discharges [e.g., *Schonland*, 1956; *Krider et al.*, 1977; *Orville and Idone*, 1982; *Idone and Orville*, 1984; *Davis*, 1999]. It is likely that differences in measurement techniques are at least in part responsible for the shorter step lengths we measured in comparison to past studies of negative stepped leaders. From examination of previously obtained streak photographs, we believe that step length could have been overestimated by measuring not only the length of the newly formed section of leader channel, but the superposition of the newly formed section of the leader channel and the luminosity wave traveling back up the existing leader channel after the step formation, the upward propagating luminosity wave often exhibiting luminosity comparable to that of the leader tip for some tens of meters up the existing channel. Finally, our measured stepped leader propagation speeds, assuming a range of 1 km, are in good agreement with those of *Schonland et al.* [1935] and *Schonland* [1956], on the upper boundary of those measured by *Berger* [1967], and on the lower boundary of those measured by *Chen et al.* [1999]. Including our maximum and minimum range corrections as listed in Table 2, the values for stepped leader speed remain within or very close to the statistical ranges calculated from past studies.

[18] The good agreement between our spatial measurements of space stems/leaders compared to those measured in association with dart-stepped leaders in triggered lightning and of our stepped leader propagation speeds in comparison with previous optical studies of stepped leaders suggest that our estimate of 1 km range is reasonable. It should also be noted that prior optical studies of leader propagation utilized such techniques as thunder ranging, cloud base height estimation, and approximations for return stroke speed to estimate the distance between a given leader channel and an optical measurement. The inherent errors in these lightning location techniques likely contribute to the relatively wide range of values for step length and 2D stepped leader propagation speed given in Table 1.

[19] Using the ALPS photodiode system, *Wang et al.* [1999] measured the total lengths of the upward propagating waves following the step formation, in this case the bottom 400 m of a dart-stepped leader preceding a rocket-triggered lightning return stroke, to be from several tens of meters to more than 200 m and the velocities of the upward propagating waves to be from 1.9×10^7 to 1.0×10^8 m/s with an average value of about 6.7×10^7 m/s. The disparity between our measured average velocity (a minimum possible value) of about 10^7 m/s and that of *Wang et al.* [1999] is likely mostly due to our necessary assumption that our observed propagation occurred for the full 3.33 μs frames.

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