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Leader/return-stroke-like processes in the initial stage of rocket-triggered lightning

R. C. Olsen III,[1] V. A. Rakov,[1] D. M. Jordan,[1] J. Jerauld,[1] M. A. Uman,[1] and K. J. Rambo[1]

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[1] Linear streak film, video, current, and electric field records from nine triggered-lightning flashes are analyzed to examine the process of cutoff and reestablishment of current during the initial stage of rocket-triggered lightning. All of the data were acquired at the International Center for Lightning Research and Testing at Camp Blanding, Florida, in 2002 and 2003. It is shown that in some rocket-triggered lightning events, the process of current cutoff and reestablishment during the initial stage is similar to a leader/return-stroke sequence, although the currents in this process are typically an order of magnitude smaller (1 kA or so) than those in a triggered or natural lightning subsequent stroke (10–15 kA). The events were separated into two groups based on observed characteristics, with the duration of the current cutoff interval being the primary differentiating characteristic. In some cases, two or three failed attempts at current reestablishment prior to the successful resumption of current flow in the channel were observed. Currents associated with the unsuccessful attempts were typically an order of magnitude smaller (100 A or so) than in the process which finally reestablished the current.

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1. Introduction

[2] The propagation characteristics of lightning leaders and return strokes have most often been studied using time-resolved optical records. Researchers using the Boys drum film camera and linear streak film camera [e.g., *Malan and Collens*, 1937; *McEachron*, 1939; *Schonland*, 1956; *Idone and Orville*, 1982; *Jordan*, 1990] have made significant contributions to the basic understanding of these and other lightning processes. The relatively short record length of streak cameras and random occurrence make capturing records of natural lightning difficult. There has been growing interest in the use of the rocket-and-wire technique in lightning research, in which a small (~1 m) rocket trailing a grounded wire is used to initiate a lightning flash [e.g., *Fieux et al.*, 1975; *Rakov*, 1999]. This allows the researcher to have advance knowledge of the time and location of a lightning flash, and hence of the exact distance to the termination point of the lightning channel. The exact distance is needed for calculation of heights along the lightning channel, which in turn are required for estimation of propagation speeds. Each rocket-triggered flash is composed of the initial stage (IS) and typically one or more leader/return-stroke sequences (strokes). Strokes in a rocket-triggered flash are similar to subsequent strokes in a naturally occurring flash, while the IS does not occur in a naturally occurring downward flash. For this reason, most of the attention in triggered-lightning research has been attracted to leader/return-stroke sequences, and the initial stage remains considerably less studied.

[3] The IS of a rocket-triggered lightning flash consists of an Upward Positive Leader (UPL) launched from the top of the wire trailing behind the rocket and the initial continuous current (ICC). The ICC typically reaches some hundreds of amperes in magnitude and lasts some hundreds of milliseconds. The triggering wire is typically vaporized during the UPL (early in the IS) with the associated current signature being referred to as the initial current variation (ICV) [*Wang et al.*, 1999]. The ICV is typically characterized by a slow (GM 8.6 ms per *Wang et al.* [1999]) rise in current magnitude up to some hundreds of amperes, followed by a relatively rapid (hundreds of microseconds) reduction of the current to near zero, as illustrated in Figure 1. Following this reduction, current may remain at or near zero for up to some milliseconds before current flow is reestablished in the lightning channel by a pulse with relatively fast risetime (100 microseconds or less) and relatively large amplitude, typically 1 kA or so. The time interval which begins with the onset of current reduction (point A in Figure 1) and which ends with the reestablishment of current (point B2 in Figure 1) will be referred to herein as the current interruption interval (CII). The destruction of the wire effectively disconnects the UPL from the ground, and the pulse at the end of the current interruption interval serves to reconnect the UPL to ground by creating a plasma channel in place of the triggering wire. The total ICV duration is reported to not exceed 10 ms by *Wang et al.* [1999].

[4] In this paper, we examine properties of the process of current cutoff and reestablishment during the Initial Stage of

[1]Department of Electrical and Computer Engineering, University of Florida, Gainesville, Florida, USA.

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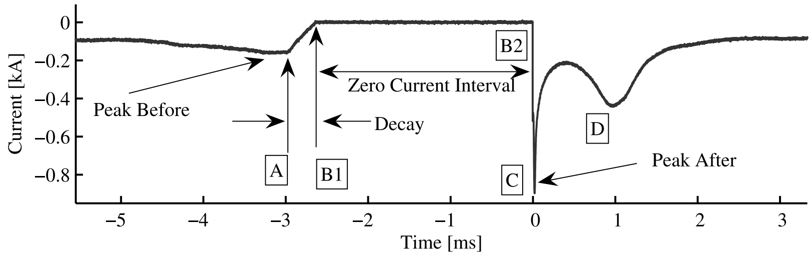

Figure 1. Definitions of the various features of ICV waveforms. A typical ICV waveform will exhibit a relatively slow increase in current magnitude to a maximum of some hundreds of amperes, which generally but not always coincides with the beginning of current decay, shown here at point A. The relatively rapid current reduction between points A and B1 is associated with the explosion of the triggering wire. The interval between B1 and B2 can vary between some hundreds of microseconds to some milliseconds, during which little or no current flows. There may be small pulses (not seen in this figure) during this interval. At point C, a relatively large and sharp pulse reestablishes current between the UPL and ground. For the purposes of estimating charge and action integral (AI), current is integrated over the interval between the beginning of the record (which is prior to the beginning of the initial stage, when no current is flowing) and the time labeled B1 on the waveform. "Peak before" denotes the peak current prior to wire explosion, which is generally but not always observed at the onset of current reduction at point A. "Decay" denotes the duration of the time interval during which the current decays to or nearly to zero, between points A and B1 on the diagram. "Zero current interval" denotes the duration of the time interval over which the current is equal to (or nearly equal to) zero, represented by the interval between B1 and B2. "Peak after" denotes the maximum current in the pulse (shown at point C) associated with reconnection of the UPL to ground. The secondary current pulse, labeled D, is discussed in section 3.4.

rocket-triggered lightning based on analysis of nine flashes whose current records exhibit an ICV with pronounced current interruption interval. Two types of current interruption interval have been identified. This study can be viewed as an extension of that of *Rakov et al.* [2003], who had previously observed similar processes in the records of three flashes, data for two of which consisted of electric field and magnetic field records and for the remaining one of which consisted of electric field, incident current, and streak photographic records. Using these records, *Rakov et al.* [2003] determined that the process of reestablishing current in a rocket-triggered lightning involved a leader/return-stroke-like sequence similar to that observed in so-called altitude-triggered lightning [*Rakov*, 1999], or inferred to occur in natural lightning when current is cut off close to the ground. On the basis of this determination, the data set presented in this paper was examined with an eye toward further investigating the phenomenon identified by *Rakov et al.* [2003].

2. Instrumentation

[5] All records discussed herein were obtained during triggered-lightning experiments at the International Center for Lightning Research and Testing (ICLRT) at Camp Blanding, Florida. The research site occupies approximately 1 km^2 on the grounds of Camp Blanding, a Florida Army National Guard base, and is operated by the University of Florida (since 2005 jointly with the Florida Institute of Technology). Three of the flashes discussed were triggered from a stationary tower launcher located approximately in the center of the site. The remaining six were triggered from a mobile launching platform, placed at two different locations within the research site. Lightning triggering was done using a 750 m spool of Kevlar-covered copper wire, about 0.2 mm in diameter, attached to a small (about 1 meter) solid-fuelled rocket. The launch locations and techniques are described in more detail by *Olsen* [2003].

[6] All streak records were obtained with a Visual Instrument Corp. Hytax II linear streak film camera, based on a Redlake design. The camera was loaded with 152.4 m of 35 mm Kodak film for each record. Two records were obtained using Linagraph Shellburst film, emulsion 2476. The remaining four records were obtained using SO-033 Hawkeye film. The film transport speed was 38.1 m s^{-1}, and a 5 kHz pulse generator drove an LED which illuminated the edge of the film to create timing marks. The objective was a Nikon 50 mm lens. After development, the film was digitized using an Epson Perfection 3200 scanner at 126 pixels per mm (3200 dpi) and 16-bit gray scale depth. Enhancement and analysis of the images were performed using Matlab.

[7] All current measurements were performed by measuring the voltage across a series resistor (shunt) in the lightning current path near ground. The resultant signal was recorded on a Yokogawa DL716 digitizing oscilloscope that sampled at either 1 MHz or 2 MHz, and at 12 bits per sample.

[8] Electric field records were obtained for two flashes (F0331 and F0350) using a circular flat-plate antenna whose area was approximately 0.16 m^2. The waveform was sampled at 10 MHz and 12 bits per sample. The distances from the antenna to the lightning termination points were 120 m and 220 m for F0331 and F0350, respectively.

3. Data and Analysis

[9] The events whose salient features were examined are listed in Table 1. It is notable that not every rocket-triggered lightning event contains the leader/return-stroke-like processes during the initial stage.

3.1. Leader-Like Processes in Streak Camera Records

[10] Leader-like processes were observed in the section of streak record corresponding to the IS of 5 different flashes.

Table 1. Availability of Streak, Video, and E Field Records for Events With Pronounced Current Interruption Intervals[a]

Flash	Streak Record?	Other Records?	Notes
F0220	yes		visible leader-like process
F0226	no	video	UPL development
F0301	yes		observed wire destruction; faintly visible leader
F0331	no	E field	leader/return-stroke-like signature in E field
F0336	no		small pulse during CII
F0341	yes		two small pulses during CII in current and streak records; leader-like process
F0345	yes		two small pulses during CII, UPL development in current and streak records; leader-like process
F0348	yes		two small pulses during CII in current and streak records; leader-like process
F0350	yes	E field	small pulse during CII in current, streak, and E field records

[a]CII, current interruption interval, defined as the interval between A and B2 in Figure 1. UPL, upward positive leader.

Three flashes, F0220, F0301, and F0345, exhibited leader-like processes during the IS which were visible but not well resolved. Contrast enhancement improved the visibility of these processes. In two flashes, F0341 and F0348, the presence of these processes was clear and unequivocal without contrast enhancement. Figure 2 shows, as an example, the segment of streak record containing the image of a leader-like process during the IS of flash F0341. There is no luminosity visible above the top of the triggering wire, which suggests that relatively low current is flowing in the UPL. The process appears to include a downward propagating ‘‘leader’’ and an upward propagating ‘‘return stroke.’’ Observation of a leader-like process during the IS in a streak camera record was previously reported by *Rakov et al.* [2003]. However, the leading edge of that leader was poorly defined, so that the authors could not identify downward progression of the leader for heights greater than 64 m above ground. *Rakov et al.* [2003] noted a decrease in luminosity above the top of the triggering wire at the time of its destruction and development of the leader.

3.2. Classification of Current Interruption Intervals in Current Records

[11] Observation of not well-resolved leader-like processes in the streak records of flashes F0220, F0301, and F0345 motivated the examination of channel base current records associated with these and other flashes. Nine events were found in which the IS exhibited a pronounced current interruption interval. These nine events could be divided into two distinct groups based upon two aspects of the current variation during the current interruption interval. The larger group, consisting of flashes F0220, F0331, F0336, F0341, F0348, and F0350, will be referred to as type I events. The smaller group, containing flashes F0226, F0301, and F0345, will be referred to as type II events.

[12] Six type I events featured current interruption interval in which the current decreased approximately linearly toward zero over a period of some hundreds of microseconds, and then flattened abruptly at zero level. The exception was flash F0350, in which the current decay slowed abruptly at about 5 A and then continued linearly over about 1 ms to zero. Current was then reestablished by a relatively sharp pulse, similar in shape to a return stroke pulse, with a peak between 200 and 2500 A. The duration of the interval over which current was zero was greater than 1 ms and less than 4 ms in all six cases. The current interruption interval in flash F0220 is shown in Figure 3a. The primary characteristics which denote a current interruption interval as being of type I are the rapid current decay to zero (or nearly zero) and the duration of the current interruption interval being greater than 1 ms.

[13] Three type II events featured current interruption interval in which the onset of current reduction was more gradual than in type I events. The decay of current lasted for some hundreds of microseconds but was generally faster

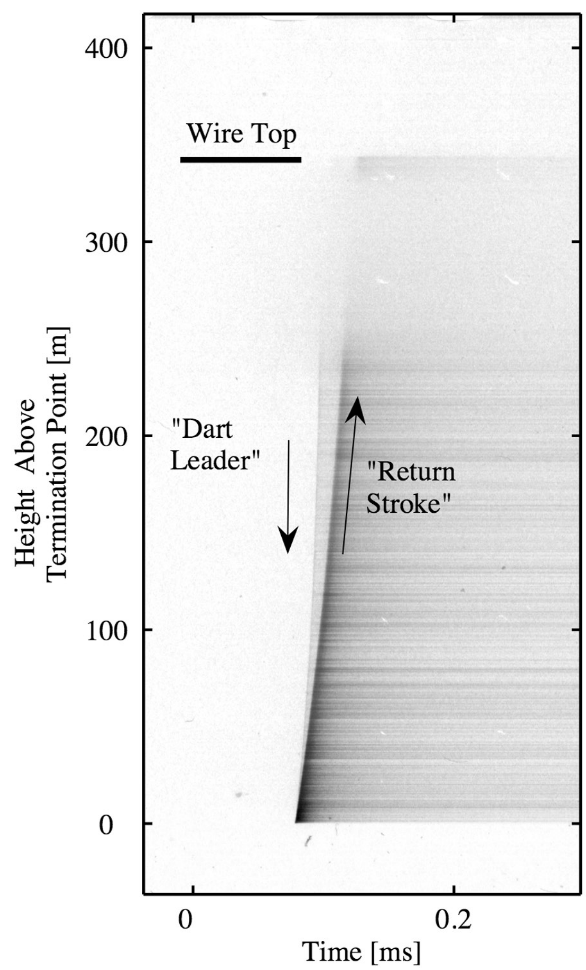

Figure 2. Leader-like process (labeled ‘‘dart leader’’) during the IS of flash F0341. Also seen is the return-stroke-like process during the IS (labeled ‘‘return stroke’’). Directions of propagation are shown by arrows.

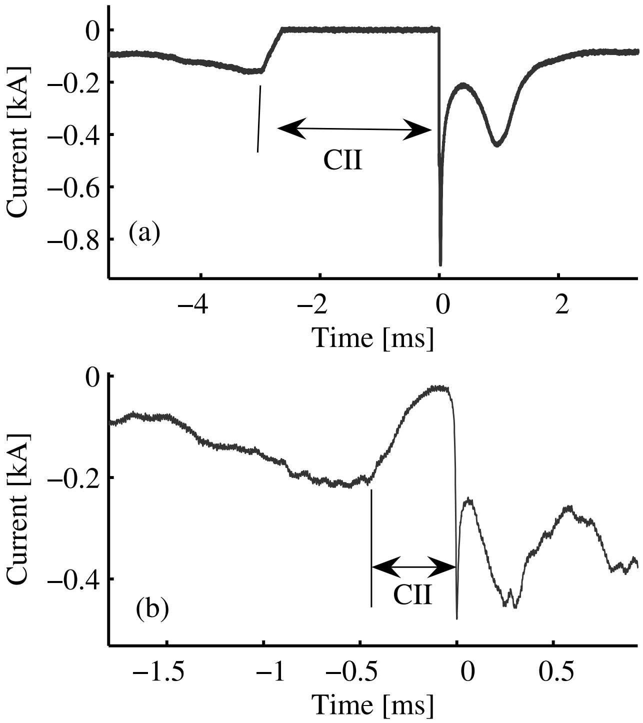

Figure 3. Type I and type II events that differ by shape and duration of the current interruption intervals. (a) Type I current interruption interval, flash F0220. (b) Type II current interruption interval, flash F0226.

than in type I events and resembling exponential, and most importantly current did not flatten abruptly at zero level. These events were characterized by a relatively short period of reduced current associated with the destruction of the wire compared to type I events, as discussed below. An example of a type II event is shown in Figure 3b. It was very difficult to identify the current decay (A to B1 in Figure 1) in the overall current interruption interval for type II events. For the three type II events in this data set, the interval between the onset of current reduction (A in Figure 1) and the reestablishment of current (B2 in Figure 1) varied between about 180 μs and about 500 μs, which was considerably shorter than the A to B2 interval in type I events. A complete cessation of current flow was not observed in two of the events, F0226 (See Figure 3b) and F0301, but instead the current settled gradually to a level of approximately 20 A. The current in flash F0345 initially followed a similar scenario of current reduction as in flashes F0226 and F0301, settling toward a nonzero level, but appeared unable to maintain this steady level and abruptly cut off some 350 μs after the onset of current reduction. All three events examined by *Rakov et al.* [2003] belong to type II, as defined above.

3.3. Pulses During the Current Interruption Interval

[14] While examining zero current intervals in the channel base current records, for purposes of classification, it was observed that several current interruption intervals contained additional current pulses occurring between the reduction of current and the reestablishment of current, as illustrated in Figure 4. The pulses were characterized by a risetime on the order of 1 μs or less, and peak currents varied between 40 and 251 A in the nine such pulses examined. It is notable that of the six events classified herein as type I events, only flash F0220 (see Figure 3a) did not contain these pulses; of the three events classified as type II events, only flash F0345 contained such pulses, but flash F0345 was the only type II event in which the current was observed to reach zero level. *Rakov et al.* [2003], who analyzed three type II events, did not observe any pulses during the current interruption interval in their optical, current, or field records.

[15] The observation of additional, smaller pulses in the current records led to the question of whether such pulses were associated with enhancements in channel luminosity. The streak film records were examined in the regions corresponding to these pulses. The contrast of the streak images was enhanced using false color mapping, and several streak images corresponding to these small pulses became faintly visible. Figure 5 shows the enhanced streak record for event F0348 time-aligned with the current record, the latter being an expansion of the current record shown in Figure 4. An optical phenomenon coinciding with the second current pulse is clearly visible, and a similar phenomenon coinciding with the first pulse is barely visible. These pulses appear to traverse the gap produced by the destruction of the wire. We will refer to the final pulse, which is associated with reestablishment of current between the UPL and ground, as a reconnection pulse (RP), and the pulses during the current interruption interval which traverse the same gap but fail to reestablish current flow as attempted reconnection pulses (ARP).

[16] Although a leader-like process can clearly be observed in association with (prior to) the reconnection pulse, no unambiguous leader-like processes can be observed in association with the two attempted reconnection pulses. This is unsurprising, as the luminosity of such a leader-like process would be much lower than that of the return-stroke-like pulse, which is itself barely luminous enough to be discernible in these records. Within this section of streak film, no luminosity is observed above the level of the top of the wire, but later sections of this streak record (not shown)

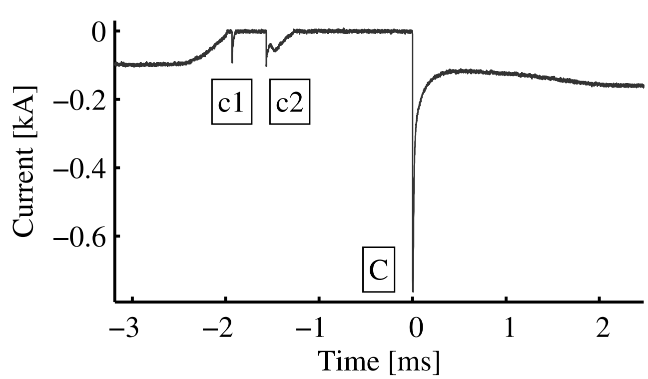

Figure 4. Current pulses, labeled c1 and c2, during the current interruption interval in flash F0348. These pulses have risetimes on the order of 1 μs and peak amplitudes on the order of 100 A. The pulse labeled C reestablishes current flow between the bottom of the floating UPL channel and ground and has amplitude on the order of 1 kA.

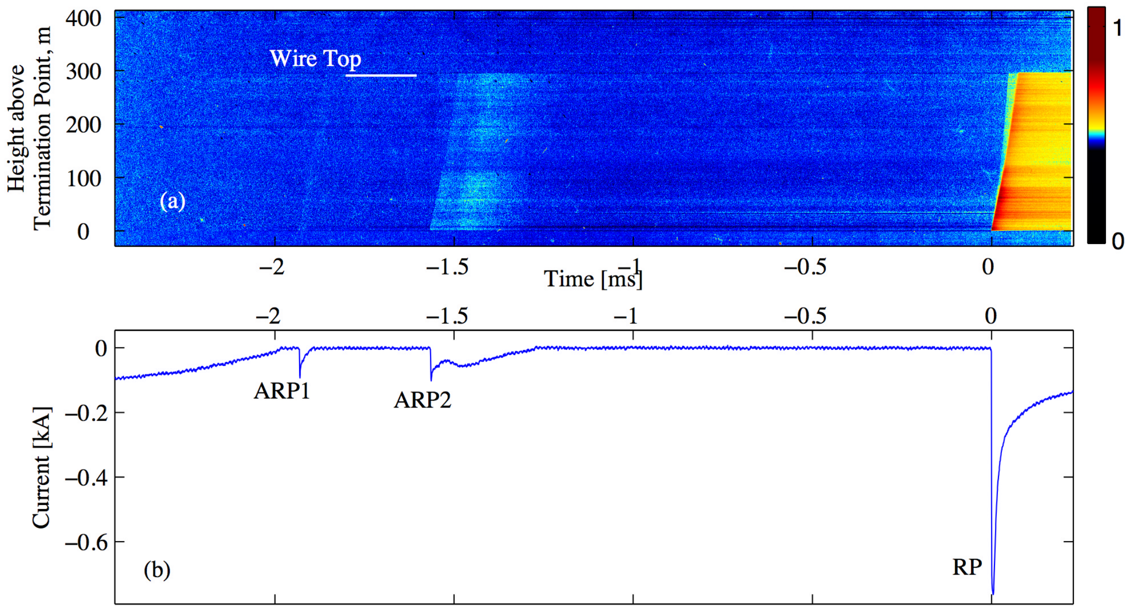

Figure 5. (a) Streak film and (b) channel base current records of flash F0348 showing two attempted reconnection pulses and a reconnection pulse (see section 3.3). The streak film record and channel base current record were manually aligned. The timescale for the current record is as recorded by the oscilloscope. The timescale for the streak record was obtained by examining timing marks (not shown) left on the film by the camera to determine the scaling factor, and then the offset was obtained by selecting the point of most rapid increase in luminosity at the channel base to be zero time for alignment with the current record. The color scale on the right is mapped to relative light intensity. The current record here is an expansion of the current record shown in Figure 4, with ARP1, ARP2, and RP corresponding to c1, c2, and C, respectively.

do exhibit luminosity above the wire top. This indicates that although the view of the region above the top of the wire is unobstructed, there is no discernible luminosity above the top of the wire during the attempted reconnection pulses and the reconnection pulse.

[17] We obtained electric field records for two events, F0331 and F0350, which exhibited attempted reconnection pulses during the current interruption interval. A streak film record was available for event F0350. Figure 6 shows an electric field record time-aligned with the channel base

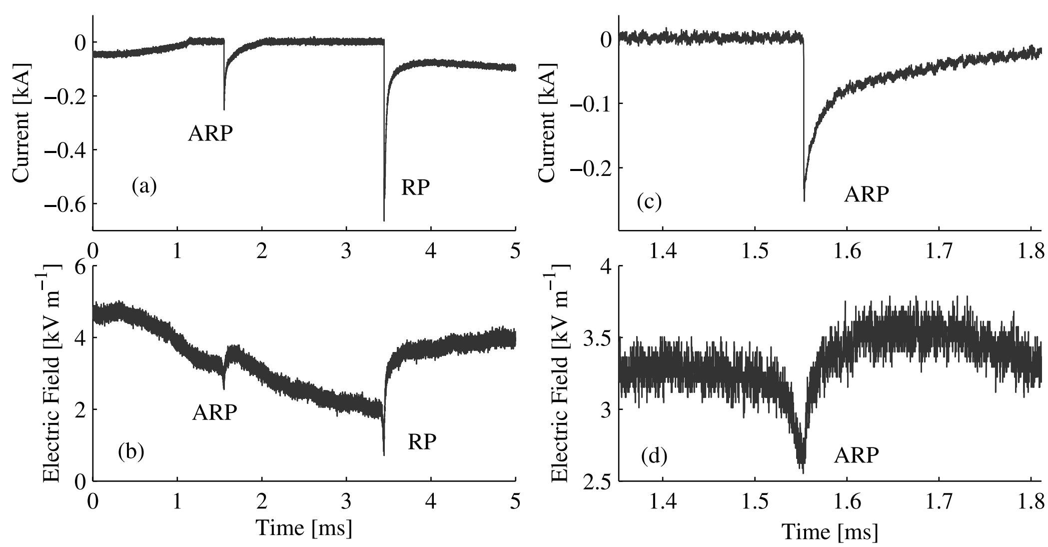

Figure 6. (a) Current of an attempted reconnection pulse during the current interruption interval and the reconnection pulse of flash F0331 and (b) the associated electric field. (c) and (d) Waveforms in Figures 6a and 6b on an expanded timescale centered around the attempted reconnection pulse. Current (Figures 6a and 6c) was measured at the lightning termination point. The electric field (Figures 6b and 6d) was measured at a distance of approximately 120 m from the lightning channel.

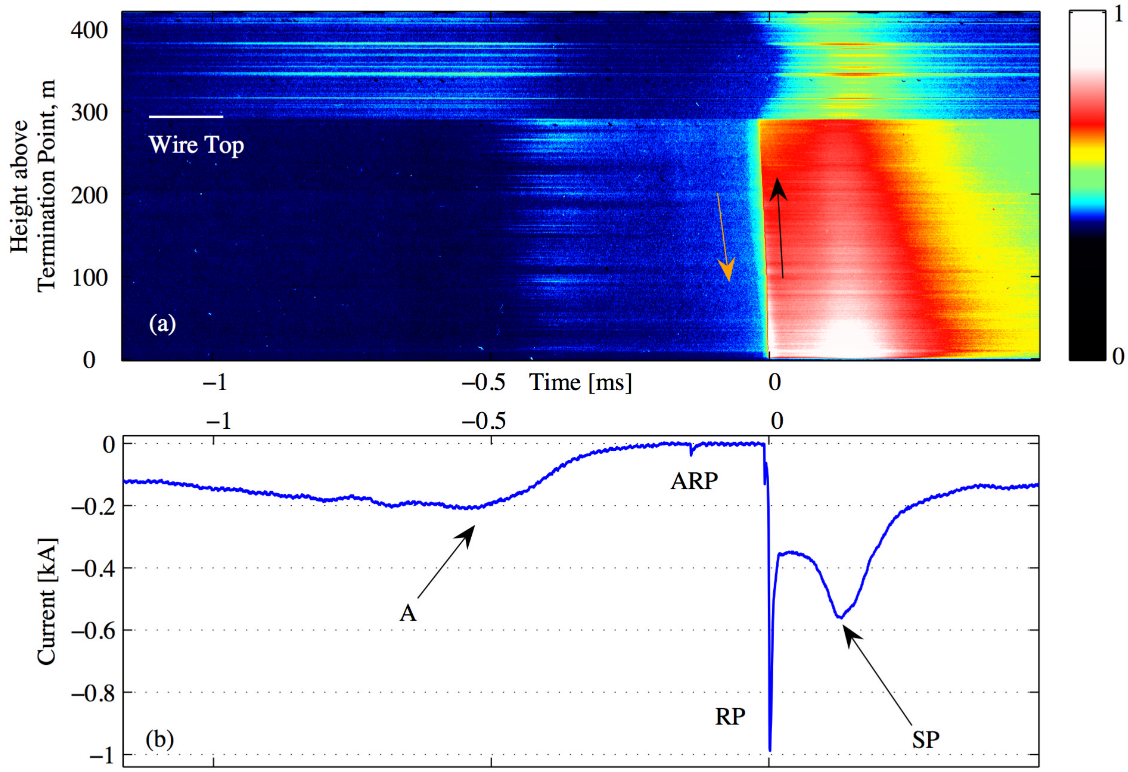

Figure 7. (a) Streak film record, color enhanced, and (b) current record for flash F0345. The streak film record and channel base current record were manually aligned. The color scale on the right is mapped to relative light intensity. One very small attempted reconnection pulse is observed in the current record but cannot be unambiguously resolved in the streak film record. The leader- and return-stroke-like processes of the reconnection pulse in the streak film record are indicated by a downward and an upward arrow, respectively. The beginning of the current interruption interval is labeled A, as in Figure 1, and the secondary pulse is labeled SP.

current record on two timescales for F0331. It can be seen that both an attempted reconnection pulse and the reconnection pulse are observed in both current and electric field records (see Figures 6a and 6b). When the timescale is expanded (see Figures 6c and 6d) to show, better resolved, the region of both records corresponding to the attempted reconnection pulse, it can be seen that the electric field contains a V-shaped signature similar to that which is normally associated with a leader/return-stroke or M component process at a close range (tens to hundreds of meters) [e.g., *Crawford et al.*, 2001; *Rakov et al.*, 2001]. This suggests that the attempted reconnection pulse, similar to the reconnection pulse, does include both a leader-like process and a return-stroke-like process. Further, the observed similarity in polarities between E field signatures of the attempted reconnection pulse and the reconnection pulse suggests that in both cases, leaders propagate downward and return strokes propagate upward.

[18] Given the apparent similarities between the observed reconnection pulses and dart leader/return stroke sequences, it is of interest to also investigate the propagation speeds of the leader and return stroke portions of the reconnection pulses. However, no return stroke propagation speed estimate can be made using a single-lens streak camera alone. Estimation of leader speeds made with a single-lens streak camera typically assume that the return stroke speed is much faster than the leader speed, and use the return stroke image as a reference. It is not unreasonable to assume that a similar relationship exists between the return stroke and leader speeds in reconnection pulses, but it is important to note that no direct evidence exists to support that assumption. On the basis of this unsupported assumption, a rough estimate of the leader speed may be found. For events F0220, F0341, F0345, and F0348, the leaders are sufficiently distinct to allow this analysis and the estimated speeds are 4.1×10^7 m s^{-1}, 1.5×10^7 m s^{-1}, 1.5×10^7 m s^{-1}, and 1.1×10^7 m s^{-1}, respectively. These speed values are comparable to those reported for regular dart leaders in rocket-triggered and natural lightning [e.g., *Jordan et al.*, 1992].

3.4. Optically Observed Upward Positive Leaders

[19] We now discuss the variation in luminosity of the UPL (above the wire-top level) using the streak film in conjunction with the current record of flash F0345, shown in Figure 7. For analysis, the rapid increase in luminosity at the channel base (observed in the streak record) is manually aligned with the reconnection pulse observed in the current record. The timescale for the current record is as recorded by the oscilloscope. The alignment was accomplished using the same procedure as that employed for aligning the

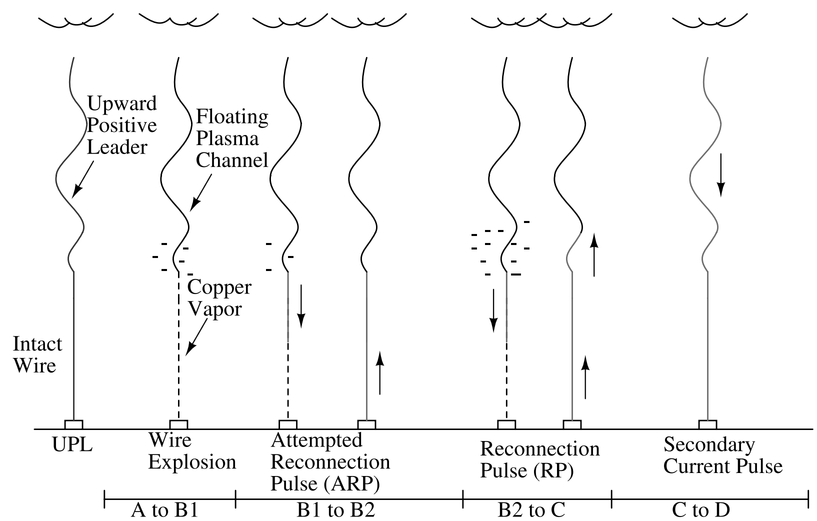

Figure 8. Diagram showing processes associated with explosion of the triggering wire and reconnection of the UPL to ground. The time intervals marked as A to B1, B1 to B2, and B2 to C correspond to the labeled points in Figure 1. During the period marked A to B1, the triggering copper wire is vaporized and the floating UPL channel polarized. Between B1 and B2, one or more attempted reconnection pulses may occur. No attempted reconnection pulse is shown in the current record of Figure 1, but attempted reconnection pulses are shown in the current records of Figures 4, 5, and 6 as well as being discussed in section 3.3. Between B2 and C, a RP occurs which serves to reconnect the UPL to ground. Between C and D, the secondary current pulse, discussed in sections 3.4 and 4.1, occurs. Downward and upward arrows indicate the direction of propagation of various processes.

records shown in Figure 5. A descending leader-like process can be observed in association with this reconnection pulse. In Figure 7, the presence of the UPL can easily be detected, as appreciable luminosity is clearly visible above the level of the top of the wire during the period prior to the destruction of the wire (prior to and a little after point A in the current record in Figure 7b). Luminosity can be observed to increase in the region of the triggering wire (below the wire top level) simultaneously with the reduction of the current at the channel base at point A. The luminosity of the UPL (above the wire top level) can be seen to decrease as the luminosity in the region of the wire (below the wire top level) increases. This is consistent with the description of the process of current cutoff given by *Rakov et al.* [2003].

[20] The leader-like process (see downward directed arrow in Figure 7a) is initiated from a point at the level of the top of the triggering wire at a time when the UPL appears to not be luminous. When the return-stroke-like process (see upward directed arrow in Figure 7a) reaches the level of the top of the wire, then the UPL (above the wire top) begins to be reilluminated. The peak illumination in this UPL is approximately coincident in time with the secondary pulse (labeled SP in Figure 7b) in the channel base current, and has approximately the same shape (luminosity versus time waveform is not shown here). Over the region between the channel base and the level of the top of the wire, the risetime of the reconnection pulse light waveform is very fast, as evidenced by the sharp transition between colors in this region in Figure 7a. Above the level of the top of the wire, however, the risetime of the reconnection pulse light waveform is considerably longer, with no such sharp transition visible. This suggests that the properties of the plasma channel formed in the region of the wire residue (below the wire top) differ significantly from those of the UPL channel (presumably not contaminated by wire residue) above the level of the top of the triggering wire. In contrast, the secondary slow pulse does propagate both in the region below the top of the wire and in the UPL channel with relatively constant waveshape. Investigation of this aspect of the reconnection process is ongoing.

4. Discussion

4.1. Reconnection Process Mechanism

[21] The first conceptual picture of current cutoff and reestablishment in rocket-triggered lightning was suggested by *Rakov et al.* [2003, Figure 8]. On the basis of the observations described above, a more detailed description of the process of wire explosion and UPL reconnection to ground in rocket-triggered lightning may be developed, as illustrated in Figure 8. The initial stage of rocket-triggered lightning begins when an upward positive leader is initiated from the top of the triggering wire. This UPL propagates toward the negative charge center in the cloud. While the UPL channel extends upward, current flows in the triggering wire. Integrated heating causes the wire to explode (be vaporized), effectively disconnecting the UPL from the ground and causing a cessation of current flow at ground level. The UPL channel is now effectively a floating vertical conductor in an external (upward directed) electric field, and thus is polarized. This causes negative charge to accumulate at the bottom of the UPL channel. From the resultant charge pocket, a downward leader-like process may be initiated followed by an upward return-stroke-like process, previously herein referred to as a reconnection pulse. Some of these reconnection pulses fail to reconnect the UPL channel to ground and are referred to as attempted

Table 2. Correlation Coefficients Between Various ICV Characteristics for Type I and II Events[a]

	Action Integral	Charge	Decay	ZeroDur	Peak Before	Peak After
Action integral	1.00					
Charge	0.46	1.00				
Decay	−0.48	0.36	1.00			
ZeroDur	0.23	***0.87***	0.47	1.00		
Peak before	0.30	−0.59	***−0.72***	−0.61	1.00	
Peak after	0.23	0.37	−0.18	0.49	0.09	1.00

[a]Characteristics are defined in Figure 1. Total data set contains nine events with current interruption intervals, six of which are type I and three of which are type II events. Action integral represents the current squared integrated over the interval prior to the current minimum during the current interruption interval; this is effectively the energy which would have been delivered into a 1 Ω resistive load. Charge is the total charge transferred prior to the current minimum during the current interruption interval. Decay represents the time between the onset of current reduction and when the current settles to approximately zero. ZeroDur (labeled zero current interval in Figure 1) represents the duration of the time interval over which the current is (approximately, in the case of type II flashes) equal to zero. Peak before represents the peak current prior to wire explosion, and peak after represents the peak current of the pulse which reconnects the UPL to ground. Values in bold and italics denote results for which the 95% confidence interval does not contain zero.

reconnection pulses. When a reconnection pulse successfully reconnects the UPL channel to ground, a slower, secondary current pulse follows, illuminating both the plasma channel which has replaced the triggering wire and the UPL channel above the wire top level. The physical process which produces this secondary pulse is unclear, but our conjecture is that the pulse propagates downward as a result of current flow being reestablished at the top of the UPL or in the cloud, if the UPL has reached the cloud. The process of reconnecting the UPL to ground is complete at this point, and the replacement of the triggering wire by a plasma channel is essentially finished. For that reason, it seems reasonable to consider the ICV, the feature associated with the destruction of the triggering wire, to end with this secondary pulse. From this time onward, the initial stage of the rocket-triggered lightning flash continues as has been described in the literature [e.g., *Rakov*, 1999; *Wang et al.*, 1999]. Interestingly, no pronounced secondary pulse was observed in the study of *Rakov et al.* [2003] (although they did observe multiple pulses attributed by them to steps of the UPL), while all events presented in this paper exhibited this feature.

4.2. Type I Versus Type II

[22] In section 3.2 the data set under consideration has been divided into two subsets (type I and type II) based on the characteristics of the current interruption interval. In this section, several additional characteristics of the current waveforms in this data set were determined and the correlations between the various characteristics were examined. A diagram illustrating the definitions of the measured parameters is shown in Figure 1, and a description of the parameters is included in the caption of Table 2, which contains linear correlation coefficients between parameters for all events, both types I and II.

[23] Table 2 shows that there is significant correlation between the duration of the interval over which the current is equal (or nearly equal) to zero during the current interruption interval and the charge transferred prior to wire explosion (see scatterplot in Figure 9), and significant negative correlation between the time required for the current to decay to (or nearly to) zero and the peak current prior to wire explosion (see scatterplot in Figure 10). As the duration of the current interruption interval is the primary differentiator between the two populations, it will be useful to examine the correlations within each group separately. Table 3 contains the correlation coefficients between the same parameters but with the data set limited to only type I events. Type I events, similar to all events combined, show strong negative correlation between the current decay to or nearly to zero and the peak current prior to wire explosion, as seen in the scatterplot in Figure 10. Less strong is the correlation between duration of the zero current interval and charge transferred prior to wire explosion (scatterplot is shown in Figure 9). Linear regression lines for type I events in Figures 9 and 10 are shown using solid lines, as opposed to dashed lines for type I and type II events combined. Additionally, strong correlation is observed between the reconnection pulse peak magnitude and the duration of the zero current interval in the current interruption interval (see scatterplot in Figure 11), and strong negative correlation between the decay to or nearly to zero current and the action

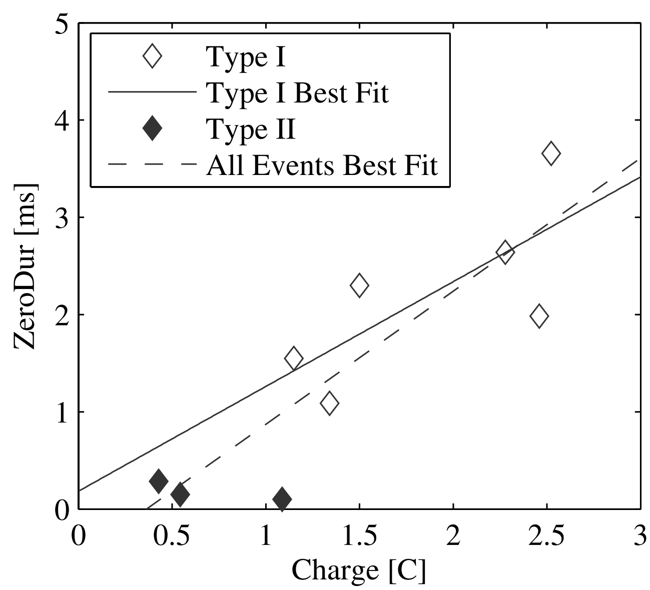

Figure 9. Zero current interval duration (ZeroDur) versus charge transferred prior to the current interruption interval. Type I events are shown as open diamonds, and type II events are shown as solid diamonds. A linear regression line (best fit) for all events is shown as a dashed line. The linear correlation coefficient for all events is 0.87. A linear regression line (best fit) for type I events is shown as a solid line. The linear correlation coefficient for type I events is 0.74.

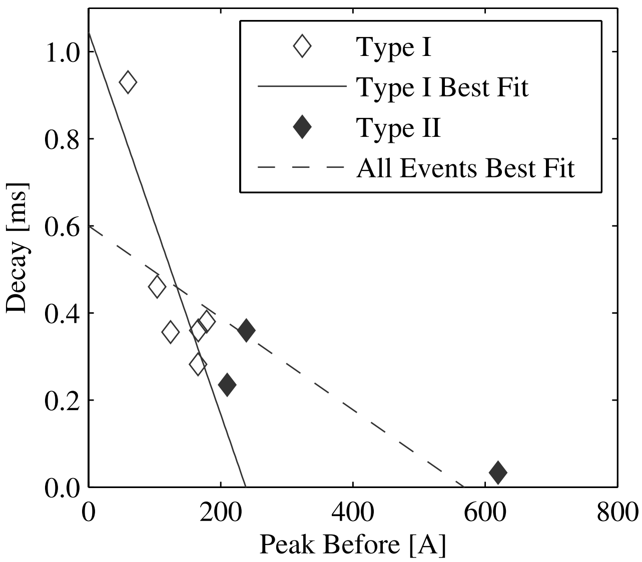

Figure 10. Peak current prior to the current interruption interval versus current decay time for type I and type II events combined. Type I events are shown as open diamonds, and type II events are shown as solid diamonds. A linear regression line (best fit) for all events is shown as a dashed line. The linear correlation coefficient for all events is −0.72. A linear regression line (best fit) for type I events is shown as a solid line. The linear correlation coefficient for type I events is −0.85.

integral (see scatterplot in Figure 12). Less strong but still significant is the correlation between peak current in the reconnection process and the charge transferred prior to wire explosion (see scatterplot in Figure 13); a fairly strong linear correlation can be seen to be reduced by an outlying data point for which the reconnection pulse peak is equal to 2 kA.

[24] The sample size of type II events was too small (only three events) to calculate a meaningful confidence interval for any correlation. However, it was observed that there was some negative correlation between the peak current after the reconnection process and the charge transferred.

[25] When the characteristics of type I and type II events were compared, several general tendencies were noted. The three type II events all transferred less charge prior to the current minimum during the current interruption interval than any of the type I events, with the largest of the type II's transferring 1.1 C and the smallest type I transferring 1.2 C. The mean action integral of type I events, at 121 A^2 s, was only slightly larger than the mean action integral of type II events at 102 A^2 s, with significant overlap of magnitudes between the two groups. The peak current prior to the current minimum during the current interruption interval in type II events was higher in every case than in any type I event. The mean of the current peak in the reconnection process was nearly identical for type I and type II events, at about 811 A and 844 A, respectively. The duration of the zero current interval in type I events tended to be an order of magnitude larger than that in type II events, which is unsurprising as the current interruption interval duration is the primary criterion for event type determination.

[26] When the charge transferred, action integral, and peak current prior to wire destruction are considered together, it appears that the wire destructions in type II events were more efficient. Despite transferring less charge prior to wire explosion, type II events exhibited greater current at the time of the wire explosion than type I events. This indicates that the rise of current was more rapid. The observed times of the current decay to zero for type II events tend to be lower than type I events. The three type II events observed had decays which took 360 μs, 33 μs, and 235 μs, but every type I event decay took longer than 350 μs.

[27] From these analyses, we can conclude that a secondary difference between type I and type II events is the rapidity of processes related to the wire destruction. The rate of current increase prior to wire destruction is more rapid in type II events, and the rate of current reduction during or after the wire destruction is higher in type II events. These differences could be due to variations in triggering wire characteristics, to cooling effects (including those of rain on the wire), or to the characteristics of the charge distribution within the cloud. As to the nature of wire destruction, it is unclear whether these events tend to destroy the wire all along its length at once or whether large gaps are created with many wire segments remaining relatively intact. In other words, it is unclear whether the heating and resultant explosion are more uneven along the length of the wire in type II events than in type I events. Nor is it clear whether there is a causal relationship between the rapidity of current increase resulting in wire destruction and the current interruption interval type, or whether both are effects of some other cause as yet undetermined.

5. Summary

[28] In this paper, we have examined the process of wire destruction and current reestablishment in the initial stage of nine rocket-triggered lightning flashes. On the basis of

Table 3. Correlation Coefficients Between Various ICV Characteristics for Type I Events Only[a]

	Action Integral	Charge	Decay	ZeroDur	Peak Before	Peak After
Action integral	1.00					
Charge	0.53	1.00				
Decay	***−0.92***	−0.18	1.00			
ZeroDur	0.15	*0.74*	0.10	1.00		
Peak before	0.58	−0.23	***−0.85***	−0.32	1.00	
Peak After	0.37	**0.78**	−0.10	***0.94***	−0.26	1.00

[a]This data set contains six type I events. Values in bold and italics denote results for which the 95% confidence interval does not contain zero. Similarly, values in bold correspond to a 90% confidence interval, and values in italics correspond to an 85% confidence interval. See also notes accompanying Table 2.

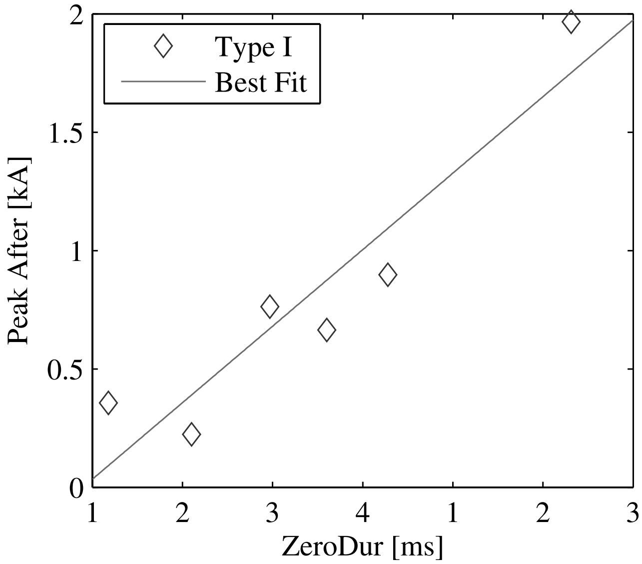

Figure 11. Reconnection pulse peak (peak after) versus duration of zero current interval (ZeroDur) during the current interruption interval for type I events. The linear correlation coefficient is 0.94.

current, linear streak film, and electric field records, the reconnection pulse (RP), which serves to reconnect the UPL to ground and to reestablish current to ground after the current interruption interval, was observed to have similarities to a leader/return-stroke process, supporting the conclusions of *Rakov et al.* [2003]. Failed attempts at reconnection were observed for the first time, and these attempted reconnection pulses were also observed to have similarities to leader/return-stroke processes. Both reconnection pulse and attempted reconnection pulse processes

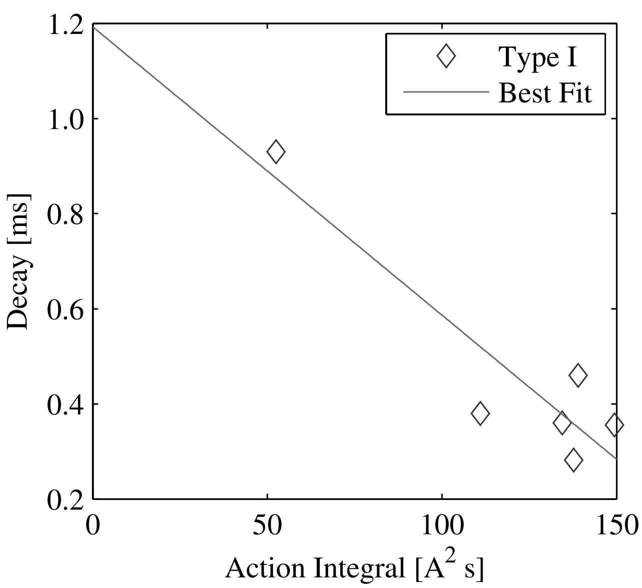

Figure 12. Current decay time versus action integral for type I events. The linear correlation coefficient is −0.92.

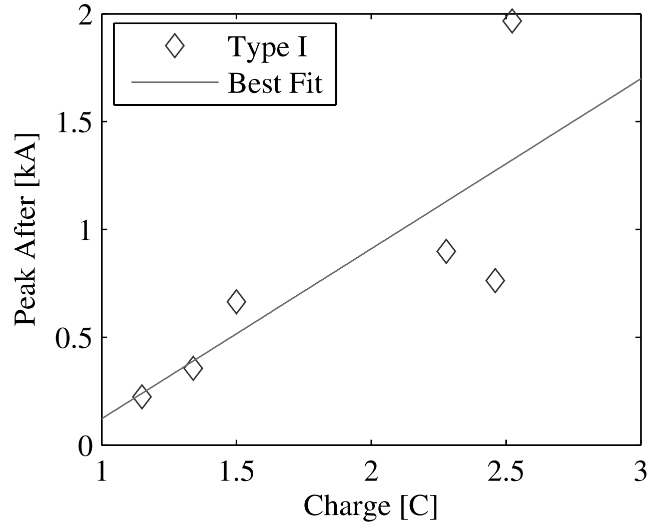

Figure 13. Reconnection pulse peak (peak after) versus charge transferred prior to zero current interval for type I events. The linear correlation coefficient is 0.78.

appear to traverse the gap, left by the destroyed triggering wire, between the bottom of the floating UPL channel and ground. Two distinct types of initial current variation (ICV) have been observed. Correlations between various parameters of the ICV were examined, and it was observed that the processes associated with type II events appear to be more rapid and violent than those in type I events, although the causal relationship remains unclear. On the basis of the entirety of observations and analyses, a more detailed description of the process of cutoff and reestablishment of current due to wire destruction during the initial stage of rocket-triggered lightning was developed.

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References

Crawford, D. E., V. A. Rakov, M. A. Uman, G. H. Schnetzer, K. J. Rambo, M. V. Stapleton, and R. J. Fisher (2001), The close lightning electromagnetic environment: Dart-leader electric field change versus distance, *J. Geophys. Res.*, *106*(D14), 14,909–14,917.

Fieux, R., C. Gary, and P. Hubert (1975), Artificially triggered lightning over land, *Nature*, *257*, 212–214.

Idone, V. P., and R. E. Orville (1982), Lightning return stroke velocities in the Thunderstorm Research International Program (TRIP), *J. Geophys. Res.*, *87*(C6), 4903–4916.

Jordan, D. M. (1990), Relative light intensity and electric field intensity of cloud to ground lightning, Ph.D. thesis, Univ. of Fla., Gainesville.

Jordan, D. M., V. P. Idone, V. A. Rakov, M. A. Uman, W. H. Beasley, and H. Jurenka (1992), Observed dart leader speed in natural and triggered lightning, *J. Geophys. Res.*, *97*(D9), 9951–9957.

Malan, D. J., and H. Collens (1937), Progressive lightning. III-The fine structure of return lightning strokes, *Proc. R. Soc. London, Ser. A*, *162*(909), 175–203.

McEachron, K. B. (1939), Lightning to the Empire State Building, *J. Franklin Inst.*, *227*, 149–217.

Olsen, R. (2003), Optical characterization of rocket-triggered lightning at Camp Blanding, Florida, Masters thesis, Univ. of Fla., Gainesville.

Rakov, V. A. (1999), Lightning discharges triggered using rocket-and-wire techniques, *Recent Res. Dev. Geophys.*, *2*, 141–171.

Rakov, V. A., D. E. Crawford, K. J. Rambo, G. H. Schnetzer, M. A. Uman, and R. Thottappillil (2001), M-component mode of charge transfer to ground in lightning discharges, *J. Geophys. Res.*, *106*, 22,817–22,831.

Rakov, V. A., D. E. Crawford, V. Kodali, V. P. Idone, M. A. Uman, G. H. Schnetzer, and K. J. Rambo (2003), Cutoff and reestablishment of current in rocket-triggered lightning, *J. Geophys. Res.*, *108*(D23), 4747, doi:10.1029/2003JD003694.

Schonland, B. F. J. (1956), The lightning discharge, *Handb. Phys.*, *22*, 576–628.

Wang, D., V. A. Rakov, M. A. Uman, M. I. Fernandez, K. J. Rambo, G. H. Schnetzer, and R. J. Fisher (1999), Characterization of the initial stage of negative rocket-triggered lightning, *J. Geophys. Res.*, *104*(D4), 4213–4222.

J. Jerauld, D. M. Jordan, R. C. Olsen III, V. A. Rakov, K. J. Rambo, and M. A. Uman, Department of Electrical and Computer Engineering, University of Florida, EB570B, Gainesville, FL 32611, USA. (rco3@ufl.edu; rakov@ece.ufl.edu)