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Cutoff and reestablishment of current in rocket-triggered lightning

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[1] A total of three negative rocket-triggered lightning flashes without return strokes (two from 1997 and one from 1993) are analyzed in this paper in order to study the processes associated with the disintegration of the triggering wire and its replacement by an air-plasma channel. It appears that the gap resulting from the vaporization of the triggering wire by the upward-positive leader current is bridged by a leader/return-stroke type process. Electric fields at distances of 50, 110, and 500 m, the corresponding magnetic fields at 500 m, and the currents to ground are examined for the two 1997 flashes. The electric field prior to the triggering wire's vaporization in these flashes exhibits a positive (atmospheric electricity sign convention) millisecond-scale ramp due to the upward-extending positive leader. The electric field changes observed at the three distances just prior to wire vaporization are consistent with an equivalent point charge of about 0.3 C at a height of 1.2 to 1.5 km, suggesting that the charge density distribution at that time is strongly skewed toward the upward positive leader tip. The length of the triggering wire at the time of its vaporization was estimated from still photographs to be about 210–220 m. Following the ramp, a microsecond-scale V-shaped negative pulse, which resembles the close electric field signature of a small dart-leader/return-stroke sequence, is observed. The corresponding magnetic field decreases abruptly, simultaneously with the onset of the leading edge of the V-shaped pulse, to values near zero and remains there for tens of microseconds, indicating the attempted interruption (cutoff) of the upward positive leader current flow to ground through the triggering wire as it is vaporized by this current. Following the abrupt decrease, the magnetic field exhibits a rapid increase at a time corresponding to the trailing edge of the V-shaped electric field pulse, suggesting that the vaporized triggering wire is replaced by an air-plasma channel that becomes part of the upward positive leader channel when electrical connection to ground is restored. For the third triggered lightning flash, from 1993, similar inferences regarding the processes involved in the replacement of the triggering wire by an air-plasma channel are made from high-speed (streak) photography and from measurements of the current to ground and electric field at 30 m. In this flash, the upward positive leader exhibited very pronounced stepping: step current pulses had peaks, as measured at the ground, that were up to a few kiloamperes, and step charges that were up to 100 mC. Characterization of the attempted interruption and the following reestablishment of current to ground in rocket-triggered lightning may have important implications for the understanding of channel current cutoff in natural lightning flashes and may provide new insights into the formation of strokes observed to occur in the same channel within a millisecond or less. *INDEX TERMS:* 3304 Meteorology and Atmospheric Dynamics: Atmospheric electricity; 3324 Meteorology and Atmospheric Dynamics: Lightning; 3399 Meteorology and Atmospheric Dynamics: General or miscellaneous; *KEYWORDS:* lightning, current cutoff, stepping

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1. Introduction

[2] Lightning discharges can be artificially initiated (triggered) from natural thunderclouds by means of the "rocket-and-wire" technique [e.g., *Rakov et al.*, 1998]. To date, probably close to a thousand lightning discharges have been triggered worldwide using this technique. The results of triggered-lightning experiments have provided considerable insight into natural lightning processes that

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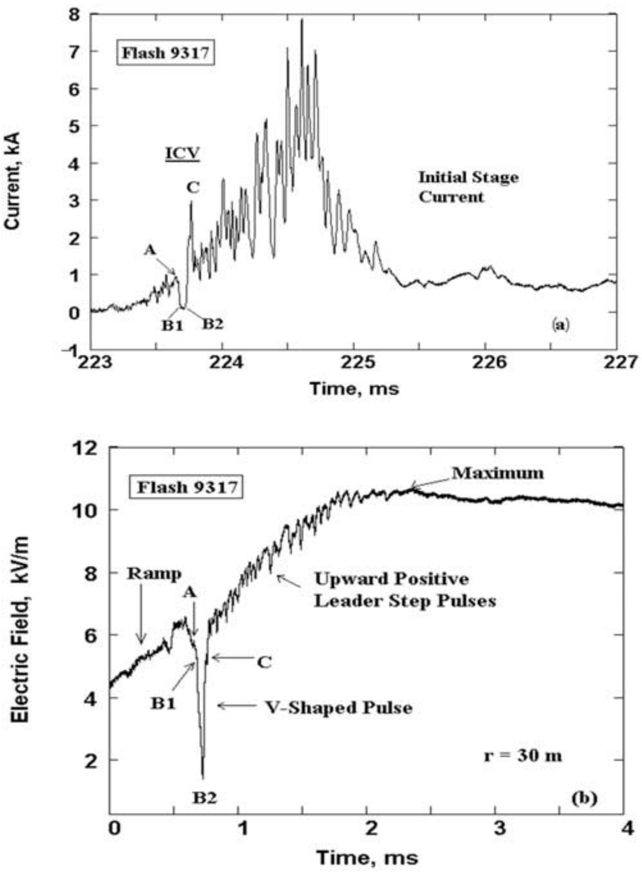


Figure 1a–1b. (a) Current to ground and (b) corresponding electric field 30 m from the lightning channel for flash 9317 triggered in 1993 at Camp Blanding, Florida. ICV stands for initial current variation which is part of the initial stage current in many rocket-triggered lightning flashes. ICV in Figure 1a begins 1.8 ms prior to A and ends at about 225.5 ms. Characteristic features of the ICV are labeled A, B1, B2, and C, and are explained in the text (see also Figures 1c and 8.

would not have been practical from studies of natural lightning due to the latter's random occurrence in space and time [e.g., *Rakov et al.*, 1998, 2001; *Wang et al.*, 1999a, 1999c; *Uman et al.*, 2000, 2002; *Crawford et al.*, 2001; *Miki et al.*, 2002a; *Schoene et al.*, 2003a]. Further, triggered-lightning experiments have contributed significantly to testing the validity of various lightning models [e.g., *Willett et al.*, 1988, 1989; *Thottappillil and Uman*, 1993; *Thottappillil et al.*, 1997; *Uman et al.*, 2002; *Schoene et al.*, 2003b] and to providing ground-truth data for the U.S. National Lightning Detection Network (NLDN) [e.g., *Cummins et al.*, 1998; *Cramer et al.*, 2001]. Finally, triggered lightning has proved to be a very useful tool to study the interaction of lightning with various objects and systems [e.g., *Horii*, 1982; *Morris et al.*, 1994; *Barker et al.*, 1996; *Fernandez et al.*, 1999; *Bejleri et al.*, 2000; *Rakov et al.*, 2002; *Mata et al.*, 2003].

[3] The "classical" (grounded-wire) negative rocket-triggered lightning can be considered to begin when an upward-propagating positively charged leader is launched from the top of the triggering wire that has been extended by the rocket to a typical height of 200 to 300 m. (Note that the so-called precursor current pulses [e.g., *Lalande et al.*, 1998; *Willett et al.*, 1999], not resolved in records examined here, are beyond the scope of this paper.) This upward positive leader vaporizes the triggering wire, bridges the gap between the cloud and ground, and establishes an initial continuous current that effectively transports negative charge from the cloud charge source to the grounded triggering facility. The initial continuous current, whose duration is typically some hundreds of milliseconds, can be viewed as a continuation of the upward positive leader when the latter has reached the main negative charge region in the cloud. At that time, the upper extremity of the upward positive leader is likely to be heavily branched to provide a steady supply of charge to the channel to ground. The upward positive leader and the initial continuous current constitute the initial stage of a classical triggered lightning discharge. After the cessation of the initial continuous current, one or more downward dart leader/upward return stroke sequences may traverse the same path to ground. These leader/return stroke sequences are similar to subsequent strokes, that is, to leader/return stroke sequences following the first stroke in natural downward lightning, as well as being similar to leader/return stroke sequences in upward flashes initiated from tall objects [e.g., *Rakov*, 2001].

[4] The initial stage of classical rocket-triggered lightning has been studied by a number of researchers including *Rakov et al.* [1996], *Wang et al.* [1999b], and *Miki et al.* [2002b]. *Wang et al.* [1999b], based on data from Fort McClellan, Alabama and Camp Blanding, Florida, reported that the initial stage had a geometric mean (GM) duration of 279 ms and lowered to ground a GM charge of 27 C. The average initial stage current in an individual lightning discharge varied from a minimum of 27 A to a maximum of 316 A with a GM value of 96 A. In many cases, a pronounced current signature, termed by *Wang et al.* [1999b] the initial current variation (ICV) and illustrated in Figure 1a, is seen at the beginning of the initial stage. The ICV begins at the onset of the initial stage current and typically includes a current drop, probably associated with the disintegration (vaporization) of the Kevlar-coated copper triggering wire (abrupt current decrease from A to B1 in Figure 1a), and the following current reestablishment (abrupt current increase from B2 to C in Figure 1a), immediately or after a time interval (B1 to B2 in Figure 1a) of up to several hundred microseconds. According to *Wang et al.* [1999b], the duration of the ICV does not exceed 10 ms. The ICV in Figure 1a begins 1.8 ms prior to A and ends at about 225.5 ms. *Fieux et al.* [1975, 1978], from triggered-lightning experiments in which the steel-wire spool was located on ground, reported that the wire first disintegrated near the spool, where the mechanical stress was maximum. The resultant gap between the spool and the ascending lower end of the wire was bridged by an arc whose length at the time of vaporization of the wire typically reached 5 m. Note that in the experiments in Florida (discussed here) and in Alabama, the 0.2-mm diameter triggering wire was made of copper, and the spool was attached to the rocket. Current cutoff due to the explosion of the 50-m grounded intercepting wire in altitude triggered lightning and its

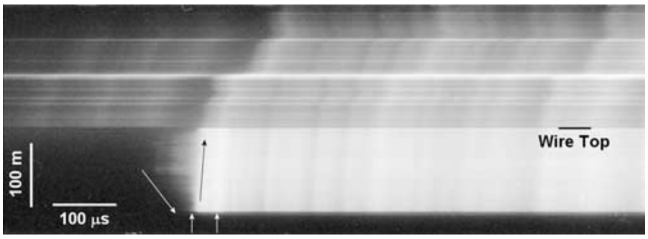


Figure 1c. Time-resolved photographic record of a 1.24-ms portion of the initial stage of rocket-triggered flash 9317. Time increases from left to right. Approximate spatial and temporal scales are indicated on the left. The record corresponds in time to the interval 223.42 ms to 224.66 ms in the current record of Figure 1a. The white negatively sloped arrow indicates the presumed dart-like "leader" progression (B1 to B2 in Figures 1a and b); the arrow is offset earlier in time (i.e., to the left) by about 15 μs for clarity. The black upward arrow indicates the "return stroke" progression, offset slightly later, again for clarity. The two upward white arrows near the bottom of the image correspond to times B2 (left arrow) and C (right arrow) of the current record in Figures 1a and the 30-m electric field record in Figure 1b (see also Figure 8). The initial phase of propagation of the upward positive leader (that created the channel above the top of the wire) was not imaged; only the last 200 μs or so just prior to the wire explosion are seen, while the leader started 1.8 ms prior to the wire explosion.

following reestablishment are discussed by *Rakov et al.* [1998].

[5] The GM time interval between the onset of the ICV and the abrupt decrease in current was found by *Wang et al.* [1999b] to be 8.6 ms, and the GM current level just prior to the current decrease was 312 A. Prior to this rapid current decrease, a GM charge of 0.8 C has been lowered through the wire and a GM action integral (energy per unit resistance) of 110 A^2s (J/Ω) has been expended. In 16 out of 22 cases studied by *Wang et al.* [1999b] the current dropped to zero, while in the remaining 6 cases the current decreased to a value around 100 A. The abrupt current decrease took typically several hundred microseconds and was followed by a pulse with a typical peak of about 1 kA and a typical risetime of less than 100 μs. *Wang et al.* [1999b] identified the ICV in 24 out of 37 triggered-lightning current records, in 22 (including S9713 and S9714) of which there was a pronounced current drop similar to that seen in Figure 1a. Thus replacement of the triggering wire with an air-plasma channel that becomes part of the upward positive leader channel can occur either abruptly, as discussed in this paper, or without a pronounced transient process.

[6] In this paper, we provide additional information on the lightning processes that produce the ICV from simultaneous electric field, magnetic field, and current measurements in 1997 and simultaneous optical, electric field, and current measurements in 1993 at Camp Blanding, Florida. Characterization of the interruption (cutoff) and the following reestablishment of current to ground in triggered lightning may have important implications for the understanding of channel current cutoff and of the generation of strokes occurring within a millisecond or less in natural lightning flashes [*Rakov and Uman*, 1994; *Idone and Davis*, 1999].

2. Data

[7] A total of three flashes, each effectively transporting negative charge to ground, are examined here, two from 1997 and one from 1993 experiments. All data were obtained at the International Center for Lightning Research and Testing (ICLRT) at Camp Blanding, Florida.

2.1. The 1993 Experiment

[8] The instrumentation and experimental set-up used at Camp Blanding in 1993 are described by *Rakov et al.* [1995, 1998] and *Crawford et al.* [2001, section 2.1]. The lightning flash, 9317, presented here was triggered on 28 June 1993 and was composed of the initial stage only (no leader/return stroke sequences). Electric field at ground level prior to rocket launch was -6.3 kV/m. Still photographs and video records indicate ground surface arcing (away from the electric field antenna) and a possibly forked channel above the wire channel section whose length was about 126 m. For this event, we obtained the current (provided by P.P. Barker of Power Technologies, Inc.) at the channel base, the electric field 30 m from the rocket launcher, and a time-resolved (streak) photographic record (see Figures 1a, 1b, and Figure 1c, respectively). The current was digitized at a 2-μs sampling interval for a total record length of over 520 ms and the electric field at a 0.1-μs sampling interval for a total record length of 51.2 ms. The overall current waveform duration was about 90 ms, of which the initial 4 ms will be examined in detail here. The overall current peak was about 7 kA. The noise floor in the current record was about 72 A. The decay time constant of the electric field measuring system was 35 ms. The highly time-resolved photographic record was obtained using a system that was deployed at a distance of 395 m from the rocket launcher and consisted of a Hycam II reel-to-reel, high-speed camera run in streak mode at a writing rate of 27.2 m/s. The recording was made on Kodak Double-X negative film, and the lens used had a focal length of 10.8-mm. The temporal resolution of the streak photographic record is about 1 μs.

2.2. The 1997 Experiment

[9] The 1997 experiment was designed primarily to study the dependence of dart-leader electric field change on the distance from the triggered lightning channel. The instrumentation used and the experimental set-up are described by *Crawford et al.* [2001, section 2.2]. During the 1997 experiment, the measuring system also recorded the initial stages of three flashes, S9712, S9713, and S9714. Two of these flashes, S9713 and S9714, triggered on 23 June 1997 and composed of the initial stage only (no leader/return stroke sequences), are considered here. Electric fields at ground prior to rocket launches for S9713 and S9714 were -3.8 and -4.3 kV/m, respectively. The length of the triggering wire at the time of lightning initiation (estimated from still photographs) was about 210 m for S9713 and about 220 m for S9714, typical values for classical rocket-triggered lightning [e.g., *Rakov et al.*, 1998]. For all three

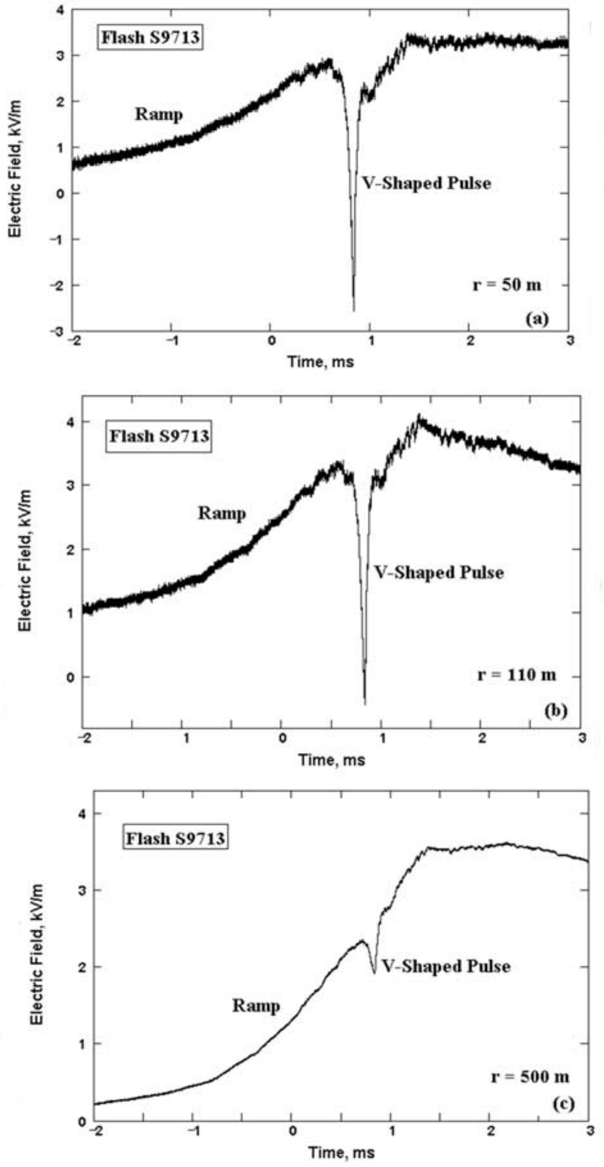


Figure 2. Electric field at (a) 50 m, (b) 110 m, and (c) 500 m for flash S9713 triggered in 1997 at Camp Blanding, Florida.

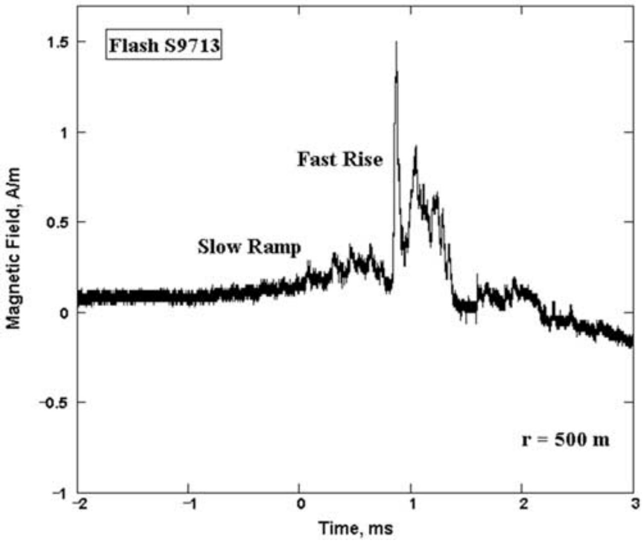


Figure 3. Magnetic field at 500 m for flash S9713 whose electric fields are shown in Figure 2.

events we obtained electric field records at 50, 110, and 500 m and a magnetic field record 500 m from the rocket launcher (the lightning attachment point). The fields were digitized at a 0.1-μs sampling interval for a total record length of 51.2 ms. Only the first 5 ms are presented here. The decay time constants of the electric field measuring systems were 5 to 6 ms, and of the magnetic field measuring system 1 ms or so. Thus electric field variations on a timescale longer than 500–600 μs and magnetic field variations on a timescale longer than 100 μs or so are likely to be distorted. Currents at the channel base and magnetic fields at 5, 10, 20, and 30 m for the entire duration of each flash, recorded on magnetic tape and subsequently digitized at 40-μs sampling interval, were also available. The noise floor in the current records was about 23 A. Electric and magnetic field waveforms, on a 5-ms timescale, for flash S9713 are shown in Figures 2 and 3, respectively, and the relative timing of the electric and magnetic field waveforms at 500 m is illustrated, on an expanded timescale, in Figure 4. Similar plots for flash S9714 are given in Figures 5 through 7.

3. Analysis

3.1. Current Records

[10] The ICV characteristics obtained from the current records of 9317, S9713, and S9714 are summarized in Table 1. Also included in Table 1 are the ICV characteristics reported by *Wang et al.* [1999b]. The current duration prior to wire vaporization, 1.8 to 2.4 ms, for the three events considered here is appreciably smaller than the geometric mean duration of 8.6 ms observed by *Wang et al.* [1999b], while the current magnitude just prior to wire vaporization is a factor of two to three higher, 631 to 1080 A versus 312 A. It appears that the triggering wire was heated more rapidly in the three events considered here than, on average, in the data set examined by *Wang et al.* [1999b]. The nonzero current values just after wire vaporization are discussed

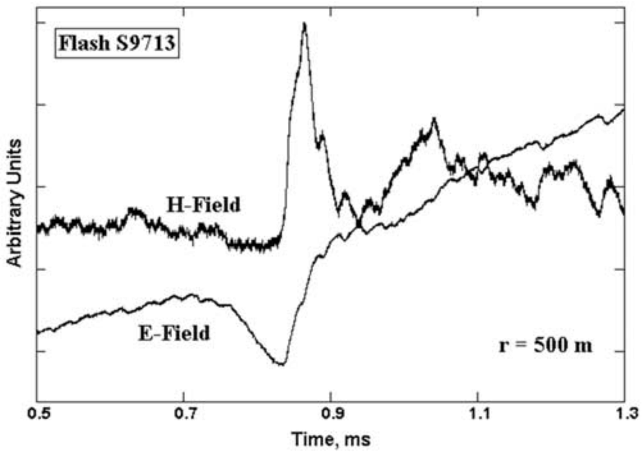


Figure 4. Relative timing of electric and magnetic fields at 500 m for flash S9713 (see also Figures 2 and 3).

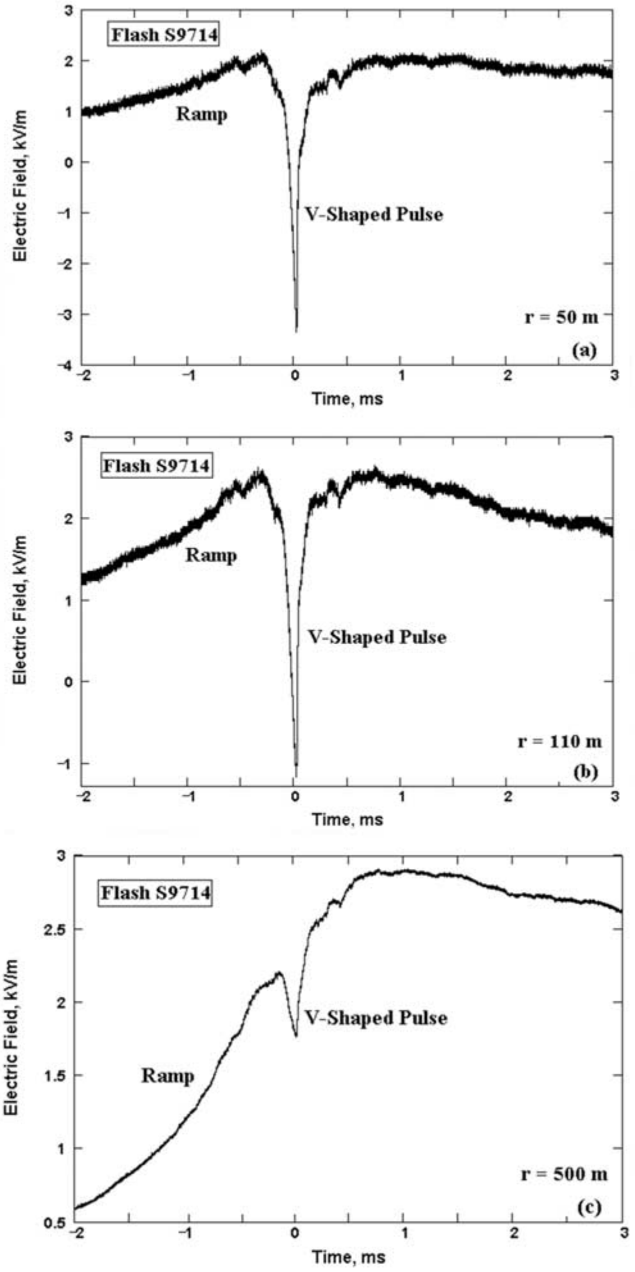


Figure 5. Same as Figure 2, but for flash S9714.

in section 3.2. As noted earlier, S9713 and S9714 are also in Wang et al.'s data set. Overall charge transfers by flashes 9317, S9713, and S9714 were about 18, 34, and 16 C, respectively.

3.2. Field Records

[11] We first present data for events S9713 and S9714 and then for event 9317.

3.2.1. Events S9713 and S9714

[12] The recorded ICV electric fields were characterized by an initial positive (atmospheric electricity sign convention) ramp lasting several milliseconds. Only a portion of this ramp (the last 2 ms or so) was recorded by the digitizer due to the pretrigger settings in 1997. Nevertheless, the magnitude of the ramp could be estimated by taking into account the zero offset for each field measuring station. Ramp magnitudes were of the order of a few kV/m and were not much different at distances ranging from 50 to 500 m (see Table 2). The ramp was followed by a pronounced V-shaped negative electric field pulse. The pulse half-peak width is of the order of 50 μs at 50 and 110 m, and about twice as large at 500 m. The magnitude of the pulse varies with distance much more slowly than r^{-1} between 50 and 110 m, but somewhat more rapidly than r^{-1} between 110 and 500 m (see Table 2). A fast rise in the current corresponds in time, as evidenced by the magnetic field measurements, to the trailing edge of the V-shaped pulse (see Figures 4 and 7). Small variations in the electric field, probably associated with upward-positive-leader steps, are seen superimposed on the millisecond-scale waveform both before and after the V-shaped pulse. (The mechanism of stepping in positive leader is different from that in negative leader [*Rakov and Uman*, 2003, pp. 136–137, 224–228]. The term "stepping" in this paper denotes an impulsive process that periodically illuminates the extending leader channel (see Figures 1c and 9), regardless of the mechanism involved.)

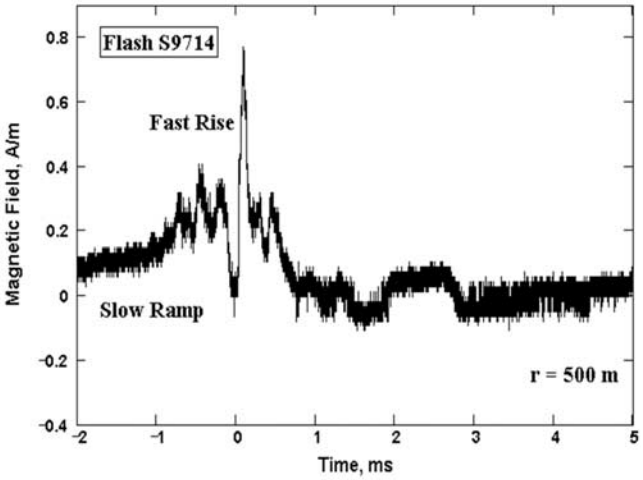


Figure 6. Same as Figure 3, but for flash S9714.

[13] Ramp electric field changes (Table 2) and charges transferred prior to wire vaporization (Table 1) were used to

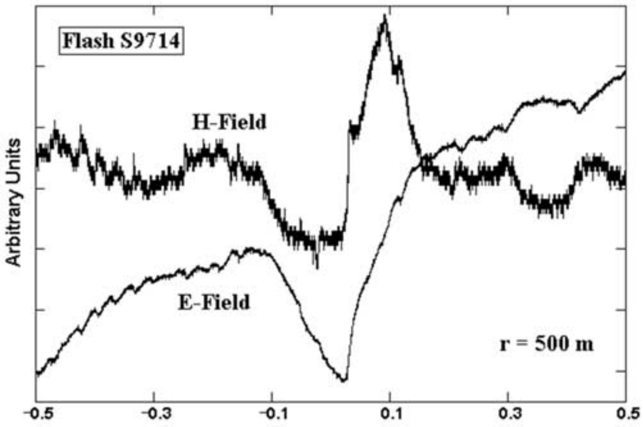


Figure 7. Same as Figure 4, but for flash S9714.

Table 1. ICV Characteristics Obtained From Current Records[a]

Flash	Current Duration Prior to Wire Vaporization, ms	Current Magnitude Just Prior to Wire Vaporization, A	Charge Transfer Prior to Wire Vaporization, mC	Action Integral Prior to Wire Vaporization, A^2s	Current Magnitude Just After Wire Vaporization, A	Current Peak, kA
9317	1.8	1080	380	198	240	7.0
S9713	2.0	646	287	83	215	4.7[b]
S9714	2.4	631	350	110	81	2.4[b]
Wang et al. [1999b]	8.6[c]	312[c]	800[c]	110[b]	0–100	~1

[a] ICV, initial current variation.

[b] Estimated from magnetic fields measured at 500 m using Ampere's law for magnetostatics.

[c] Geometric mean values.

obtain the heights of the equivalent point charges just prior to wire vaporization. The results are presented in Table 3. The estimated heights vary in a relatively narrow range (1.2 to 1.4 km for S9713) or are the same (1.5 km for S9714) for distances ranging from 50 to 500 m, which suggests that the charge density distribution is strongly skewed toward the upward positive leader tip. The charge density on an upward positive leader channel is expected to increase with height from a nearly zero value at the top of the grounded triggering wire to a maximum value at the tip of the leader. Average propagation speeds of the upward positive leaders approximated by equivalent point charges moving upward over the 2.0 or 2.4 ms of the current flowing prior to wire vaporization (Table 1) are 6×10^5 to 7×10^5 m/s. For comparison, *Idone* [1992] presented an upward positive leader in rocket-triggered lightning whose speed increased from 1.2×10^5 m/s to 6.5×10^5 m/s with a mean value of 3.6×10^5 m/s over a channel length of 530 m.

[14] Further, we differentiated numerically the electric field records to estimate dE/dt for the trailing edges of the V-shaped pulses, that is, for the "return strokes" (see section 4 and Figure 8) of the ICV events. The results are summarized in Table 4. Interestingly, the dE/dt values (underestimated by less than 10 to 20% due to the numerical differentiation process) at 30 and 50 m for the ICV events are a factor of 200 to 300 lower than the dE/dt values, of the order of 100 kV/m/μs, typically observed at 30 m for regular return strokes in triggered lightning [*Schoene et al.*, 2003a]. This possibly indicates that the ICV "leader/return stroke sequences" (see section 4 and Figure 8) presented here are somewhat similar to the waves comprising M components that require a background steady current in the channel for their development [*Rakov et al.*, 1995, 2001], an inference that is consistent with non-zero current after the wire has been vaporized (Table 1).

[15] The recorded ICV magnetic fields are characterized by an initial slow positive ramp of millisecond duration (Figures 3 and 6). A fast decrease in the magnetic field, on the order of 100 μs duration, is observed after the ramp, indicating a temporary decrease (attempted interruption) of current flow. This decrease coincides with the negative leading edge of the V-shaped electric field pulse (Figures 4 and 7). The magnetic field drop is followed by a fast magnetic field rise to a peak value. At 500 m, the magnetic field peak is 1.5 and 0.77 A/m for S9713 and S9714, respectively. The corresponding currents inferred using Ampere's law for magnetostatics are 4.7 and 2.4 kA, respectively.

[16] The features of the 1997 electric and magnetic field records described above are likely associated with the attempted current interruption due to the vaporization of the triggering wire and the following reestablishment of the current via a process somewhat similar to a leader/return-stroke sequence (or to an M component which also involves a sequence of upward and downward waves [*Rakov et al.*, 1995, 2001]), although the detailed dynamics of this process is not known. It is worth noting that tape-recorded current waveshapes (as well as tape-recorded magnetic field waveshapes at 5 to 30 m) are similar to those of the digitally-recorded 500-m magnetic fields, although the pulse peak values in the tape-recorded data are close to the recorder saturation level and are therefore unreliable.

3.2.2. Event 9317

[17] The 30-m electric field waveform for flash 9317 in Figure 1b exhibits the features, slow ramp and large V-shaped pulse, seen in the 50-m and the 110-m electric field waveforms for flashes S9713 and S9714. In 1993, only the last 0.6 ms of the electric field ramp were recorded. The electric field and current waveforms in Figures 1b and 1a were recorded by different digitizers, at different sampling rates, and with different pretrigger times. We aligned these two waveforms assuming, based on the analysis of the 1997 data (see above), that the abrupt decrease in current and the following 50-μs or so of low current correspond to the negative leading edge of the V-shaped electric field pulse. The positive trailing edge of the large electric field pulse corresponds to the current pulse following the low-current interval.

Table 2. Measured Electric Field Characteristics for ICV Events[a]

	Ramp Field Change, kV/m				V-shaped Pulse Field Change,[b] kV/m			
Flash	30 m	50 m	110 m	500 m	30 m	50 m	110 m	500 m
9317	>2.3	-	-	-	−5.2	-	-	-
S9713	-	3.5	3.3	2.3	-	−5.5	−3.9	−0.44
S9714	-	2.8	3.1	2.4	-	−5.6	−3.8	−0.44

[a] ICV, initial current variation.

[b] Measured at the leading edge of the pulse.

Table 3. Heights of the Equivalent Point Charge Just Prior to Wire Vaporization Estimated From Measured Ramp Electric Field Changes (Table 2) and Charge Transfer to Ground (Table 1)

		Height, km			
Flash	Charge, mC	30 m	50 m	110 m	500 m
9317	380	<1.8	-	-	-
S9713	287	-	1.2	1.3	1.4
S9714	350	-	1.5	1.5	1.5

Table 4. dE/dt for "Return Strokes" of the ICV Events[a]

	dE/dt, kV/m/μs			
Flash	30 m	50 m	110 m	500 m
9317	0.48	-	-	-
S9713	-	0.37	0.25	0.032
S9714	-	0.44	0.28	0.029

[a] ICV, initial current variation. See section 4 and Figure 8.

[18] The magnitude of the ramp was greater than 2.3 kV/m at 30 m. In contrast with the 1997 data, no information on zero offset is available. If there were no zero offset, the magnitude of the ramp would be 6.6 kV/m. A ramp electric field change at 30 m greater than 2.3 kV/m corresponds to an equivalent point charge of 380 mC (Table 1) at a height of less than 1.8 km (or 1.0 km if we assume that the background electric field was equal to zero), which is fairly similar to the heights inferred for S9713 and S9714 (Table 3). The V-shaped pulse half-peak width is 48 μs, similar to those observed at 50 and 110 m for the two 1997 events.

[19] The electric field record in Figure 1b exhibits relatively regular pulses having peaks ranging from 126 to 958 V/m (513 V/m on average) that correspond to the pronounced pulses, having peaks ranging from 0.14 to 4.7 kA (1.6 kA on average), in the current record shown in Figure 1a and to enhancements in channel luminosity seen in Figure 1c (up to 224.66 ms in Figure 1a). These

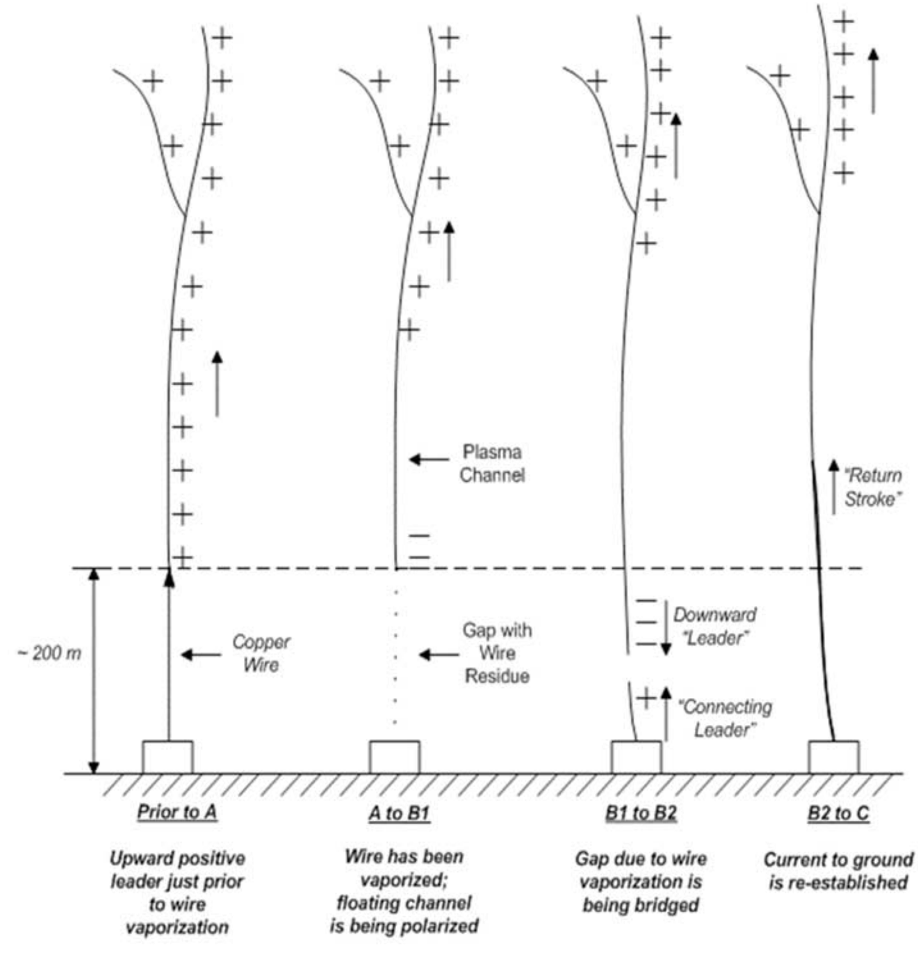


Figure 8. Conceptual picture of current cutoff and reestablishment in classical rocket-triggered lightning. The lengths of the wire and the following gap are exaggerated relative to the plasma channel length (which is a kilometer or two) for illustrative purposes. Time instants A, B1, B2, and C are indicated in Figures 1a and b. Time instants B2 and C are also indicated by two white vertical arrows in Figure 1c. The time interval shown (A to C) is typically of the order of 100 μs, so that the upward positive leader channel extending at a speed of 10^5 to 10^6 m/s is expected to show a relatively small increase in length of 10 to 100 m during this time interval. A similar scenario may explain the occurrence of two return strokes along the same channel within a millisecond or less, as observed by *Rakov and Uman* [1994] and *Idone and Davis* [1999].

pulses, separated by about 50 μs on average, are likely to be associated with upward positive leader steps. From measurements of electric field pulses radiated from leader steps in natural downward lightning, *Krider et al.* [1977] inferred that the peak step current is at least 2–8 kA close to the ground. Individual step pulses in Figure 1a are associated with a charge transfer ranging from 2.7 to 100 mC, 31 mC on average, which is an order of magnitude larger than the step charge estimated for one downward-moving negative dart-stepped leader by *Rakov et al.* [1998] and the minimum step charge estimated for stepped leaders by *Krider et al.* [1977]. The total charge associated with 27 pronounced steps seen in Figure 1a (obtained by summing the charges of individual steps) is about 826 mC.

3.3. Time-Resolved Photographic Record

[20] The time-resolved photographic record of a 1.24-ms portion of the initial stage of flash 9317 is shown in Figure 1c. This record corresponds in time to the interval 223.42 ms to 224.66 ms in the current record of Figure 1a and documents several luminous events between ground level and a height of about 300 m. The correspondence between current pulses in Figure 1a after C and the associated luminous events in Figure 1c is unequivocal. Indeed, the intervals between the five most prominent current peaks subsequent to peak C of Figure 1a agree to within a few microseconds with the luminosity peaks obtained from a horizontal profile of the optical image (not shown). The optical record intervals (in microseconds) are 264, 72, 168, and 113, versus the current record intervals of 259, 72, 161, and 116.

[21] The optical record of Figure 1c does not document the very initial phase of propagation of the positive leader that created the channel above the top of the wire (labeled Wire Top in Figure 1c). Only the last 200 μs or so just prior to the wire explosion were imaged, while the upward positive leader started 1.8 ms prior to the wire explosion, as evidenced by the current record. This is unfortunate, but typical, as apparently the brightness of such early upward-positive-leader stages is often below the threshold of photographic recording using moderate speed films under usual ambient lighting conditions. The record begins with three luminous events that are imaged above the top of the wire (see the leftmost portion of the record), but not below it, because the triggering wire remains intact and capable of carrying the current without significant luminous emission. These three luminous events correspond to three current pulses prior to and at A in Figure 1a. Next there is a diminishment of the light aloft, this commencing as the wire section just below brightens as it is vaporized due to the integrated heating to that point. This is immediately followed by a faint and poorly defined downward "leader" process (see just to the right of the downward sloping white arrow). For this process, an effective propagation speed of roughly 1.1×10^6 m/s is calculated over the lowest 64 m of channel. Above this channel section the downward progression is not apparent, possibly due to abnormal variation in the luminosity of the "leader" process or due to additional processes occurring near the top of the wire. The immediately ensuing return-stroke type event is evident as the luminous edge just to the left of the upward pointing black arrow of Figure 1c. It is not possible to calculate the speed of this luminous event with the available record. However, on physical grounds, it is quite likely that this event involves upward propagation. In contrast, all subsequent optical events in the record are likely to be the result of downward propagating luminous waves associated with the formation of individual steps of the upward positive leader, which continues extending (beyond the camera's field of view), but now with renewed vigor due to the arrival of the return-stroke type wave at the upper levels of the channel. There is, nevertheless, a hint of an increased separation at lower levels between the return-stroke edge and the very next luminous enhancement, consistent with the hypothesis of upward propagation of the return-stroke like event and downward propagation of an ensuing step luminosity pulse.

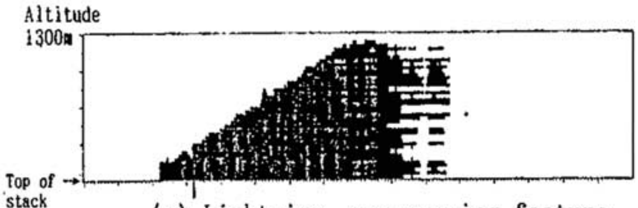
4. Interpretation of the Triggered Lightning Results and Implications for Natural Lightning

[22] The results presented and discussed above lead to the conceptual picture of current cutoff and reestablishment shown in Figure 8. Time instants A, B1, B2, and C indicated in Figure 8 correspond to the similarly labeled features in Figures 1a and 1b. Time instants B2 and C are also indicated by two white vertical arrows in Figure 1c. Prior to A (see Figures 1a and 1b), the copper triggering wire is intact, and upward positive leader current flows, via the wire and the rocket launcher, to ground. From A to B1 (see Figures 1a and 1b), the wire is vaporized by the upward positive leader current, and an air gap of 200-m or so in length is created. Electrically-exploded wires in general attain a high impedance state in the process of vaporization, so the current to ground dramatically decreases [e.g., *Zischank*, 1992, Figure 4]. (The resistance of copper increases by a factor of 2.1 at the melting point and by several orders of magnitude during the explosive vaporization.) Thereafter, the triggering wire residue becomes a part of conducting air-plasma channel that replaces the wire, as described below. The upward positive leader channel above the 200-m altitude that corresponds to the top of the vaporized wire has a length of the order of a kilometer or two (Table 3) at the time of wire vaporization, and its upper end probably continues to extend toward (or into) the cloud. As long as (1) the upward positive leader channel is a fair conductor and (2) the vaporized wire exhibits high impedance, the situation is similar to that in altitude triggered lightning: when an upward positive leader develops from the top of the ungrounded copper wire [see *Rakov et al.*, 1998, Figure 2] negative charge accumulates at the bottom of the wire. At B1 (see Figures 1a and 1b), a sufficient amount of negative charge is accumulated at the bottom of the floating channel, extending from about 200 m to a kilometer or two and polarized by the cloud electric field, that a downward negative "leader" is launched into the gap. It is also likely that at some point an upward "connecting leader" is initiated from the grounded rocket launcher, possibly in part explaining the non-zero current from B1 to B2. (*Lalande et al.* [1998] observed an upward connecting leader current of some tens of amperes from a grounded 50-m wire in altitude triggered lightning.) From B1 to B2 (see Figures 1a, 1b, and 1c), the gap is bridged by a "leader" that exhibits a pronounced downward progression

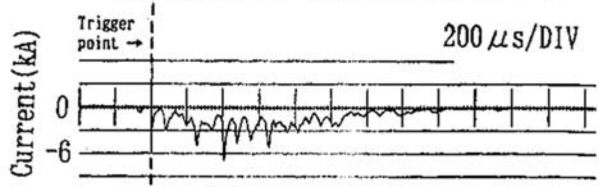
only along the lower half of the gap (negatively-sloped white arrow in Figure 1c), and at B2 a "return stroke" (upward black arrow in Figure 1c) is formed. This "return stroke", whose current peak at ground occurs at C (see Figures 1a, 1b, and 1c), traverses the newly formed (200 m or so in length) channel and then probably catches up with the upward propagating positive leader tip, as described by *Rakov et al.* [1998] for the case of altitude triggered lightning. Thus current flow to ground via the rocket launcher is reestablished.

[23] *Rakov and Uman* [1994], from single-station electric field and multiple-station TV records, reported on six return strokes (in six different flashes) that occurred in the same channel within a millisecond or less (72 to 1023 μs) of the preceding return stroke. A streak photograph of a similar event in triggered lightning was discussed by *Idone and Davis* [1999]. In order to explain the occurrence of such "abnormal" strokes, *Rakov and Uman* [1994] suggested that the "primary" return stroke current could be cut off near ground while current still flowed in the upper channel sections. As a result, the lightning channel, effectively disconnected from ground and extending in the thundercloud electric field, could become polarized, so that a downward negative leader could be launched from the bottom end of this channel with a short travel time to ground because of the short length of the cutoff channel. This leader would bridge the gap associated with the current cutoff and initiate the "secondary" return stroke. The described scenario appears to be very similar to the current cutoff and reestablishment in classical rocket-triggered lightning discussed above (see also *Mazur and Ruhnke* [1993, Figure 14] illustrating a similar scenario for regular subsequent strokes). It is also similar to the bidirectional leader/upward return stroke sequence during the initial stage of altitude triggered lightning [*Rakov et al.*, 1998, Figure 2]. One can speculate that a cutoff of current in any extending lightning channel, grounded or ungrounded, should be followed by breakdown processes attempting to bridge the resulting gap.

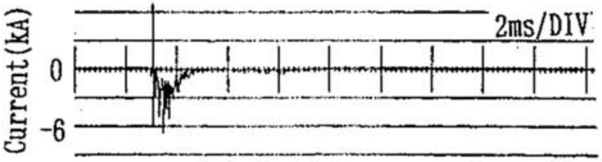
[24] *Kawasaki and Mazur* [1992, Figure 3] and *Mazur and Ruhnke* [1993] suggested that a maximum and the following decrease of the close lightning electric field is indicative of current cutoff near ground. We used the correlated 30-m electric field and current records for flash 9317 to evaluate this assumption. The overall electric field waveform in Figure 1b exhibits a maximum about 1.6 ms after the V-shaped pulse, while the current continued to flow to ground for a considerably longer time, over 80 ms after the field maximum until it became indistinguishable from the current noise floor of 72 A. The average value of current during this interval was about 180 A, and the corresponding charge transfer was about 15 C. (Interestingly, from the complete streak camera record, not shown here, the luminosity of the channel after the field maximum decreased more significantly above the top of the vaporized wire than below it.) Thus a decrease of the electric field of an upward positive leader cannot serve as an indication of current cutoff near ground, as assumed by *Kawasaki and Mazur* [1992, Figure 3] and by *Mazur and Ruhnke* [1993]. Such an electric field decrease could be due, for example, to a change in the charge density distribution along the extending channel with time. Note that the field variation in Figure 1b after the V-shaped pulse is reproduced faithfully since the instrumentation decay time constant of 35 ms is much greater than the duration of the field variation shown in Figure 1b.



(a) Lightning progressing feature



(b) Lightning current



(c) Lightning current

Figure 9. (a) Time-resolved optical record (Lightning progressing feature) and (b, c) current record of an upward positive leader (94-F-05) that was initiated from the 200-m Fukui chimney and exhibited pronounced stepping. Current is shown on two timescales, 200 μs/div (same as the timescale of the time-resolved image) and 2 ms/div. Note similarities with the event presented in Figure 1a, except for the features labeled A, B1, B2, and C in Figure 1a. Adapted from *Wada et al.* [1996].

5. Other Relevant Observations of Upward Positive Leaders that Exhibited Pronounced Stepping

[25] *Wada et al.* [1996] reported on an upward positive leader from the 200-m Fukui chimney in Japan, that exhibited pronounced optical steps and associated current pulses. This leader, event 94-F-05, occurred on 1 May 1995 and was not followed by leader/return stroke sequences; that is, the event was an upward flash composed of the initial stage only, similar to flashes 9317, S9713, and S9714 considered here. *Wada et al.* [1996] presented a time-resolved optical image of the leader within 1.3 km of the chimney top and associated current (on two timescales) measured at the top of the chimney, all reproduced in Figure 9. The upward positive leader propagated at a two-dimensional speed of 8×10^5 m/s and periodically increased in brightness, probably due to stepping. The current appeared as a unipolar wave with superimposed kilampere-scale pulses separated by some tens of microseconds, these pulses being coincident with enhancements (not well reproduced in Figure 9 but clearly seen in the original image) in the leader channel brightness. The overall

current duration was about 2 ms (probably an underestimate due to the lower current measurement limit being about 200 A) and its peak was about 6 kA. Overall, object-initiated lightning event 94-F-05 appears to be very similar to rocket-triggered lighting flash 9317 discussed above.

[26] We now briefly consider the formation of upward positive leader steps. It is likely that the step current can be viewed as being generated at the upward-moving leader tip and then propagating in the downward direction. Indeed, *Idone* [1992] found that luminosity waves associated with individual steps of the upward positive leaders in triggered lightning propagated from the leader tip down the channel. Since these waves traversed an air-plasma channel carrying a current of the order of 100 A, they were likely to be similar to incident downward M-component waves [*Rakov et al.*, 1995, 2001] with the associated upward (ground reflected) M-component waves being unresolved. *Idone* [1992] also estimated lower bounds of the downward speed for two steps to be 5×10^7 m/s and 6×10^7 m/s over 600 m and 400 m, respectively. As noted in section 3.3, there is some evidence that the luminous events following the right vertical white arrow in Figure 1c and associated with upward-positive-leader steps involved a downward propagation, consistent with *Idone*'s [1992] findings. Similarly, for a downward negative dart-stepped leader in rocket-triggered lightning, *Wang et al.* [1999c] reported step luminosity pulses that propagated from the leader tip upward (in the backward direction), toward the cloud.

6. Summary

[27] 1. In three triggered-lightning discharges considered here, the gap resulting from the vaporization of the triggering wire by the upward-positive-leader current is apparently bridged by a leader/return-stroke type process. The overall process of replacement of the grounded triggering wire by a plasma channel involves a bidirectional leader (involving the polarized channel above the vaporized wire) and is somewhat similar to the process of bridging the gap between the bottom of the floating triggering wire and ground in altitude triggered lightning [*Rakov et al.*, 1998, Figure 2]. Further, this process is probably similar to the formation of a downward leader when the channel current is cut off near ground [*Mazur and Ruhnke*, 1993, Figure 14] in natural lightning, particularly when the time elapsed after the preceding return stroke is a millisecond or less [*Rakov and Uman*, 1994; *Idone and Davis*, 1999].

[28] 2. Upward positive leaders in classical rocket-triggered lightning discussed here exhibited pronounced stepping. In one event, step current amplitudes were on average 1.6 kA, and individual steps were associated with an average charge transfer of 31 mC. The characteristics of these steps are similar to those observed for an upward positive leader from a tall object in Japan.

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