2016 24th International Lightning Detection Conference & 6th International Lightning Meteorology Conference
18 - 21 April | San Diego, California, USA

High-speed video observation of bidirectional leader whose negative end contacted ground and produced a return stroke

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***Abstract*—A bidirectional leader, the negative end of which contacted ground, was observed at the Lightning Observatory in Gainesville, Florida, on 2 August 2014. The bidirectional leader developed during the late stage of a cloud discharge and appeared to be initiated in a decayed (not luminous for at least 43 ms) channel of the latter. The leader extended bidirectionally in virgin air for at least 12 ms with both ends branching. After turning toward ground, its negative end exhibited features characteristic of preliminary breakdown and stepped leader of first negative cloud-to-ground strokes, while the positive end most of the time remained almost stationary or showed rapid extensions followed by retractions. The development of positive end involved a very bright process that caused abrupt creation of 1-km long, relatively straight branch, forked at its far end. The bidirectional leader connected, via its positive end, to another considerably longer bidirectional leader (floating channel) to form a larger bidirectional leader, whose negative end attached to the ground and produced a 36-kA return stroke.**

***Index Terms*—Lightning, initiation, bidirectional leader, recoil leader, preliminary breakdown, stepped leader, return stroke, high-speed camera.**

I. INTRODUCTION

The first experimental evidence of bidirectional development of lightning leader was presented by Mazur et al. [1984] [1], who studied the radar echoes of lightning strikes to aircraft. They observed radar echoes of lightning channels extending in opposite directions from the metallic aircraft, with the latter producing the most pronounced echo. Bidirectional leaders have been also well documented in negative altitude rocket-triggered lightning that is initiated by a vertical floating wire polarized in the electric field of thundercloud [e.g., Lalande et al., 1998] [2]. Leaders of opposite polarity developed from the upper and lower wire ends, with the positive (upward) leader starting before the negative (downward) one. In all those observations, the origin of bidirectional leader was a metallic object (aircraft or triggering wire). Rakov et al. [2003] [3] presented evidence of bidirectional leader formed in the absence of metallic object in classical triggered lightning. It occurred when the triggering wire exploded (effectively disconnecting the upward positive leader channel from the ground) and the lower end of the floating upward positive leader channel accumulated negative charge sufficient for launching a downward negative leader. It was observed that such an "electrodeless" bidirectional leader initiated a return-stroke-like process upon attachment of its negative end to ground.

To date, there is only one observation of bidirectional leader in natural lightning found in the literature. It was published by Montanya et al. [2015] [4], who imaged an about 1 km long luminous channel that developed bidirectionally in virgin air until one of its ends attached to a pre-existing, continuously luminous cloud discharge channel. Thus, their bidirectional leader facilitated the formation of a branch of the cloud discharge channel. In their high-speed video record, both ends of the leader appeared to initiate at the same time from a single point. The negative end speed varied from 0.8 $\times 10^5$ to 1.3 $\times 10^5$ m/s, being about twice that of the positive end. The positive end was mostly a single channel, while the negative end was heavily branched. The bidirectional leader was visible in 66 consecutive video frames, with its positive part being brighter. When the negative end had made contact with the cloud discharge channel, only the channel section between the contact point and the initiation point was illuminated. This was interpreted by Montanya et al. [2015] [4] as an indication that the polarity reversal point was stationary during the entire bidirectional leader lifetime (6 ms).

Bidirectional leaders were observed and studied in laboratory discharges when a floating metallic object was placed inside the gap. Bazelyan and Raizer [2000, Figure 4.5] [5] presented streak camera images of bidirectional leaders developing from a 50 cm long metallic rod in the uniform electric field of a 3-m long plane-plane gap. Generally, the positive and negative parts of the bidirectional leader were initiated at different moments and propagated at different speeds. The two parts appeared to be interrelated: any enhancement of brightness at one end was accompanied by an increased brightness of the other end. For example, a flash associated with a negative leader step appeared to cause brightening of the positive leader channel. Mazur et al. [2015] [6] reported observations of bidirectional leaders initiated from an array of

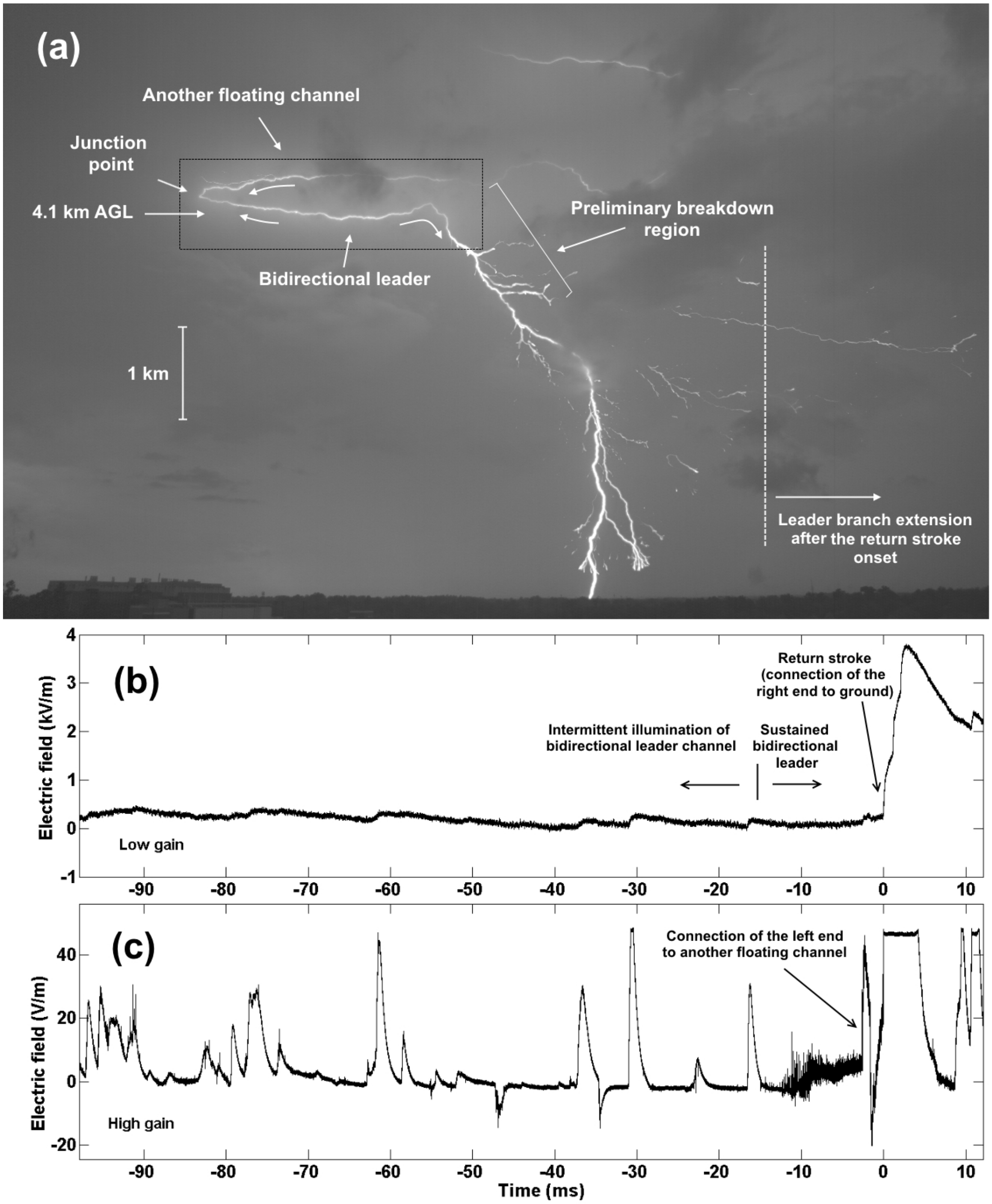

Fig. 1: (a) Composite image of 41 selected frames (from -123 to 9.8 ms) showing the bidirectional leader, another floating channel that connected to the left end of the bidirectional leader, and channel to ground. The high-speed video record started at -178 ms. (b-c) Low-gain and high-gain electric field records (from -98 to 12 ms), respectively. No electric fields were recorded prior to -98 ms. The left end of the bidirectional leader made contact with another floating channel (the junction point is labeled in (a) and the electric field signature of the connection process is seen in (c)) prior to the right end's making contact with ground. Note that some leader branches kept extending to the right after the return stroke onset. Individual-frame and composite images of the rectangular area seen in the upper-left corner of (a) that show important stages of the bidirectional leader development are presented in Figure 2.

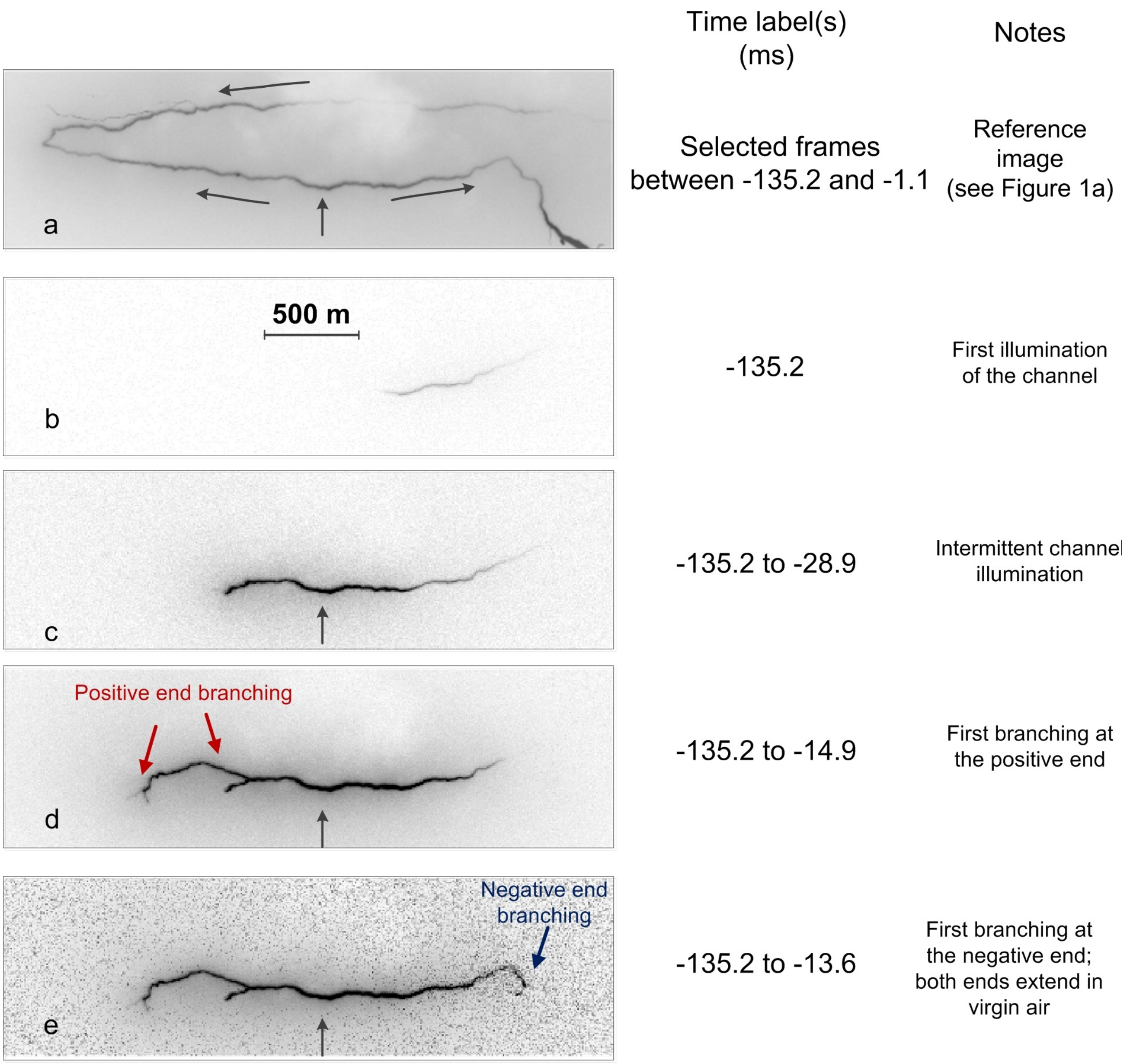

Fig. 2: Important stages of the bidirectional leader development: (a) reference image (same as that shown in the rectangular box in Figure 1a), (b) first illumination of the bidirectional leader channel, (c) intermittent channel illumination, (d) first unambiguous branching in virgin air at the positive end, (e) first branching at the negative end (one branch is not clearly seen in reproduction), (f) negative end clearly turning toward ground, (g) abrupt acceleration of the negative end (outside the image boundary) with a floating channel visible in the upper-left corner, (h) transient event creating a 1-km long positive branch, (i) transient event junction point; floating channels in the upper-left corner, and (j) connection of the positive end to a floating channel in the upper-left corner (the frame immediately following the connection is not included from this composite image due to saturation). The vertical upward arrow near a trough-like feature of the channel can be used as a reference in comparing different images. It does not indicate the leader neutral (polarity reversal) point, which is somewhere to the right from the vertical arrow (see positive end branching in (g)). In (g) through (j) the negative end is outside the image boundary, with both ends being shown in Figures 4 and 5).

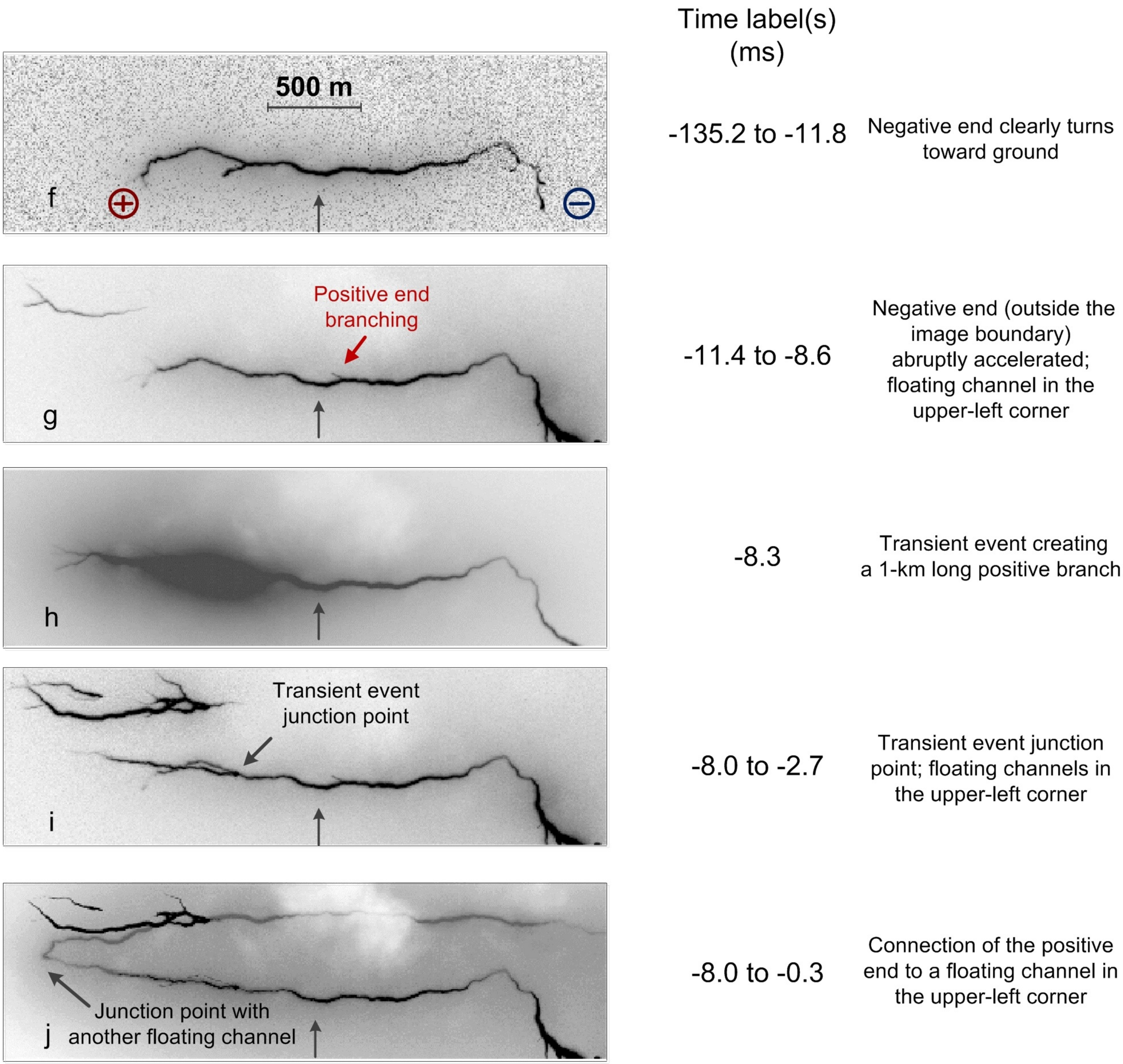

Fig. 2: (Continued)

small metal balls separated by short gaps and placed in the middle of a 0.9-m long gap stressed with a 2.4-MV impulse generator. The array acted as a single conductor, since at the early stage of discharge the short air gaps between the metal balls were bridged by electric arcs.

Kostinskiy et al. [2015] [7], using infrared (2.7-5.5 µm) high-speed camera, studied bidirectional leaders produced by positively-charged clouds of water droplets. The use of infrared imaging allowed them to observe the in-cloud part of the leaders. The positive end of the leader developed downward, toward the grounded plane, while the negative end extended upward, toward and into the cloud. The overall bidirectional leader length was of the order of 1 m.

Bidirectional extension has been observed in some recoil leaders developing in defunct positive leader channels (branches). It was apparently first reported by Mazur et al. [2011] [8] (see also Mazur et al. [2013, Figure 4] [9]). Warner et al. [2012a, Figure 12 and Section 5.2] [10] described in detail the behavior of two recoil leaders that developed along the same upward positive leader branch 13 ms apart. Their

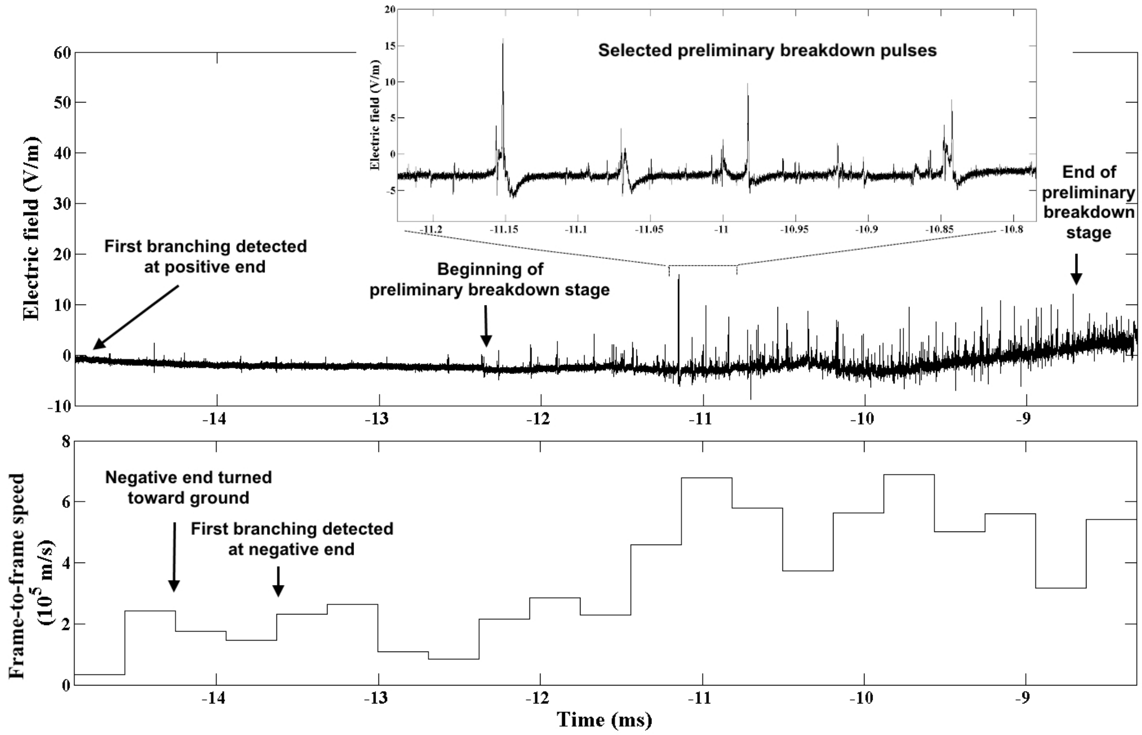

Fig. 3: (Top) high-gain electric field record obtained at LOG and (bottom) frame-to-frame speeds of negative end from -14.9 to -8.3 ms. Speed measurement between -8.0 and -6.4 ms were not possible due to obscuration of negative stepped leader by cloud debris.

negative ends propagated at 2-D speeds ranging from 4.5 $\times 10^6$ to 1.4 $\times 10^7$ m/s with an arithmetic mean of 1.4 $\times 10^7$ m/s and geometric mean of 9.1 $\times 10^6$ m/s. It appears that the negative end of recoil leaders can deviate from the remnants of the previously-created channel. Indeed, Warner et al. [2012b] [11] observed two such cases, in one of which the negative end formed a different connection on the upward positive leader channel and in the other one faded without making connection. Warner et al. [2012b] [11] estimated the 2–D speeds of the negative end of recoil leaders that were "favorable for 2-D speed measurements" (the number of events is not given) to range from 3.82 $\times 10^4$ to 1.89 $\times 10^7$ m/s with a mean of 4.53 $\times 10^6$ m/s. For the positive end (only two events) the minimum, maximum, and average speeds were 7.85 $\times 10^5$, 1.08 $\times 10^7$, and 3.75 $\times 10^6$ m/s, respectively. It appears that the speed of positive part is slightly lower than that of negative part, although the sample size for the positive part is very small. Sometimes recoil leaders exhibit unidirectional extension. For example, Jiang et al. [2014, Figure 3] [12] observed unidirectional extension for one recoil leader propagating along a decayed positive leader branch toward the main channel of an upward lightning flash. Also, Mazur et al. [2013] [9] stated that in the majority of their recoil leaders only the propagation of the negative end was "highly visible".

Negative stepped leaders of long sparks and lightning involve space leaders that also extend bidirectionally [Gorin et al., 1976; Gamerota et al., 2014] [13, 14]. In the latter study, the positive end speed ranged from 6 to 12 $\times 10^5$ m/s, with an average of 8.4 $\times 10^5$ m/s. For the negative end, the range was 4 to 6 $\times 10^5$ m/s and the mean was 4.8 $\times 10^5$ m/s, lower than of that of its positive counterpart. Space leaders facilitate connection of the newly formed step to the existing leader channel.

In this paper, we present a kilometer-scale bidirectional leader that was observed at the Lightning Observatory in Gainesville (LOG), Florida. This observation is unique in that one end of the bidirectional leader contacted ground and produced a return stroke. The leader was initiated as a recoil-leader-type process along the remnants of a channel possibly created by a preceding cloud flash, and then extended bidirectionally in virgin air for at least 12 ms. Each end of the bidirectional leader exhibited more than 10 branches during the leader lifetime (133 ms). Its negative end attached to the ground and produced a cloud-to-ground return stroke, whose peak current was reported by the National Lightning Detection Network (NLDN) to be 36 kA.

II. Instrumentation

The LOG is located on the roof of a five-story building on the campus of the University of Florida. The instrumentation

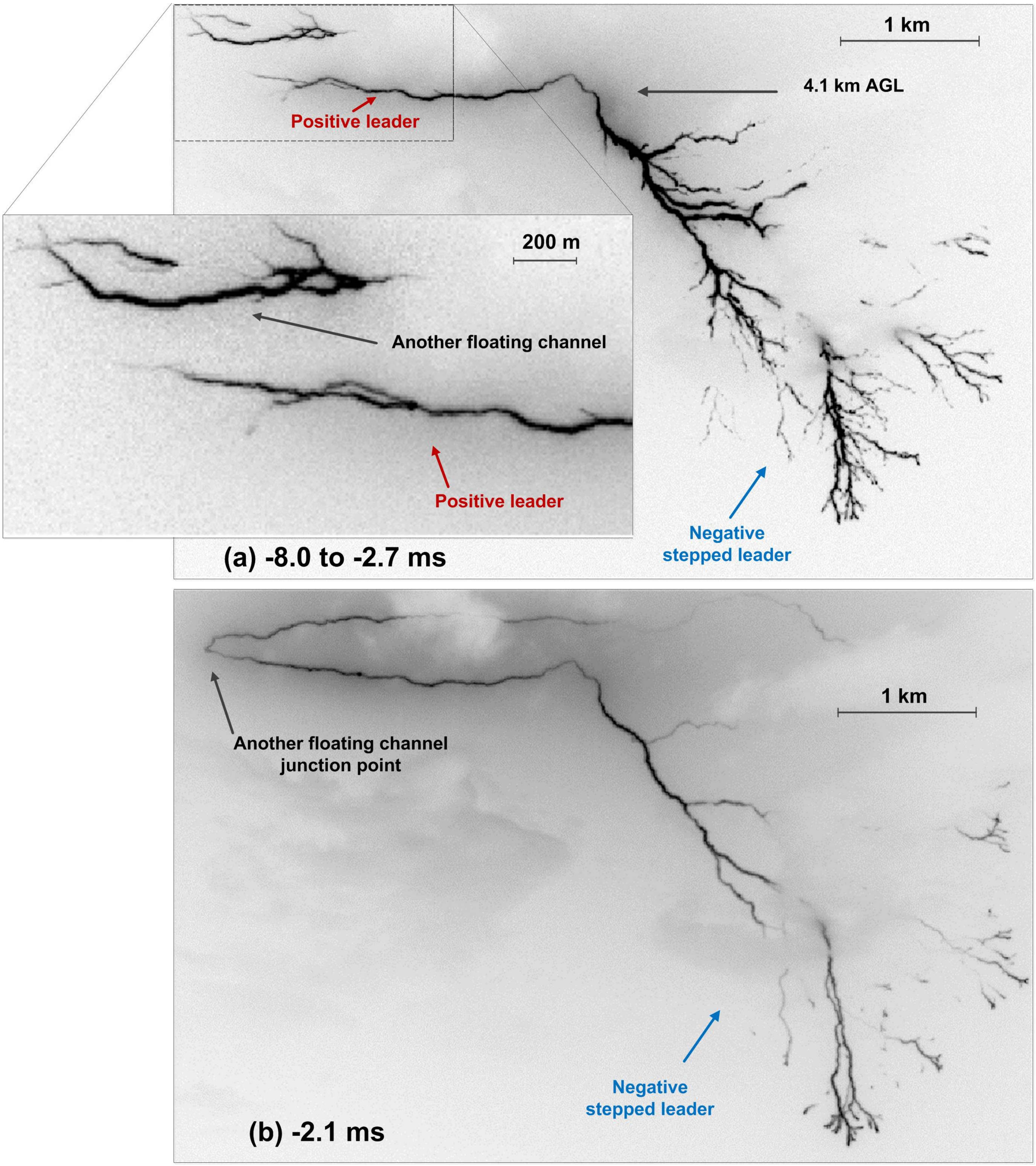

Fig. 4: (a) Composite image from -8.0 ms (after the transient event) to -2.7 ms (prior to the connection to the channel labeled “Another floating channel” in the enlargement of the positive-end area in (a)) showing both positive and negative ends of the bidirectional leader. (b) Single-frame (-2.1 ms) image showing the enlarged bidirectional leader, resulting from the positive end’s (see (a)) coming in contact with another floating channel, after the connection to the floating channel. Frame at -2.4 ms, between the images shown in (a) and (b), was saturated. The negative end (stepped leader) exhibited numerous branches, while the positive end seen in (a) had 5 branches, 2 of which are indiscernible in this reproduction.

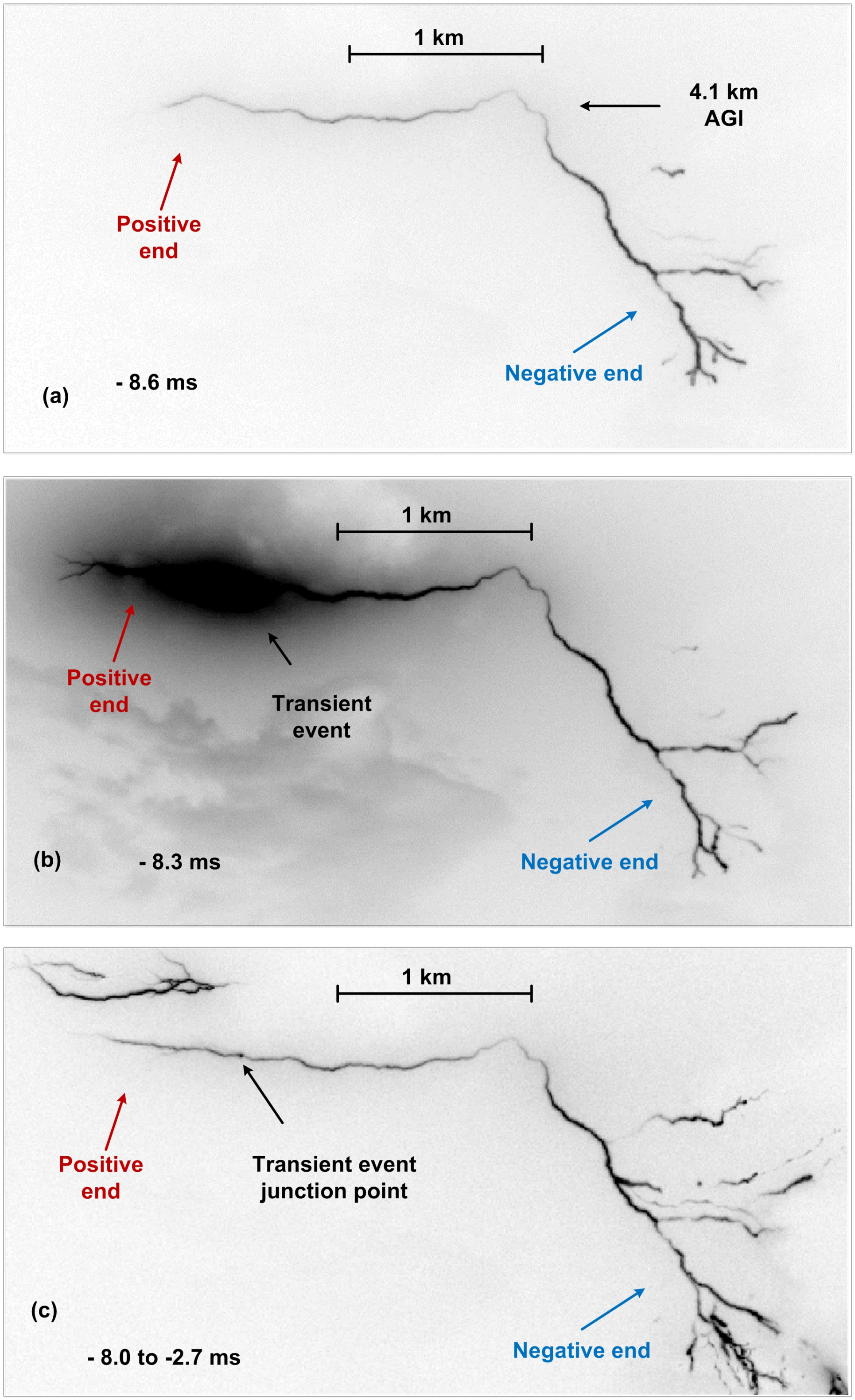

Fig. 5: Transient event at the positive end: (a) frame at -8.6 ms, just prior to the transient event, (b) frame at -8.3 ms containing the transient event, during which a 1-km long branch was formed, (c) composite image (from -8.0 to -2.7 ms) showing the transient event junction point.

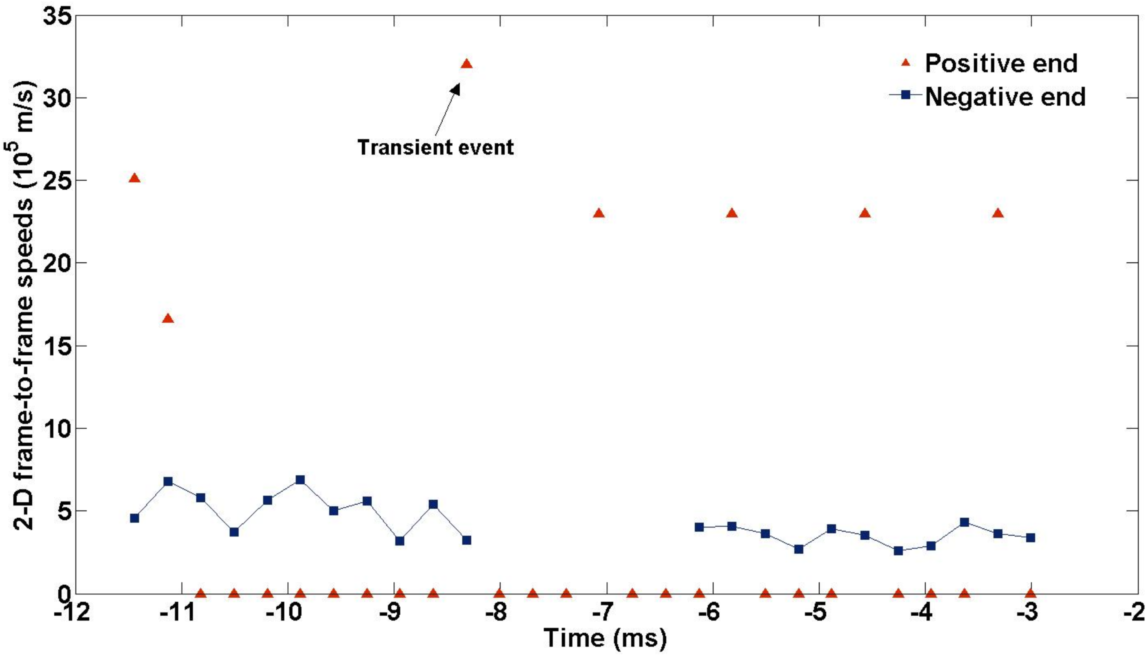

Fig. 6: Frame to frame speeds of positive (red triangle) and negative (blue rectangle) ends from -11.4 to -3.0 ms. At t =-2.7 ms, the connection to another floating channel was established. Negative end speeds are not available from -8.0 to -6.4 ms due to channel obscuration by cloud debris. The majority of positive end speeds are equal to zero, because the positive end was either stationary or exhibited abrupt extensions/retractions separated by relative long inactive intervals.

setup presently includes two high-speed (HS) video cameras, low-gain and high-gain electric field, electric field derivative (dE/dt), and magnetic field derivative measuring systems, and an x-ray detector. The flash studied here was captured by both high-speed cameras (Phantom V310 and HHC-X2). The corresponding electric field and dE/dt records were also obtained. The magnetic field derivatives were not recorded and no x-rays were detected. The useful bandwidth of the low-gain electric field measuring system was 16 Hz to 10 MHz. The instrumental decay time constant was 10 ms. For the high-gain system, the bandwidth was from 360 Hz to 10 MHz, and the decay time constant was 440 µs. The upper frequency response of the dE/dt measuring system was 10 MHz. The field measuring systems have been synchronized with Phantom V310 and HHC-X2 cameras with accuracy better than 2.4 µs and 1 ms, respectively [Tran and Rakov, 2015] [15]. For the former, the synchronization accuracy has been better than 1.3 µs since 3 July 2014. The Phantom V310 camera was coupled with a Sigma 20 mm lens, whose f-number (f-stop) was set to f/4. The camera framing rate was 3200 frames per second with the exposure time of 80 µs and dead time of 232.5 µs. A C-mount fisheye lens was used for the HHC-X2 camera. The f-number was set to f/4 and the framing rate was 1000 frames per second with the exposure time of about 1 ms. The deadtime of the HHC-X2 camera was negligible in comparison with the exposure time. The pre-trigger time of the field measuring system was 100 ms, and for both cameras, it was 200 ms. The distance (8.4 km) to the LOG from the lightning strike location reported by the National Lightning Detection Network (NLDN) was used to estimate 2–D lengths and 2–D speeds presented in this paper. We additionally used data provided by the National Weather Service radar located near Jacksonville, FL, 112 km from the LOG.

III. Data Presentation and Analysis

A. Overview

At about 20:03 UT (16:03 local time) on 2 August 2014, a cluster of about 8 thunderstorm cells in a large (hundred kilometers in extent) thunderstorm system crossed the Gainesville area, moving from southwest to northeast. The horizontal extent of the cell cluster (with radar reflectivity $\geq$ 35 dBZ and at an altitude of 5 km above ground level (AGL)) reached its maximum of about 44 km at 21:54 (UT). Its 35-dBZ upper boundary was higher than 10 km AGL. At about 21:49 (UT) the flash rate estimated from NLDN data reached its peak of 19 flashes per minute. Afterwards, the cell cluster was shrinking in horizontal extent and its upper boundary was descending. At 22:45 (UT) the 35-dBZ cloud top was at about 7 km AGL and the cluster disintegrated into 4 isolated cells, each being smaller than 8 km in horizontal extent (with $\geq$ 35 dBZ reflectivity and at a height of 5 km AGL). The 0°C temperature level was 4.8 km AGL, according to two balloon sounding measurements at 12:00 (UT) and 24:00 (UT) on 2 August 2014 at the weather station in Jacksonville.

At 22:43:33 (UT), when the thunderstorm was in its dissipating stage (flash rate dropped to 4 flashes per minute), it produced a clearly documented bidirectional leader that evolved into a single-stroke, negative cloud-to-ground flash.

Figure 1a shows the composite image of 41 selected frames acquired with the Phantom V310 camera. According to the HS video images and electric field records (see Figures 1b and 1c), the bidirectional leader apparently occurred during the late stage of a preceding cloud flash. Its channel was intermittently illuminated, for the first time 135.2 ms prior to the return stroke onset. It is possible that each reillumination resulted from a recoil-leader-type process occurring along the remnants of in-cloud channel created during the initial stage of the cloud discharge, which occurred prior to the beginning of any of the LOG records, but is evidenced by NLDN data (discussed below). Sustained bidirectional leader extension was observed starting with 28.9 ms prior to the return stroke. Individual-frame and composite images of the rectangular area in the upper-left corner of Figure 1a showing important features of the bidirectional leader development are presented in Figure 2. The return stroke occurred about 2.4 ms after the left end had come in contact with another floating channel (see "Junction point" in Figure 1a). The return stroke was followed by continuing current, whose duration (inferred from high-speed video images) was 21.9 ms.

The NLDN reported a total of 7 events from -522 to 1.2 ms (relative to the return-stroke onset), including a 36-kA cloud-to-ground (CG) stroke and 6 cloud pulses, 5 preceding and 1 following the CG stroke. Of the 5 cloud pulses preceding the CG stroke, 4 were reported by the NLDN to occur within (less than 2.7 km of each other) a compact region of radar reflectivity greater than 26 dBZ, at heights ranging from 1 to 4 km AGL. The high radar reflectivity region apparently corresponded to the denser cloud region seen in the images of two HS cameras to the right from the bidirectional leader channel. The sources of 4 NLDN-reported cloud pulses were 8.2-11.1 km from the channel to ground, the duration of the 4-pulse burst was 64 ms, and the time interval between the last reported pulse in the burst and the return stroke was 458 ms. The other NLDN-reported cloud pulse was 5.4 km from the ground termination, and occurred 319 ms prior to the return stroke.

The left end of the bidirectional leader was identified as positive and the right end as negative (see Appendix A). All times in this paper are relative to the return stroke onset, which is set to zero ($t = 0$).

B. *Bidirectional leader development*

Figure 2a shows, as a reference, the negative of image seen in the rectangular box in Figure 1a. Single-frame and composite images for different time intervals are given in Figures 2b-j to illustrate the major features of bidirectional leader development.

The first illumination of the bidirectional leader channel (see Figure 2b), which was 860 m long, was detected 135.2 ms prior to the return stroke onset at a height of 4.1 km above ground level (AGL). A significant portion of the first luminous channel was very faint. There was no luminosity seen in the leader channel in 43 ms from the beginning of the HS video record to the first illumination. The composite image of all frames from -135.2 to -28.9 ms is given in Figure 2c. The channel was repeatedly illuminated with the time intervals between illuminations ranging from 8.8 to 29 ms (mean value was 17.1 ms). It is likely that these intermittent channel illuminations were produced by recoil-leader-type processes.

The first unambiguous extension (and branching) of the positive end in virgin air was observed at -14.9 ms (as seen in Figure 2d). The negative end apparently started turning toward ground 14.3 ms prior to the return stroke. It initially extended (in virgin air) as a single channel for 1 ms and then split into two branches 13.6 ms prior to the return stroke. The left branch decayed, while the right one became the main channel of the return stroke. The right branch descended for about 1 ms without pronounced pulses seen in the high-gain electric field record. The extension speeds of the negative end between -14.9 and -12.4 ms ranged from 0.33×10^5 m/s to 2.65×10^5 m/s with a mean of 1.67×10^5 m/s, while the positive end was largely not luminous.

After turning toward ground, the negative end of the bidirectional leader exhibited features characteristic of preliminary breakdown and stepped leader of negative cloud-to-ground strokes. We defined the start of the preliminary breakdown stage as the occurrence of the first electric field pulse whose peak-to-peak magnitude was more than one fifth that of the largest preliminary breakdown pulse, seen near -11 ms in the top panel of Figure 3. So defined the preliminary breakdown stage started at -12.4 ms. The high-gain electric field and negative-leader frame-to-frame speeds between -15 and -8.5 ms are given in Figure 3. Between -11.8 to -9 ms, the negative end significantly brightened, accelerated, and reached its maximum 2D speed of 6.89×10^5 m/s, which was nearly 3 times greater than its highest speed (2.65×10^5 m/s) from -14.9 to -12.4 ms.

A strong increase in luminosity (see Figures 5b and 2g) resulting in a long (about 1 km) branch was observed at the positive end 8.3 ms prior to the return stroke. The frame-to-frame speed at which the positive branch was formed was relatively high, 3.2×10^6 m/s. We termed this event transient. A total of 4 branches can be seen at the positive end in the transient event frame (Figure 5b). Interestingly, other positive branches that had been previously visible (see Figures 2e and f) were not re-illuminated during this transient event. The frame-to-frame speed of negative end branches did not change noticeably as a result of this transient event.

Figure 4a is the composite image from -8.0 through -2.7 ms showing the dramatic difference in branching at positive and negative ends. At about -2.4 ms, the bidirectional leader connected, via its positive end, to the channel labeled "Another floating channel" in the enlargement of the positive-end area in Figure 4a to form a larger bidirectional leader as seen in Figure 4b.

Figure 6 shows variation versus time of frame-to-frame speeds of positive and negative ends from -11.4 to -3.0 ms. The highest speed of the positive end, 3.2×10^6 m/s, was associated with the transient event. Other non-zero speeds of the positive end were associated with retracing existing channel (the positive end exhibited a number of extension/retraction cycles). At the same time, the negative end exhibited speeds ranging from 2.6×10^5 to 6.9×10^5 m/s with a mean of 4.3×10^5 m/s, which is not far from the typical speed of "normal" negative stepped leaders.

It appears that the behavior of at least positive end of our bidirectional leader is different from that reported by Montanya et al. [2015] [4]. The fact that one of the ends of our bidirectional leader produced a cloud-to-ground stroke (including the preliminary breakdown stage) has important implications for understanding the lightning initiation process.

IV. Summary

We presented the first optical observation of a bidirectional leader giving rise to a negative stepped leader/return-stroke sequence. The leader started with a 860-m long luminous channel segment, which was likely the manifestation of recoil-leader-type process along the remnants of a channel created by the preceding cloud flash. Following a sequence of re-illuminations lasting 120 ms, the leader channel extended bidirectionally through virgin air and exhibited branching. After turning toward ground, the negative end exhibited features characteristic of negative preliminary breakdown and stepped leader, while the positive end was almost stationary or exhibited abrupt extensions/retractions separated by relatively long inactive intervals. The development of positive end involved a very bright process that created a 1-km long, relatively straight branch. The branching (or junction) point was on the lateral surface of the existing positive leader channel, and the far end of the new branch was forked. The bidirectional leader connected, via its positive end, to another, considerably longer bidirectional leader (floating channel) to form a larger bidirectional leader, whose negative leader attached to the ground and produced a normal return stroke with a peak current of 36 kA.

Appendix A
Identification of polarity of bidirectional leader ends

Since the right end of the bidirectional leader after the connection of the left end to another floating channel produced a negative return stroke, the right end after the connection must have been a negative stepped leader. We argue below that the right end was also negative prior to the connection of the left end with the floating channel.

1. During the preliminary breakdown stage, the right end was extending in virgin air, while the left end was retracing the previously-created channel and showed very little overall extension (see Figures 2f and 2g) until -8.3 ms. Therefore, the observed pronounced preliminary breakdown pulses (seen in the enlargement of preliminary breakdown pulses in Figure 3 (top panel)) are to be attributed to the right end. Since, the preliminary breakdown pulses are positive (same polarity as that of the following return-stroke pulse), we conclude that the right end was negatively charged prior to the connection of the left end with the floating channel.
2. Figure 4a is the composite image (from -8.0 to -2.7 ms) of bidirectional leader prior to the connection of its left end to the floating channel. The morphology of the right end in Figure 4a is characteristic of negative stepped leaders, which is in support of the above inference that the right end was negative prior to the connection of the left end with the floating channel.

Acknowledgment

This research was supported in part by NSF and DARPA/STO under AFRL/RYWN's Spatial, Temporal and Orientation Information in Contested Environments (STOIC) contract FA8650-15-C-7535. We would like to thank William Brooks of Vaisala Inc. for providing NLDN data. Shreeharsh Mallick significantly contributed to the LOG experimental setup.

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