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Bipolar cloud-to-ground lightning flash observations

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[1] Bipolar lightning is usually defined as a lightning flash where the current waveform exhibits a polarity reversal. There are very few reported cases of cloud-to-ground (CG) bipolar flashes using only one channel in the literature. Reports on this type of bipolar flashes are not common due to the fact that in order to confirm that currents of both polarities follow the same channel to the ground, one necessarily needs video records. This study presents five clear observations of single-channel bipolar CG flashes. High-speed video and electric field measurement observations are used and analyzed. Based on the video images obtained and based on previous observations of positive CG flashes with high-speed cameras, we suggest that positive leader branches which do not participate in the initial return stroke of a positive cloud-to-ground flash later generate recoil leaders whose negative ends, upon reaching the branch point, traverse the return stroke channel path to the ground resulting in a subsequent return stroke of opposite polarity.

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1. Introduction

[2] A lightning discharge is usually defined as bipolar lightning if it sequentially lowers both positive and negative charge to the ground.

[3] Most reported bipolar flashes are associated with upward lightning. Upward lightning flashes start with an upward leader and may or may not be followed by a dart leader-return stroke sequence. The upward lightning may show polarity reversal during the initial slowly varying (millisecond scale) current component produced by the upward leader propagation. If return strokes are present, they may have a different polarity from the initial current. The return strokes themselves may also be of different polarities [see, for example, *Rakov*, 2003; *Zhou et al.*, 2011]. In some past studies of upward flashes, the percentage of bipolar upward lightning can reach up to 20% of the total upward lightning [e.g., *Miki et al.*, 2004].

[4] Natural downward bipolar cloud-to-ground (CG) flashes are not as common, and very few events have been documented to date [*Nag and Rakov*, 2012]. These downward bipolar flashes can be divided into those that have return strokes of opposite polarity that occur in different channels (i.e., different termination points) and those that have return strokes of opposite polarity in the same channel. When strokes of different polarities occur in different channels, one could argue that they do not belong to the same flash but are two different flashes occurring close in time and space. This is not the case when strokes of different polarities use the same channel.

[5] There are very few cases of CG bipolar flashes using only one channel reported in the literature. Reports on this type of bipolar flashes are not common due to the fact that in order to confirm that currents of both polarities follow the same channel to the ground, one needs video records and simultaneous electric field measurements or lightning location systems that give reliable polarity identification as well as a reliable intracloud/CG discrimination.

[6] There appears to be only three cases of single-channel CG bipolar flashes reported in the literature. *Jerauld et al.* [2009] examined one natural bipolar lightning flash that produced two channel terminations to the ground and contained two positive return strokes (strokes 1 and 2) followed by four negative return strokes. All return strokes occurred within 1 km of an electric field measuring network at Camp Blanding, Florida. Return strokes 1 and 2 (both positive) were in separate channels, while return strokes 3 to 6 (all negative) followed the same channel as return stroke 2. The two positive return strokes were separated in time by approximately 53 ms, followed by a negative return stroke approximately 526 ms later. The interstroke intervals for strokes 3 to 6 were 280, 260, and 300 ms The National Lightning Detection Network (NLDN)-estimated peak currents for the first five strokes of the flash were +51, +50, −14, −14, and −10 kA. The sixth stroke (negative) was not detected by the NLDN. *Fleenor et al.* [2009], using video cameras (60 images per second) and electric field sensors, observed two bipolar flashes that occurred in the U.S. Both flashes began with a positive return stroke that was followed by a negative return stroke that used the same path to the

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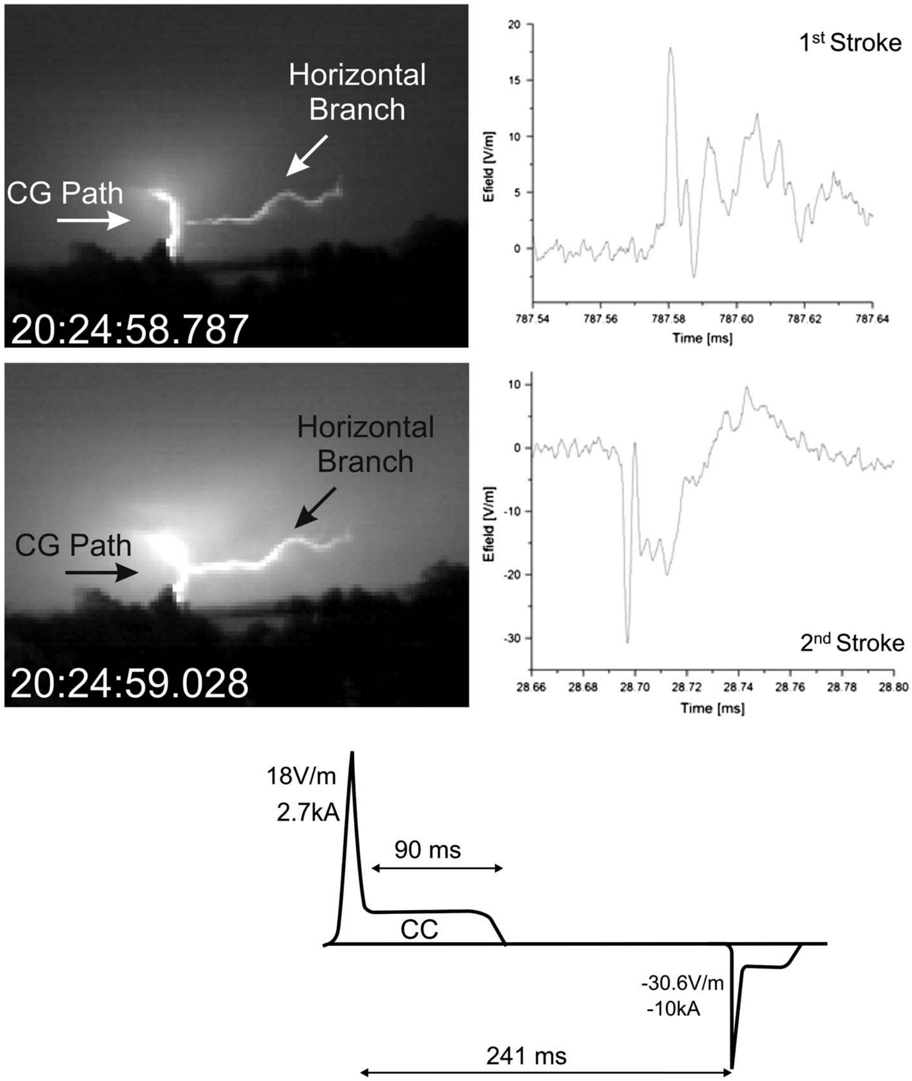

Figure 1. Video images and electric field variation produced by the first and second return strokes for Case 1. The estimated peak current and peak field for each return stroke, interstroke time intervals, and duration of CC are shown in the sketch and timeline below.

ground. The time intervals between the positive first and negative second return strokes were 43 ms for one flash and approximately 200 ms for the other. The magnitudes of the NLDN-estimated peak currents for all strokes were lower than 40 kA.

[7] The purpose of the present study has been to investigate the nature of the same channel of CG bipolar flashes. This study will analyze the common characteristics of five cases measured in S. Paulo, Brazil, and in South Dakota, U.S., between 2008 and 2012.

2. Instrumentation

[8] All bipolar flashes presented in this study were measured simultaneously by electric field sensors and high-speed video cameras. They were also detected by lightning location systems. A positive CG return stroke is a return stroke that travels up the leader path formed by a downward propagating positive leader after the leader connects with the ground. Utilizing the physics sign convention, which is used in this paper, the electric field change due to a positive CG return stroke is positive. Some characteristics of this instrumentation are described here.

2.1. Lightning Location Systems

[9] All flashes were recorded in locations covered by lightning location systems (BrasilDAT in Brazil and the NLDN in the U.S.). Further information about these nearly identical systems and their performance is given by *Naccarato and Pinto* [2009] and *Cummins and Murphy* [2009]. Data from the lightning location systems (LLS) were used to obtain an estimate of the locations of the ground strike points and the peak current in each stroke. Note that to date, there are not enough experimental data that can be used to evaluate errors in peak current estimates for positive return strokes.

2.2. Electric Field Sensor

[10] The measuring system for the electric field sensor consisted of a flat plate antenna with an integrator and amplifier. A GPS receiver is connected to a PC with two Peripheral

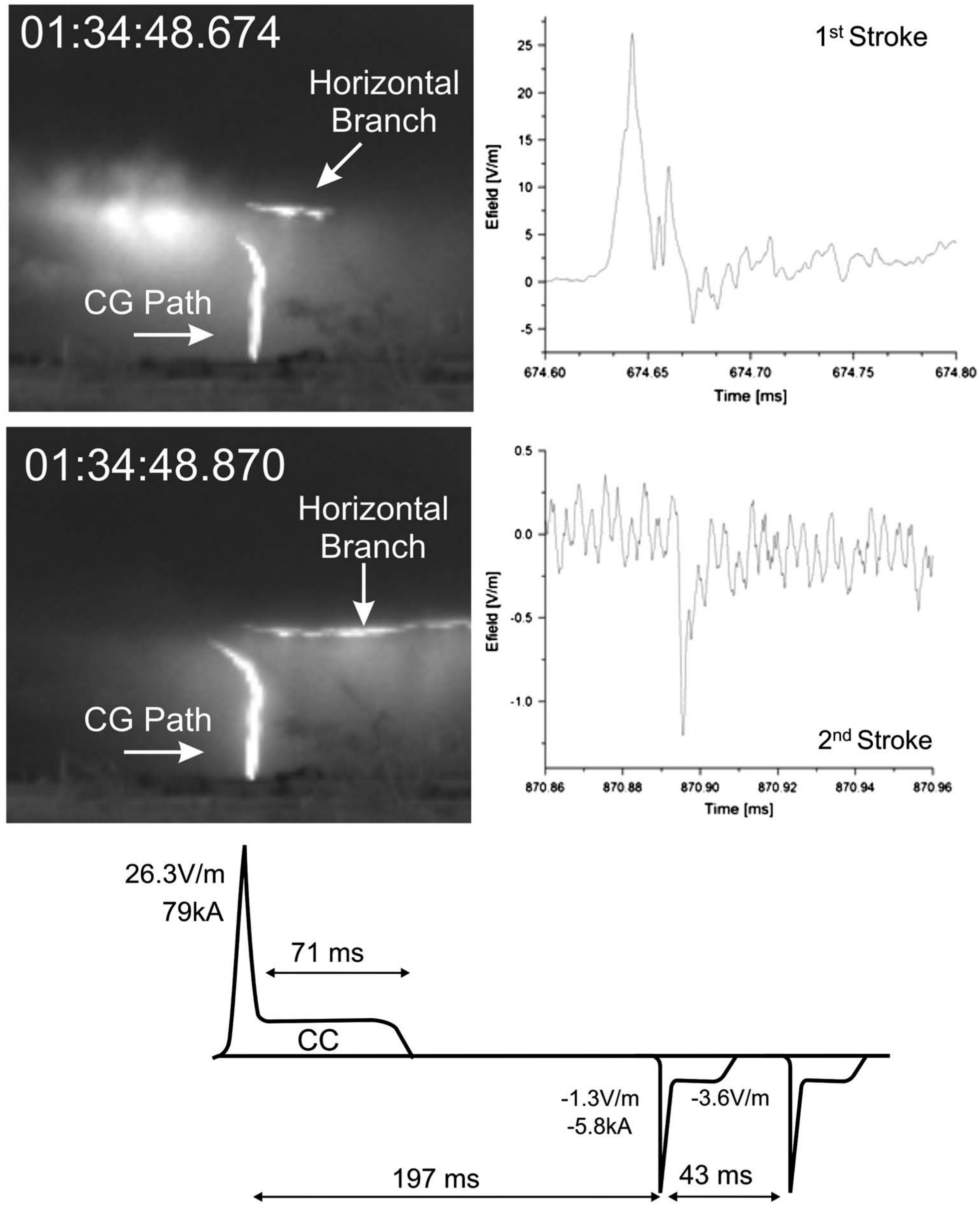

Figure 2. Video images and electric field variation produced by the first and second return strokes for Case 2 and a schematic of the timeline of these events.

Component Interconnect (PCI) cards (a GPS card Meinberg GPS170PCI and a 12 bit data acquisition card NI PCI-6110). The sampling rate of the waveform recording system was configured to operate at 5 MS/s on each channel. The lower frequency and upper frequency bandwidths of the system are 306 Hz and 1.5 MHz, respectively. The same type of measuring system has been used in Austria and Sweden and is described in detail by *Zhou et al*. [2012].

2.3. High-Speed Cameras

[11] Three different high-speed digital video cameras (Phantom v12.1, v310, and Photron Fastcam 512 PCI), with time resolutions and exposure times between 100 µs (10,000 frames per second) and 250 µs (4000 frames per second), have been used to record images of cloud-to-ground lightning in southeastern Brazil and South Dakota (USA). The minimum recording length of all the cameras was 2 s. All video imagery was recorded with a time-stamp accuracy of less than 1 ms. For more details about the measuring systems and about the use of high-speed camera for lightning observations, see the works by *Saba et al*. [2006] and *Warner et al*. [2012].

3. Observations

[12] We present video images and electric field waveforms of the first two return strokes for each of the five bipolar flashes observed. In all cases, the video confirmed that all strokes followed the same channel to the ground, and the E-field records confirmed the opposite polarities of the discharges. Video images and electric field waveforms together with a summary of all measurements (peak E-field and estimated peak current for the return strokes, duration of continuing current for the first stroke, and time interval

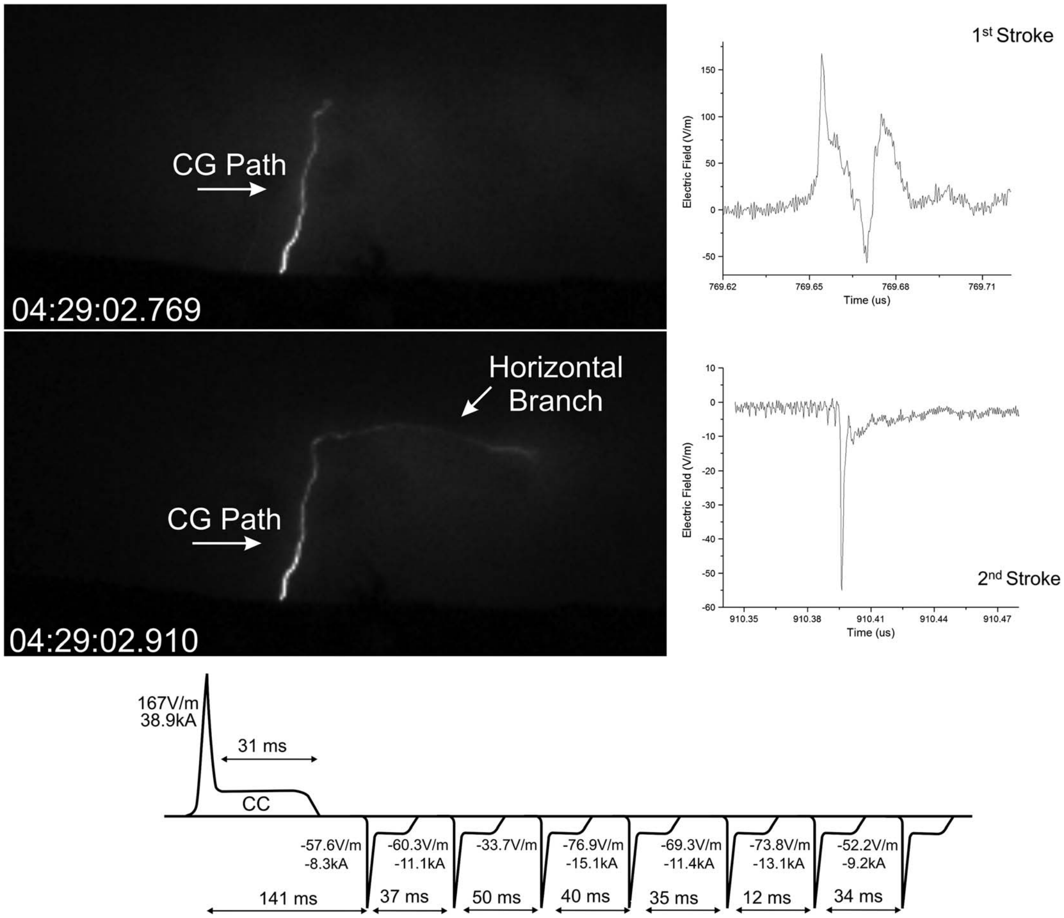

Figure 3. Video images and electric field variation produced by the first and second strokes for Case 3.

between strokes) are shown for each case. The interstroke time interval and electric field peaks are not in scale in the sketches shown for each case. The values given by the electric field sensor are not corrected for the attenuation or enhancement effects introduced by placing them close to or on top of buildings.

3.1. Case 1: Southeastern Brazil

[13] This flash occurred in southeastern Brazil (20:24:58 UT, 29 October 2008). All return strokes had their peak current estimated. According to BrasilDAT LLS, the return strokes occurred at a distance of 29 km from the video camera and the E-field system. The estimated peak current for the positive and the negative strokes were +2.7 and −10 kA, respectively. The return strokes were separated in time by 241 ms, and the first return stroke (positive) was followed by a continuing current lasting 90 ms. Figure 1 shows the images of the first and second return stroke of a cloud-to-ground bipolar flash and their respective E-field change; it also shows a summary of peak E-field and estimated peak current for the return strokes, duration of continuing current for the first stroke, and time interval between strokes.

3.2. Case 2: South Dakota

[14] This three-return stroke single-channel CG bipolar was recorded in Rapid City, SD, U.S. (01:34:48 UT, 3 July 2011). Analysis of NLDN data indicated that the return strokes occurred at a distance of 38 km from the video camera and 41.5 km from the E-field system. The first return stroke (positive, estimated peak current of +75.9 kA) was separated in time from the second return stroke (negative, −1.3 kA) by 197 ms and was followed by a continuing current lasting 71 ms (Figure 2). A third return stroke (negative, not recorded by the NLDN) occurred in the same channel 43 ms after the second return stroke.

3.3. Case 3: South Dakota

[15] This eight-stroke single-channel CG bipolar flash was observed in Rapid City (04:29:02 UT, 12 July 2012). According to NLDN LLS, the return strokes were located at a distance of 19.3 km from the video camera and 23.8 km from the E-field system. The first return stroke (positive, peak current of +38.9 kA) was separated in time from the second return stroke (negative, −8.3 kA) by 141 ms and was followed by a continuing current lasting 31 ms (Figure 3). The following negative return strokes (from third to eighth) had concurrent events recorded by the NLDN except for the fourth return stroke, which was observed by the high-speed camera, but there was no corresponding NLDN record.

3.4. Case 4: South Dakota

[16] This two-return stroke single-channel CG bipolar was recorded in Rapid City (05:24:41 UT, 18 July 2012; Figure 4). According to NLDN records, the return strokes occurred at a distance of 27.1 km from the video camera

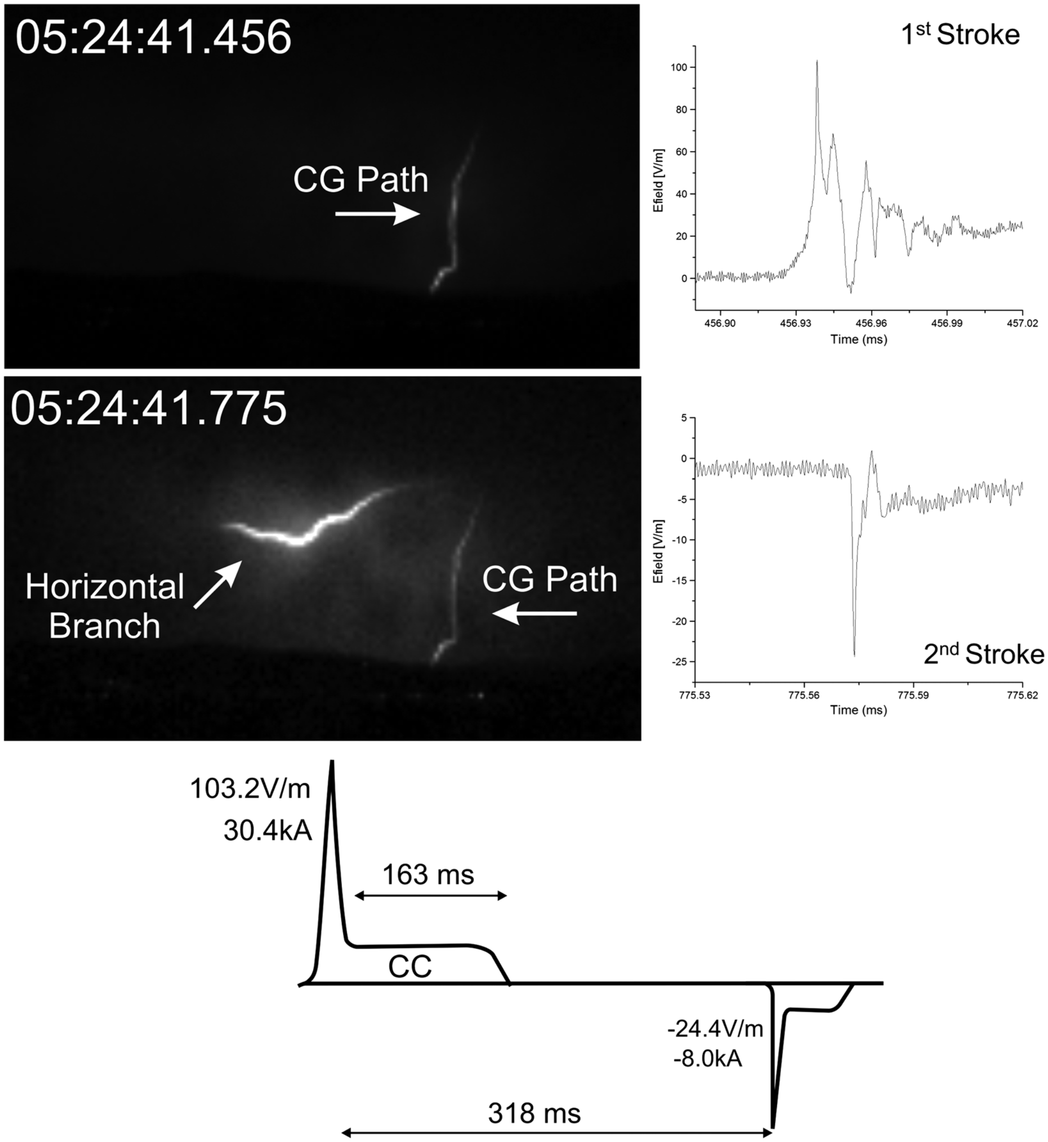

Figure 4. Video images and electric field variation produced by the first and second return strokes for Case 4.

and 27.0 km from the E-field system. The estimated peak current for the positive and the negative strokes were +30.4 and −8.4 kA, respectively. The return strokes were separated in time by 318 ms, and the first stroke (positive) was followed by a continuing current lasting 163 ms.

3.5. Case 5: South Dakota

[17] This bipolar lightning flash recorded in Rapid City (00:43:50 UT, 22 July 2012) produced two channel terminations to the ground and contained two positive return strokes (strokes 1 and 2) followed by two negative strokes (Figure 5). Strokes 1 and 2 (both positive) were in separate channels (i.e., separate termination points), while strokes 3 and 4, all negative, followed the same channel path as return stroke 2. The estimated peak currents for the first and second positive return strokes were 72.9 kA and 51.7 kA, respectively. The estimated peak currents for negative return strokes, which followed the same path created by the second positive return stroke, were −20.3 kA and −8.7 kA, respectively. Analysis of NLDN records indicated that the return stroke 2 and the subsequent negative return strokes occurred at a distance of 21.8 km from the video camera and 21.5 km from the E-field system.

4. Discussion and Conclusion

[18] Interestingly, all bipolar flashes observed in this study had very similar characteristics. Similar to the three cases previously reported in the literature [*Jerauld et al.*, 2009; *Fleenor et al.*, 2009], all of them initiated with a positive CG return stroke, and all were followed by a continuing current with duration longer than 31 ms (90, 71, 31, 163, and 125 ms). Also, in all cases, after the cessation of the continuing current, a no-current time interval longer than 110 ms (151, 126, 110, 155, and 122 ms) preceded the subsequent negative return strokes. The geometric mean of the no-current time intervals (132 ms) is 1.4 times larger than the average interstroke interval in positive CG flashes (94 ms

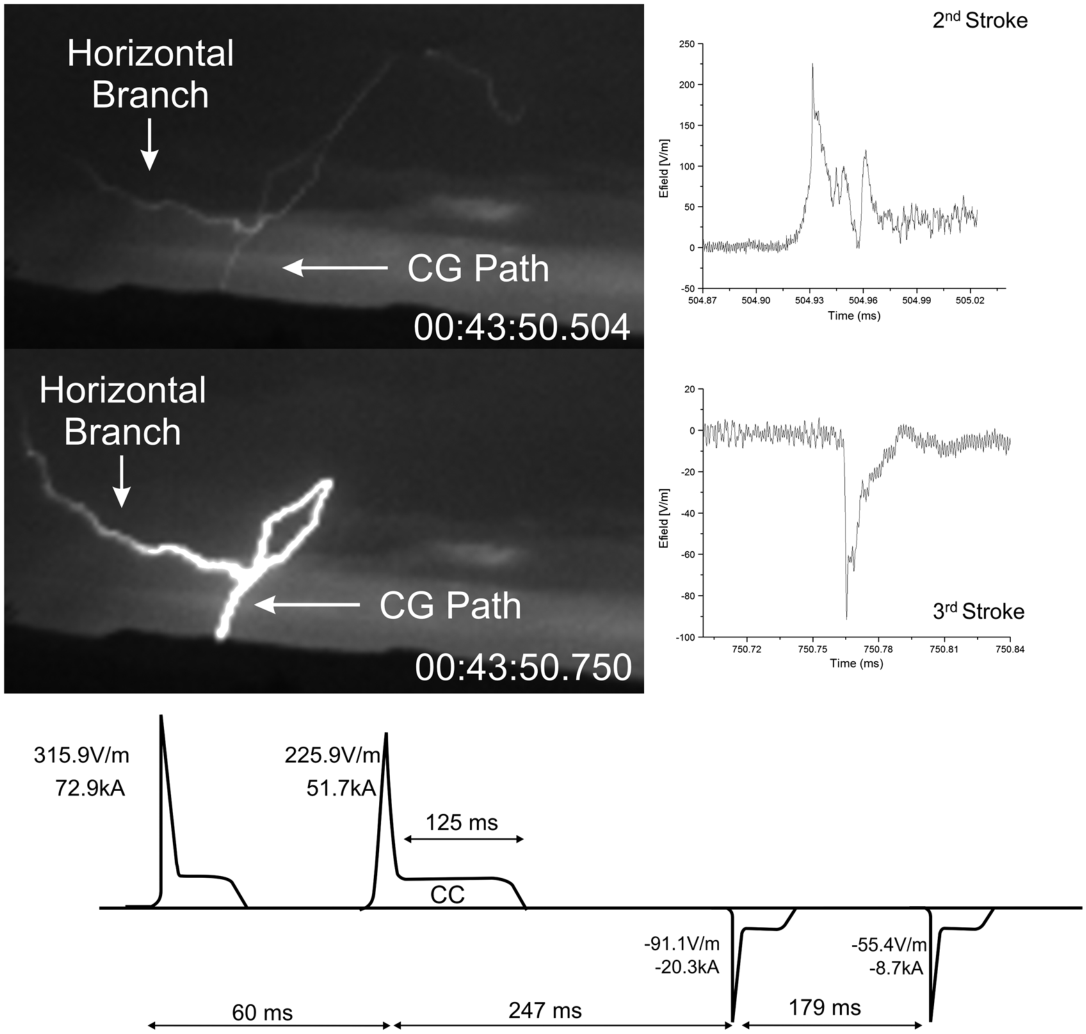

Figure 5. Video images and electric field variation produced by the second and third return strokes for Case 5.

as reported by *Saba et al*. [2010]) and 2.1 times larger than the average interstroke interval in negative CG flashes (61.5 ms as reported by *Saraiva et al*. [2010]).

[19] The similarity of all bipolar CG flashes mentioned in the previous paragraph suggests a common process that may explain how return strokes of different polarity traverse the same channel. The suggested common process will be explained in this section. In order to do this, we will analyze details of the Case 5 bipolar flash. This flash was recorded by two different high-speed cameras, and good quality of the images helps to follow the process described below. Figure 6 shows a sequence of high-speed video frames prior to each of the two positive return strokes (each of which had different termination points) and the first negative return stroke, which occurred in the channel path of the second positive return stroke. Figure 7 shows a more detailed high-speed video sequence of the events prior to the negative return stroke.

[20] Figure 6a shows three downward propagating positive leaders. The middle positive leader connects with the ground in Figure 6b causing a positive CG return stroke (NLDN indicated +72.9 kA estimated peak current). The first positive return stroke channel decays and is no longer visible in Figure 6d. However, the left positive leader, which did not participate in the first return stroke, continues to propagate toward the ground as seen in Figures 6d–6g. A branch from the left positive leader is visible in Figure 6d, and this branch propagates to the left out of the field of view of this particular camera. In Figure 6h, the left positive leader connects with the ground forming a positive CG return stroke (NLDN indicated +51.7 kA; sensor trace shown in the top right of Figure 5). The return stroke channel path is visible in Figure 6i following the decline of the saturating bright luminosity of the return stroke seen in Figure 6h.

[21] Recoil leaders (RLs) are bipolar leaders that form on a positive leader branch that has been cut off from the main positive leader channel from which it branched [*Mazur et al*., 2013]. The RLs initiate in trail of the positive leader branch tip and develop in a bipolar/bidirectional manner in an attempt to reionize and reconnect the cutoff branch. The negative end of the RL (RLNE) propagates in a retrograde direction away from the advancing positive leader branch tip and toward the branch point. A dart leader occurs when a RL follows the channel all the way to the ground [*Mazur*, 2002; *Mazur et al*., 2013].

[22] In Figure 7, a sequence of video images shows the initiation and development of a RL that formed on a previously

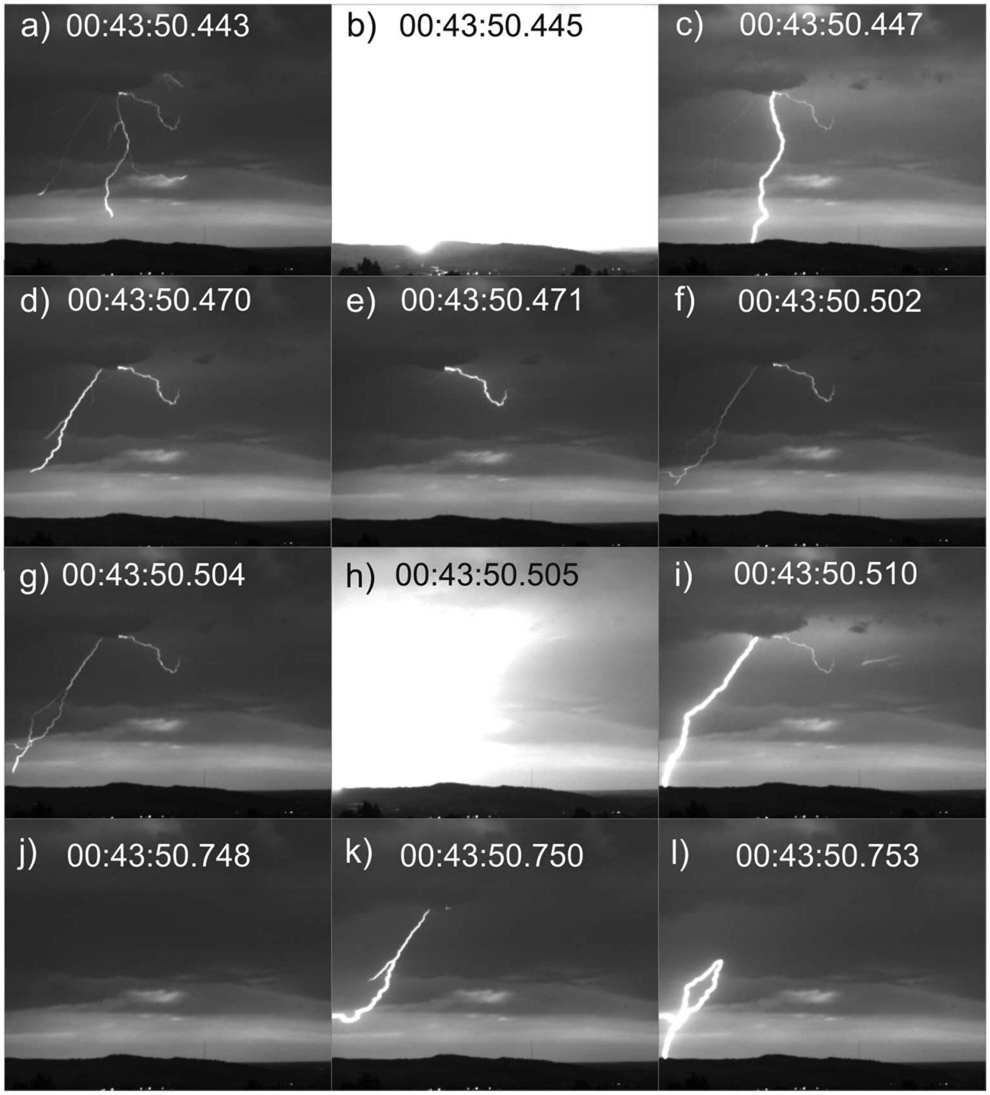

Figure 6. Contains a sequence of high-speed video images that encompass the first two positive CG return strokes and negative return stroke.

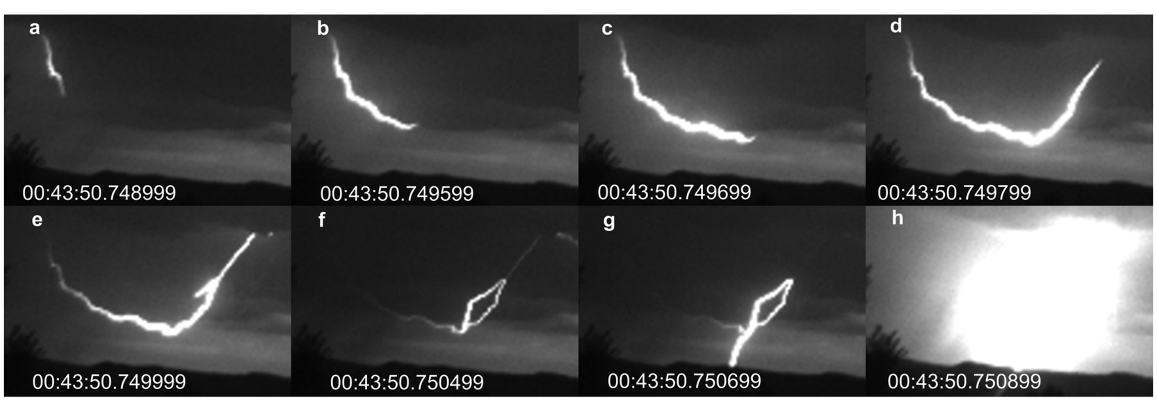

Figure 7. Sequence of high-speed video images from Case 5 showing the initiation and development of a RL along the path of a previously formed positive leader branch. The RLNE travels to the right and upon reaching the branch point, travels down the previous return stroke channel path and connects with the ground forming a negative return stroke.

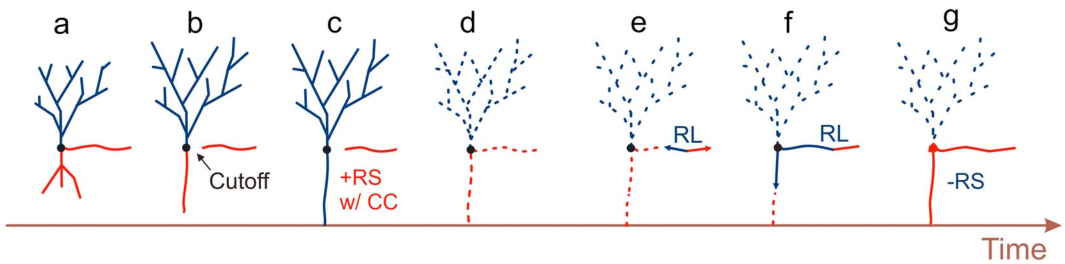

Figure 8. Sequence of events that could explain the occurrence of a bipolar single-channel flash: (a) bidirectional leader propagation (positive leaders in red and negative leaders in blue), (b) cutoffs may occur before the return stroke leaving segments of the positive leader disconnected, (c) return stroke and continuing current occur, (d) channel decay, (e–f) recoil leader retraces the decayed channel and propagates to the ground, and (g) negative return stroke.

established horizontal positive leader branch that formed from the left positive leader shown in Figures 6d–6g. At the time of the second positive return stroke, this horizontal positive leader branch was apparently decayed (cut off) from the main positive leader branch so that it did not participate in the return stroke (i.e., return stroke luminosity did not extend out the horizontal branch). At 250 ms following the second positive CG return stroke, a RL formed on the horizontal branch (Figure 7a), and the RL negative end traveled back to the branch point (Figures 7b–7e) and then propagated downward to the ground using the same channel path of the previous positive return stroke (Figures 7e–7g). Upon reaching the ground, the RLNE caused a negative return stroke (Figure 7h), which is reflected by the negative field change in the sensor (see lower right field change trace in Figure 5), and had a correlated −20.3 kA NLDN event.

[23] Video and electric field evidence suggests that the same sequence of events was found in the other four cases. Specifically, a positive leader branch formed from the main downward propagating positive leader prior to the first positive return stroke. The positive leader branch traveled horizontally near the cloud base and did not participate in the return stroke. Following the decay of the positive return stroke, a RL formed on the horizontal branch, and the RLNE traveled back to the branch point and down to the ground following the previous return stroke channel path. When the RLNE connected with the ground, a negative return stroke occurred. In all cases presented, it was possible to observe that the horizontal branch retraced by the RL was present before the positive return stroke.

[24] The cutoff of the horizontal positive leader branch (Figures 8a and 8b) makes possible the occurrence of the recoil leader that retraces it (Figure 8e). In addition, it is not uncommon to see recoil leaders retracing horizontal channels after a positive return stroke, as shown in Figure 6d, but in order for this flash to become bipolar, the RLNE must find a way down to the ground. In high-speed videos, we see that sometimes RLs fade before reaching the positive leader branch point from the main channel or may, upon reaching the branch point, go upward into the upper portion of the decayed flash. So the RLNE must reach the main channel and move toward the ground to form a subsequent negative CG return stroke (Figures 7 and 8f). Furthermore, the RLNE must occur before the residual conductivity in the return stroke channel decays beyond the point that it provides a favorable path to the ground.

[25] As far as we know, there is no report in the literature of a single-channel CG bipolar flash having a first return stroke of negative polarity. There are some reasons that may require a bipolar flash to be initiated by positive discharges:

[26] 1. Contrary to what is usually observed in negative CG discharges, positive CG flashes often involve long, horizontal channels, up to tens of kilometers in length [e.g., *Fuquay*, 1982; *Kong et al*., 2008; *Saba et al*., 2008, 2009, 2010]. Frequently, these channels are formed by positive leaders that propagate horizontally at or near the cloud base instead of propagating downward and connecting with the ground.

[27] 2. According to *Heckman* [1992], these long horizontal channels are unstable and contribute to the current cutoff. This current cutoff and resulting floating conductor can result in the development of recoil leaders. [*Mazur*, 2002; *Mazur et al*., 2013].

[28] 3. The negative subsequent return stroke has its origin in RLs that retrace the paths of previously formed horizontal positive leader branches. An opposite situation, that is, a positive subsequent return stroke following a negative return stroke is likely not viable given that RLs 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 [*Mazur and Ruhnke*, 2011 and *Mazur et al*., 2013].

[29] The reason why bipolar single-channel flashes are rare is probably due to the combination of factors that are needed for its occurrence. The horizontal branch formed by the positive leader branch must cut off from the main positive leader channel before the positive return stroke. This keeps the horizontal branch from participating in the positive return stroke (Figures 6c, 6i, and 8c).

[30] In conclusion, the present study presents several common characteristics in single-channel cloud-to-ground bipolar flashes and a hypothesis that explain its occurrence. These characteristics shed some light into the physics of the lightning processes for positive and negative ground flashes. More observations of single-channel CG bipolar flashes with expanded instrumentation such as a Lightning Mapping Array are needed to confirm the hypothesis presented.

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