International Conference on Lightning Protection
33rd International Conference on Lightning Protection
25 - 30 September 2016
Estoril, Portugal

2016 International Conference on Lightning Protection (ICLP), Estoril, Portugal

A Subsequent Positive Stroke Developing in the Channel of Preceding Negative Stroke and Containing Bipolar Continuing Current

Yanan Zhu, Vladimir A. Rakov, Manh D. Tran
Department of Electrical and Computer Engineering
University of Florida
Gainesville, FL, USA
rakov@ece.ufl.edu

Weitao Lu
State Key Laboratory of Severe Weather
Chinese Academy of Meteorological Science
Beijing, China

***Abstract*— A bipolar cloud-to-ground lightning flash was observed to exhibit two types of polarity reversal associated with the first two strokes separated by a not-unduly-long time interval of 70 ms. The first, negative stroke had a peak current of -101 kA and was followed by a second, positive stroke whose peak current was 16 kA. The latter contained a 122-ms long bipolar continuing current. The first two strokes, including the bipolar continuing current, occurred in the same channel to ground, whose imaged 2D length was 4.2 km. The occurrence of positive stroke in the negative-stroke channel is highly unusual. The 2D speed versus height profiles for the negative stepped leader of the first stroke and, for the first time, for the positive leader in the previously conditioned, first-stroke channel were examined and the average speeds were found to be 4.7×10^5 m/s and 7.2×10^5 m/s, respectively.**

Keywords- bipolar lightning, subsequent positive leader, leader speed

I. Introduction

Rakov [1] introduced three types of bipolar lightning discharges and defined them as follows. Type 1 is related to a polarity reversal during a slowly-varying current component, for instance, the initial continuous current in object-initiated (natural upward) lightning or in rocket-triggered lightning. Type 1 can also occur in natural downward lightning when the continuing current following a return stroke changes its polarity, which can also occur in object-initiated and rocket-triggered lightning. Type 2 is associated with the different polarities of the initial stage current and of the following stroke or strokes, which can happen only in object-initiated and rocket-triggered lightning. Type 3 is characterized by different polarities of individual strokes in the same flash. Jerauld et al. [2] further divided Type 3 bipolar lightning discharges into two subcategories. Type 3a is more common and is associated with natural upward or rocket-triggered lightning, while Type 3b events are natural downward cloud-to-ground flashes. In order to reliably identify an event as a natural downward cloud-to-ground bipolar flash (Type 3b event), simultaneous video observations and electric field measurements are needed. The latter are used for identification of the sign of charge transfer to ground by individual strokes, with this sign determining the polarity of lightning stroke.

Correlated optical and electric field records of natural downward cloud-to-ground bipolar flashes are rarely reported. Based on video observations and multi-station field measurements, Jerauld et al. [2] gave the first well-documented description of a natural downward bipolar flash containing two initial positive strokes with strike points separated by about 800 m, followed by four negative strokes that traversed the same channel as the second positive stroke. Fleenor et al. [3] reported four bipolar flashes that all started with a positive stroke followed by one or two negative strokes. Out of five subsequent negative strokes in the four flashes, two followed the pre-existing but decayed channel of the first, positive stroke. Saba et al. [4] presented five natural downward, “single-channel” bipolar flashes in which two strokes of different polarity occurred in the same channel, although there could have been other strokes in different channels. Each of their bipolar flashes started with a positive stroke and all the second, negative strokes were initiated by optically imaged recoil leaders in decayed upper-level branches of the first, downward positive leader. Saraiva et al. [5] observed one single-channel downward bipolar flash and one multi-channel downward bipolar flash. Each of these two started with a positive stroke and all the negative subsequent strokes occurred as a result of recoil leaders, in the manner described above. Chen et al. [6] reported a downward bipolar flash with a first, positive stroke followed by five negative strokes, all occurring in the same channel terminated on a 90-m tall structure. Tian et al. [7] reported a downward bipolar flash containing a first, positive stroke followed by three negative strokes along the same channel. Similarly to Saba et al. [4] and Saraiva et al. [5], they found that the three subsequent negative strokes were initiated by recoil leaders. There is only one case found in the literature, in which a subsequent positive stroke developed in the channel of preceding negative stroke. It was recently reported by Xue at al. [8] who attributed the polarity change to some intracloud process that altered the cloud charge structure during the time interval (136 ms) between the two strokes.

In this paper, we present correlated electric field and high-speed video records of a natural four-stroke cloud-to-ground flash having a negative first stroke followed by a positive stroke in the same channel whose 2D length was 4.2 km. As follows from the literature review given above, this scenario is highly unusual. The second, positive stroke was followed by bipolar continuing current (with the initial positive charge transfer to ground followed by negative charge transfer to ground), so that the flash exhibited the features of both Type 1 and Type 3b bipolar discharges identified by Rakov [1]. The third and fourth strokes in our flash were negative and followed a newly created channel, different from the one of the first and second strokes. The atmospheric electricity sign convention, according to which the electric field change vector produced by a negative return stroke is positive, is used throughout this paper.

II. INSTRUMENTATION

The bipolar flash (labeled 2117) was recorded at 01:55:20 UT on Aug. 22nd (at 21:55:20 local time on Aug. 21st), 2014 at the Lightning Observatory in Gainesville (LOG), Florida, by two high-speed video cameras, Phantom V310 and Megaspeed HHC-X2, and by electric field measuring systems. Additionally, the event was recorded by the Total-sky Lightning Channel Imager (TLCI) installed at LOG as part of our collaboration with the Chinese Academy of Meteorological Sciences. The electric field measuring systems include the low-gain and high-gain electric field measuring systems and the electric field derivative (dE/dt) measuring system. The record length for the field measuring systems was 1 s with 200 ms pretrigger time. The Phantom V310 was operated at 3200 frames per second (fps) with 80 µs exposure time (232.5 µs deadtime) and resolution of 1280×800 pixels. The HHC-X2, equipped with a fish-eye lens to provide a wider field of view, was operated at 1000 fps with 1 ms exposure time (essentially no deadtime) and resolution of 832×600 pixels. The electric field records and high speed video records were GPS time stamped. The synchronization accuracy between the Phantom records and electric field records was better than 1.3 µs. The spatial resolution of Phantom records used in this study was 5 m. The TLCI had a fish-eye lens and was operated at 40 fps with 25 ms exposure time [9]. Outputs of all three optical instruments are generally consistent with each other. Only Phantom images are presented in this paper. Additionally, U.S. National Lightning Detection Network (NLDN) data, including locations and peak current estimates for lightning strokes, were used in this study.

III. OBSERVATIONS AND ANALYSIS

A. General Description

According to the NLDN, flash 2117 contained four strokeswith peak currents, in the order of occurrence, of -101 kA, 16 kA, -20 kA, and -32 kA. Based on the locations of strike points provided by the NLDN, the distances between the 1st and 2nd strokes, 2nd and 3rd strokes, and 3rd and 4th strokes were 0.14 km, 1.87 km, and 0.12 km, respectively. The corresponding interstroke intervals (measured between return-stroke field peaks) were 70 ms, 210 ms, and 65 ms. The distance between the strike-point of the first, negative stroke and LOG was 5 km. This distance was used for estimating all the heights, as well as 2D distances and speeds presented in this paper. The Phantom high-speed video camera captured all the strokes of this flash. The Megaspeed HHC-X2 high-speed video camera and TLCI captured only the first and second strokes, with the third and fourth strokes being outside their fields of view.

From all the video records, it was unambiguously determined that the second stroke followed the same channel as the first stroke, except for the bottom 115 m, where the channels of the first two strokes were found, from the Phantom record, to be slightly different from each other. It appears that the second-stroke, positive leader, after extending from 3.9 km (the upper limit of the Phantom camera's field of view) to 115 m above ground along the path of the first, negative stroke, deviated from that path and contacted ground 40 m from the first-stroke termination point. About 210 ms after the second return stroke, the third, negative stroke occurred. It exhibited branching and created an entirely new (within the Phantom camera's field of view) channel whose termination point was about 1.87 km from that of the second stroke. The fourth stroke was not branched and followed the main channel of the third one. Leaders of the third and fourth strokes had propagation speeds that were characteristic of stepped and dart leaders, respectively. In the field of view of Phantom camera, no clear relation was seen between the former two strokes and the latter two strokes, but they all do satisfy the spatial and temporal stroke grouping into flash criteria used by the NLDN [10]. The third and fourth strokes are not further discussed in this paper.

Composite images of the first two leader-return stroke sequences are shown in Figure 1. As noted above, within about 115 m of the ground, the first and second strokes followed slightly different paths and formed separate ground terminations, which were 40 m apart (2-D distance estimated from the Phantom camera record). The separate terminations are clearly seen in a magnified superposition of the bottom portions of the channels of the first and second strokes shown in the inset in Figure 1. As discussed below, the bottom part of the second-stroke channel could be actually created by the first-stroke leader. Based on the Phantom camera record, the durations of continuing currents (CCs) following the first, negative stroke and second, positive stroke were 5 ms and 122 ms, respectively.

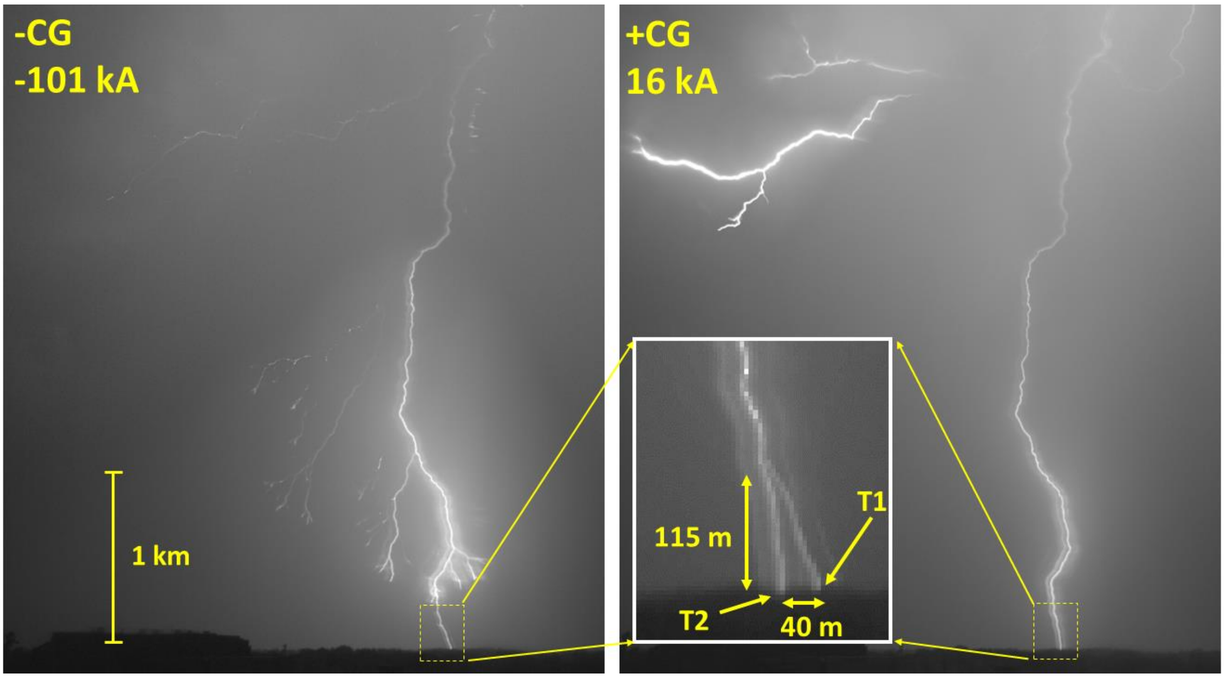

Figure 1 Composite Phantom images of the first, negative stroke (left panel labeled -CG) and second, positive stroke (right panel labeled +CG). They were produced using all the frames (except for one and three saturated ones for the negative and positive strokes, respectively) corresponding to the leader, return stroke, and continuing current processes. The top of the imaged channel was about 3.9 km above ground. The inset shows the magnified composite image of the bottom portions of channels of the first, negative stroke and second, positive stroke. T1 and T2 mark the ground terminations of the first and second strokes, respectively. The predominantly horizontal branches seen in the upper left corner of the right panel were repeatedly illuminated before and during the development of downward positive leader, as well as during and after the continuing current following the positive return stroke. These branches were apparently associated with concurrent in-cloud discharge activity and were possibly connected to the faintly luminous channel segment in the upper right corner (to the right from the main channel) of the right panel, although the connection was obscured by cloud debris. The faintly luminous channel segment (maybe indiscernible in the reproduction) probably had intermittent connection to the main channel to ground.

Figures 2a to 2c show simultaneous low-gain electric field, high-gain electric field, and dE/dt records of the two strokes of interest. The time interval between the first, negative return stroke and second, positive return stroke is 70 ms, which is comparable to the median interstroke interval in negative flashes of 60 ms. The leader durations (measured in the low-gain electric field record) for first and second strokes are similar, 9.5 ms and 9.4 ms, respectively. The net electric field change produced by the leader of the first stroke has the same polarity as the corresponding return stroke field change, while for the second stroke the net electric field changes due to the leader and return stroke have opposite polarities. This disparity is likely to be caused by different charge source locations relative to the channel to ground for the two strokes, as discussed by Rakov and Uman [11]. Based on the high-gain electric field record, the first preliminary breakdown (PB) pulse, which had the same polarity as the negative return stroke pulse, occurred 9.5 ms before the first, negative return stroke onset, which is consistent with the stepped-leader duration obtained by measuring the duration of leader electric field waveform in the low-gain record. The expansions of the first, negative and second, positive return-stroke electric field and dE/dt waveforms are shown in Figures 2d to 2g. Note that the first, negative return stroke exhibited a double-peak electric field waveform (see Figure 2d), which might be indicative of two channel terminations on ground created by the forked first-stroke leader, even though this can't be confirmed by our optical records. It is possible that the ground termination labeled T2 in the inset of Figure 1 was one of the terminations formed by the first, negative stroke leader, but appeared only in the first frame containing the return stroke, which was saturated, and was too faint to be imaged in the following frames. If so, the apparent deviation of the second-stroke leader from the first-stroke channel at height of 115 above ground level could actually be the second-stroke leader following one of the decayed paths to ground created by the forked first-stroke leader.

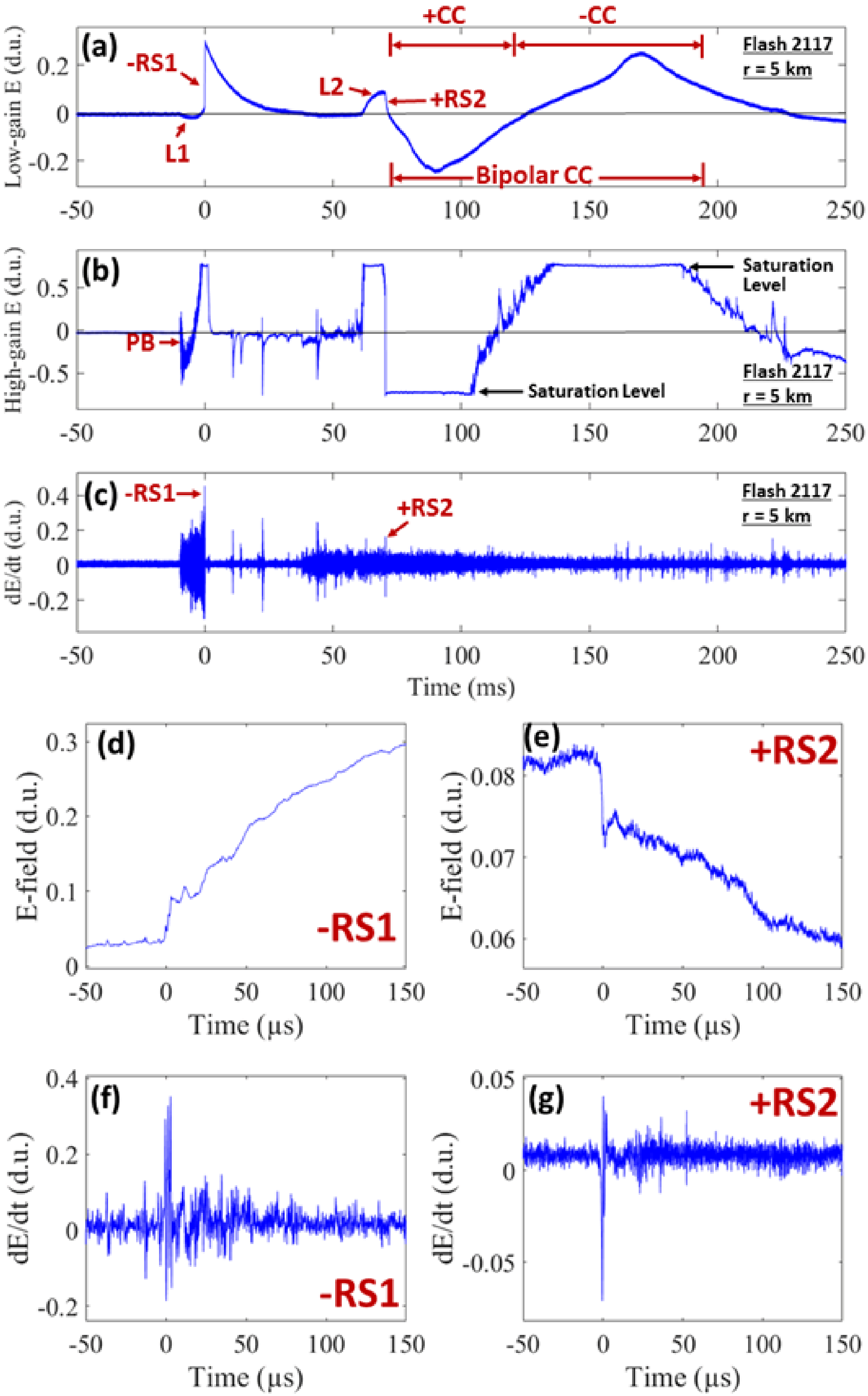

Figure 2. Panels (a) to (c) show simultaneous low-gain electric field, high-gain electric field, and dE/dt records of the initial part of the bipolar flash, including the preliminary breakdown (PB), the first and the second leader (L) /return stroke (RS) sequences and bipolar continuing current (CC). Duration of the latter was estimated from the Phantom camera record. In panels (d) to (g), low-gain electric field (panels (d) and (e)) and electric field derivative (panels (f) and (g)) waveforms of the first, negative and second, positive return strokes are shown on a 200-μs time scale. All records have been obtained at a distance of 5 km from the lightning channel.

The RC decay time constants of the low-gain and high-gain electric field measuring systems were 10 ms and 440 µs, repectively, so that only field changes occurring on the time scale shorter than 1 ms or so (see, for example, Figures 2d and e) were faithfully reproduced by the former and only shorter than 44 µs or so by the latter. The instrumental decay can be compensated for using the method proposed by Rubinstein et al. [12]. We have used this method in determining the CC polarity-reversal point in our low-gain field record (see Figure 2a). Our approach was as follows. We assumed that 1) electric field change produced by CC is essentially electrostatic, 2) the electrostatic field change is proportional to the charge transfer Q, and 3) the corresponding current I is given by dQ/dt. Under these assumptions, the CC polarity change should correspond to the zero rate of change (negative maximum) of the bipolar CC electric field signature after its compensation for instrumental decay. Using the compensated electric field waveform (not shown here), in which the negative maximum occurred considerably later than seen in Figure 2a, we found that the initial 44-ms long portion of the CC following the second return stroke was positive (positive charge transported to ground) and the following 78-ms long portion was negative (negative charge transported to ground). The average luminosity of the main channel during the positive CC was 3.7 times higher than that during the negative CC, which is likely indicative of about 3.7 times higher current of the positive CC. For comparison, average currents associated with upward negative leaders (positive charge transported to ground) initiated from tall objects are considerably higher than their counterparts associated with upward positive leaders. For example, the average current for negative charge transfer to ground at the Gaisberg tower (Austria) was 113 A [13], while for positive charge transfer to ground it was 707 A [14]. It is likely that upward negative leaders are more heavily branched inside the cloud than the upward positive ones, which makes the former more efficient in collecting the cloud charges and funneling them to the channel to ground.

B. Characteristics of the Negative and Positive Leaders

One can see from the left panel of Figure 1 that the stepped leader (labeled L1 in Figure 2a) initiating the first, negative stroke, like most negative stepped leaders, was branched. Its 26 frame-to-frame speeds range from 2.6×10^5 m/s to 13.1×10^5 m/s with an arithmetic mean of 4.7×10^5 m/s, which is equal to the average speed calculated by dividing the entire 2D length of the channel by the time it took the leader to traverse that channel. This average speed is somewhat higher than the typical negative stepped-leader speed of 2×10^5 m/s given in [15], possibly because the stroke was of higher than typical intensity. Variation of the frame-to-frame speed of the negative stepped leader versus height of the leader tip above ground is shown in red in Figure 3. The speed varied irregularly between 2.6 and 6.4×10^5 m/s at heights ranging from 3600 m to 1000 m above ground and then significantly increased in the last few frames before the leader attachment to ground.

The positive leader (labeled L2 in Figure 2a) initiating the second, positive stroke exhibited no low-level branches. It was fainter than L1 and became clearly visible only when it was at the height of 3.2 km above ground. For comparison, the typical cloud-base height during summer thunderstorms in Florida is about 1.5 km above ground. Variation of the frame-to-frame 2D speed vs. height for the positive leader is shown in blue in Figure 3. Similar to L1, L2 accelerated as it was approaching the ground. Its minimum, maximum, and mean values of 14 frame-to-frame speeds are 4.8×10^5 m/s, 12×10^5 m/s, and 7.2×10^5 m/s, respectively.

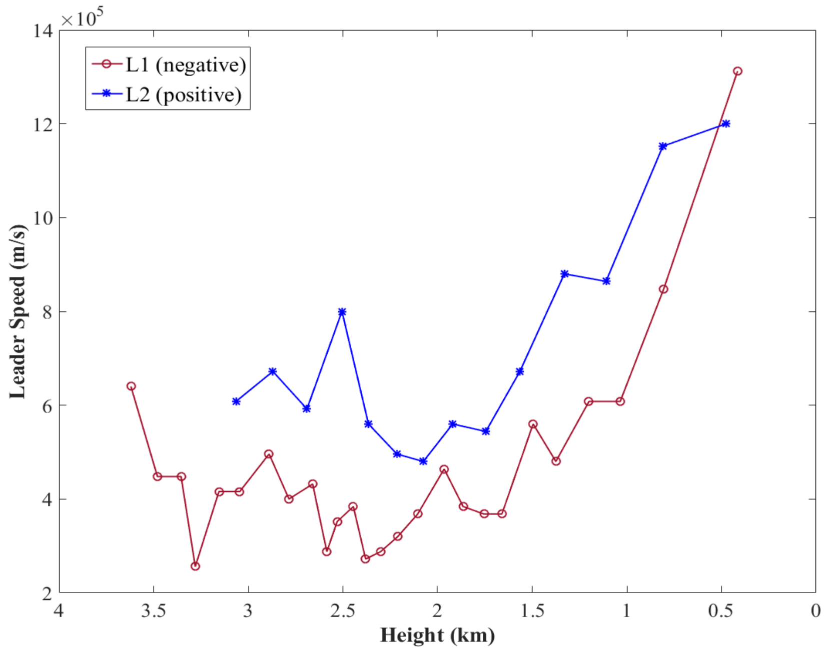

Figure 3. The frame-to-frame 2D speeds of the negative stepped leader (L1) and the following positive leader (L2), developing in the same channel, versus height of the leader tip above ground. Both leaders significantly accelerated below 2 km above ground.

IV. Discussion

Some researchers, based on the various observations of "polarity asymmetry" (see, for example, Ch. 5 of [15] and references therein), believe that subsequent strokes never transport positive charge to ground along the previously created channel. For example, for the case of channel created by a negative stroke, Saba et al. [4] stated that "a positive subsequent return stroke following a negative return stroke is likely not viable given that recoil leaders (RL) would be required to retrace the horizontal channels created by negative leaders. To date, RLs forming on decayed negative leader branches have not been reported." However, this generalizing statement is not supported by our observations and those of of Xue at al. [8] who presented correlated high-speed video and electric field records of a two-stroke bipolar cloud-to-ground flash with the second, negative stroke retracing the channel of the first, positive stroke. Additionally, the occurrence of recoil-leader-like processes that formed in decayed negative leader branches was recently reported by Montanyà et al. [16] and Stolzenburg et al. [17]. In our view, a recoil leader is an electrical breakdown in warm, low-density air which the decayed lightning channel branches are filled with. The polarities of its ends should be determined by the direction of local electric field or electric field change vector. It is not clear how the conditions for occurrence of this breakdown can be influenced by the sign of charge previously hosted by the branches.

The average speed of L2 is about 1.5 times higher than that of L1. For negative lightning, it is expected (e.g., [15]) that a leader traversing previously-created channel is considerably (1 to 2 orders of magnitude) faster than the stepped leader that created the channel. For positive strokes traversing previously-created channels, such information is not available. Prior to this writing, speeds of positive leaders that traversed the pre-existing channel (regardless of preceding-stroke polarity) were not reported, except for the results of Xue et al. [8]. In the latter study, the authors optically observed one bipolar flash with only two video frames being recorded for each the negative stepped leader and the subsequent positive leader, the latter following the same channel as the first leader. The corresponding frame-to-frame 2D speeds were 3.6×10^5 m/s and 1.7×10^6 m/s and the interstroke interval was 136 ms. The typical speeds of negative dart-stepped and dart leaders are $(1\text{-}2)\times10^6$ m/s and $(1\text{-}2)\times10^7$ m/s, respectively [15], and, hence, the subsequent, positive leader speed reported by Xue et al. [8] is similar to that expected for negative dart-stepped leaders. In our case, the 7.2×10^5 m/s value is lower than expected for negative subsequent leaders in the previously formed channel. As noted above, the interstroke interval between the first two strokes in our bipolar flash, was not too long, 70 ms (in contrast with the event reported by Xue et al. [8]), which is not much different from the median value of 60 ms for interstroke intervals in negative flashes. Further, the magnitude of NLDN-reported first-stroke peak current was very large (101 kA). Thus, the lightning channel traversed by the positive leader might be expected to be warm enough to allow faster than observed leader propagation.

Saba et al. [18] reported that the average speeds of 29 positive leaders (it is not specified if all of them were developing in virgin air) ranged from 0.24 to 11.8×105 m/s with the arithmetic mean of 2.76×105 m/s, which is about 2.5 times lower than the average speed of the subsequent positive leader observed in our study. Considering that positive flashes normally contain a single stroke or have subsequent strokes following newly-created channels, the majority of the 29 positive leaders studied in Saba et al. [18] probably propagated through virgin air, and hence, are not directly comparable to our positive leader traversing the previously conditioned channel.

Additional data on positive leaders developing in warm air are needed to explain our observations. One possible explanation of the relatively low speed of our positive subsequent leader is the relatively low (but rather typical for negative subsequent strokes) magnitude of corresponding return-stroke peak current, only 16 kA vs. 101 kA for the preceding negative stroke. Indeed, Jordan et al. [19] reported positive correlation between the subsequent-leader speed and return-stroke peak current in both natural and triggered negative lightning. Also, Zhu et al. [20] found a tendency for negative first return strokes with higher peak current to be preceded by faster stepped leaders. Another possible factor is the height above sea level, 2496 m in the work of Xue et al. [8] vs. 52 m in our study. Clearly, further research of this rare phenomenon is needed.

V. Conclusions

Using simultaneous high-speed video camera records and electric field measurements, we observed a bipolar flash that started with a negative stroke with a peak current of -101 kA, which was followed by a second, positive stroke with a peak current of 16 kA, the latter being followed by a bipolar continuing current. The first two strokes (including the continuing current) followed the same channel to ground, whose imaged 2D length was 4.2 km, except for the bottom 115 m, where the paths of the two strokes were slightly different. As of this writing, there is only one previously documented case of positive leader following the path of preceding negative stroke. The average leader speeds for the first, negative and second, positive strokes were 4.7×10^5 m/s and 7.2×10^5 m/s, respectively. The speed of the positive leader traversing the previous-stroke channel after not-unduly-long (70 ms) interstroke interval was lower than typical speeds of negative leaders following previously formed channels. The speeds of both the negative leader and the positive leader increased as they approached the ground.

Acknowledgment

This effort was funded in part by DARPA/STO under AFRL/RYWN's Spatial, Temporal and Orientation Information in Contested Environments (STOIC) contract FA8650-15-C-7535 and by NSF. The authors would like to thank Amitabh Nag of Vaisala Inc. for providing the NLDN data.

REFERENCES

[1] V. A. Rakov, "A Review of Positive and Bipolar Lightning Discharges," *Bull. Am. Meteorol. Soc.*, vol. 84, no. 6, pp. 767–776, 2003.

[2] J. E. Jerauld, M. A. Uman, V. A. Rakov, K. J. Rambo, D. M. Jordan, and G. H. Schnetzer, "Measured electric and magnetic fields from an unusual cloud-to-ground lightning flash containing two positive strokes followed by four negative strokes," *J. Geophys. Res. Atmos.*, vol. 114, no. 19, pp. 1–17, 2009.

[3] S. A. Fleenor, C. J. Biagi, K. L. Cummins, E. P. Krider, and X. M. Shao, "Characteristics of cloud-to-ground lightning in warm-season thunderstorms in the Central Great Plains," *Atmos. Res.*, vol. 91, no. 2–4, pp. 333–352, 2009.

[4] M. M. F. Saba, C. Schumann, T. a. Warner, J. H. Helsdon, W. Schulz, and R. E. Orville, "Bipolar cloud-to-ground lightning flash observations," *J. Geophys. Res. Atmos.*, vol. 118, no. 19, pp. 11098–11106, 2013.

[5] A. C. V. Saraiva, L. Z. S. Campos, E. R. Williams, G. S. Zepka, J. Alves, O. Pinto, S. Heckman, T. S. Buzato, J. C. Bailey, C. A. Morales, and R. J. Blakeslee, "High-speed video and electromagnetic analysis of two natural bipolar cloud-to-ground lightning flashes," *J. Geophys. Res. Atmos.*, vol. 119, no. 10, pp. 6105–6127, May 2014.

[6] L. Chen, W. Lu, Y. Zhang, and D. Wang, "Optical progression characteristics of an interesting natural downward bipolar lightning flash," *J. Geophys. Res. Atmos.*, vol. 120, no. 2, pp. 708–715, 2015.

[7] Y. Tian, X. Qie, G. Lu, R. Jiang, Z. Wang, H. Zhang, M. Liu, Z. Sun, and G. Feng, "Characteristics of a bipolar cloud-to-ground lightning flash containing a positive stroke followed by three negative strokes," *Atmos. Res.*, vol. 176–177, pp. 222–230, 2016.

[8] S. Xue, P. Yuan, J. Cen, Y. Li, and X. Wang, "Spectral observations of a natural bipolar cloud-to-ground lightning," *J. Geophys. Res. Atmos.*, vol. 120, no. 5, pp. 1972–1979, Mar. 2015.

[9] W. Lu, Y. Ma, Y. Zhang, J. Yang, W. Yao, D. Zheng, Q. Meng, and Y. Zhang, "Total-Sky Lightning Event Observation System and Method," US8902312B2, 2014.

[10] K. L. Cummins, M. J. Murphy, E. A. Bardo, W. L. Hiscox, R. B. Pyle, and A. E. Pifer, "A Combined TOA/MDF Technology Upgrade of the U.S. National Lightning Detection Network," *J. Geophys. Res.*, vol. 103, no. D8, p. 9035, 1998.

[11] V. A. Rakov and M. A. Uman, "Waveforms of first and subsequent leaders in negative lightning flashes," *J. Geophys. Res.*, vol. 95, no. D10, pp. 16561–16577, 1990.

[12] M. Rubinstein, J. Bermdez, V. Rakov, F. Rachidi, and A. Hussein, "Compensation of the Instrumental Decay in Measured Lightning Electric Field Waveforms," *IEEE Trans. Electromagn. Compat.*, vol. 54, no. 3, pp. 685–688, 2012.

[13] G. Diendorfer, H. Zhou, and H. Pichler, "Review of 10 years of lightning measurement at the Gaisberg Tower in Austria," in *The 3rd International Symposium on Winter Lightning (ISWL)*, 2011, pp. 185–190.

[14] H. Zhou, G. Diendorfer, R. Thottappillil, H. Pichler, and M. Mair, "Characteristics of upward positive lightning flashes initiated from the Gaisberg Tower," *J. Geophys. Res. Atmos.*, vol. 117, no. 6, pp. 1–13, 2012.

[15] V. A. Rakov and M. A. Uman, *Lightning: Physics and Effects*. Cambridge University Press, 2003.

[16] J. Montanyà, O. Van Der Velde, E. Williams, N. Pineda, D. Romero, and G. Solà, "Observation and properties of a sub-cloud bidirectional leader," in *XV International Conference on Atmospheric Electricity (ICAE)*, 2014.

[17] M. Stolzenburg, T. C. Marshall, S. Karunarathne, N. Karunarathna, and R. E. Orville, "Transient luminosity along negative stepped leaders in lightning," *J. Geophys. Res. Atmos.*, vol. 120, no. 8, pp. 3408–3435, Apr. 2015.

[18] M. M. F. Saba, W. Schulz, T. A. Warner, L. Z. S. Campos, C. Schumann, E. P. Krider, K. L. Cummins, and R. E. Orville, "High-speed video observations of positive lightning flashes to ground," *J. Geophys. Res.*, vol. 115, no. D24, p. D24201, 2010.

[19] D. M. Jordan, V. P. Idone, V. A. Rakov, M. A. Uman, W. H. Beasley, and H. Jurenka, "Observed dart leader speed in natural and triggered lightning," *J. Geophys. Res. Atmos.*, vol. 97, no. D9, pp. 9951–9957, Jun. 1992.

[20] Y. Zhu, V. A. Rakov, S. Mallick, and M. D. Tran, "Characterization of negative cloud-to-ground lightning in Florida," *J. Atmos. Solar-Terrestrial Phys.*, vol. 136, pp. 8–15, Dec. 2015.