A triggered lightning flash containing both negative and positive strokes

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[1] We present measured current, luminosity, and electric and magnetic fields for a rocket-triggered two-stroke flash. The first stroke lowered negative charge to ground and the second stroke lowered positive charge via the same channel. A triggered positive stroke is a very rare event. The measured negative return stroke peak current was −11 kA and the positive +5 kA, with the total charge transfers being −1 C and +24 C, respectively. Electric field measurements at 120 to 520 m indicate that the negative and positive dart leader charge densities were approximately constant with height, -7.2×10^{-5} C m^{-1} and $+5.5 \times 10^{-5}$ C m^{-1}, respectively. Magnetic field measurements indicate a negative leader current of −1.9 kA and a positive leader current of +400 A. Negative and positive dart-leader speeds are estimated to be 2.7×10^{7} m s^{-1} and 0.7×10^{7} m s^{-1}, respectively. Negative and positive return stroke speeds are estimated to be 1.6×10^{8} and 0.92×10^{8} m s^{-1}, respectively. *INDEX TERMS:* 3300 Meteorology and Atmospheric Dynamics; 3304 Meteorology and Atmospheric Dynamics: Atmospheric electricity; 3324 Meteorology and Atmospheric Dynamics: Lightning. **Citation:** Jerauld, J., M. A. Uman, V. A. Rakov, K. J. Rambo, and D. M. Jordan (2004), A triggered lightning flash containing both negative and positive strokes, *Geophys. Res. Lett.*, *31*, L08104, doi:10.1029/2004GL019457.

1. Introduction

[2] "Classical" rocket-triggered lightning typically is initiated by launching a small rocket extending a grounded wire toward the overhead thundercloud. When the rocket reaches an altitude of a few hundred meters, a few seconds or less after launch, an upward-propagating electrical discharge (referred to as a leader) is often initiated at the top of the wire. Most triggered lightning lowers negative charge to Earth, the main negative charge center in Florida summer thunderclouds being at an altitude of 6 to 8 km. The "initial stage" of triggered lightning lowering negative charge involves tens of milliseconds of upward leader propagation followed by hundreds of milliseconds of relatively steady current between the cloud charge source and ground. When the initial stage ends and no current has flowed for a period of milliseconds or more, the remnant channel between the cloud charge source and ground is often traversed by a negatively-charged downward-propagating dart leader/upward-propagating return-stroke combination (the two-stage process being referred to as a stroke). These triggered strokes are very similar to the subsequent strokes (all strokes after the first) in natural negative cloud-to-ground lightning.

[3] The description above refers primarily to triggered strokes lowering negative charge to ground, since there is no statistical information available on triggered positive strokes. In fact only one well documented triggered positive stroke has been previously reported [*Idone et al.*, 1987]. That positive stroke was the third of an eight-stroke flash, the other strokes being negative, and was recorded at the Kennedy Space Center both optically and by a single-station electric field measuring system. The positive stroke attached to ground in a separate location from the first two negative strokes, each of which terminated on the rocket launcher, and hence its current could not be directly measured but was identified by the electric-field polarity. The positive stroke peak current was estimated to be about +21 kA, based on a single-station electric field record obtained 2.2 km away from the channel. The positive stroke was initiated by a positive stepped leader that departed from the previous negative stroke channel about 150 m above ground (apparently near the top of the vaporized triggering wire), with the 1 km or so of channel above the diversion point in the photo of *Idone et al.* [1987] being traversed by a positive dart leader.

[4] Natural positive lightning flashes are most often single-stroke events (99.6 percent are single-stroke according to *Lyons et al.* [1998]), in contrast to negative lightning flashes which most often (about 80 percent of flashes according to *Rakov and Huffines* [2003]) are composed of a first stroke followed by subsequent strokes. Clearly, positive subsequent strokes in natural lightning are rare. The reason for this is unknown but it is likely that the same physics renders positive triggered strokes rare.

2. The Experiment

[5] A two-stroke flash, containing a negative stroke followed by a positive stroke, was triggered on 22 July 2003, 21:16 UT, at the International Center for Lightning Research and Testing (ICLRT), about 45 km north-east of the University of Florida campus in Gainesville. Video images were recorded from several different locations. A mobile rocket launcher was elevated to a height of approximately 12 m above ground, and its bottom was connected by a conductive braid to three ground rods. Triggered lightning current was measured at the base of the rocket launcher with a current-measuring resistor. Current was digitized in two modes: at a sampling rate of 20 MHz for 5 ms time windows around each return stroke (5 MHz upper frequency limit) and continuously for 2 s at a sampling rate of 2 MHz (500 kHz upper frequency limit).

[6] The vertical electric field intensity at ground was measured at 5 locations, at distances ranging from about 120 m to about 520 m from the launcher, with capacitive flat-plate antennae having a bandwidth of 1 Hz to 4 MHz.

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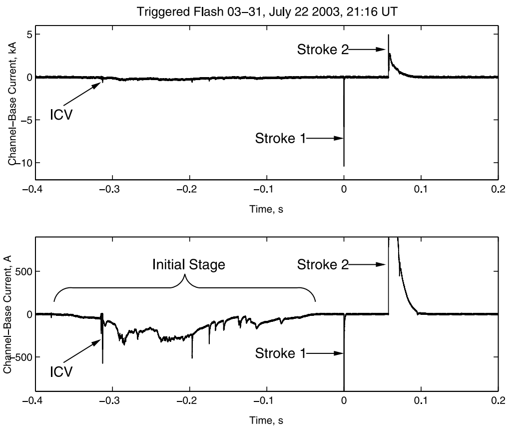

Figure 1. Overall flash current records. The initial stage, the initial current variation (ICV), and the two return strokes are labeled. The top and bottom records are displayed on the same time scale but on high and low amplitude scales, respectively. The bottom record is clipped (both polarities) at 900 A.

The east-west component of the horizontal magnetic field intensity at ground was measured at a single location, about 240 m from the launcher, with a coaxial-cable loop antenna having a bandwidth of 10 Hz to 4 MHz. All field measurements were digitized continuously for 1.6 s at a sampling rate of 10 MHz. *Jerauld et al.* [2003] give a complete description of the field sensors and the data acquisition system.

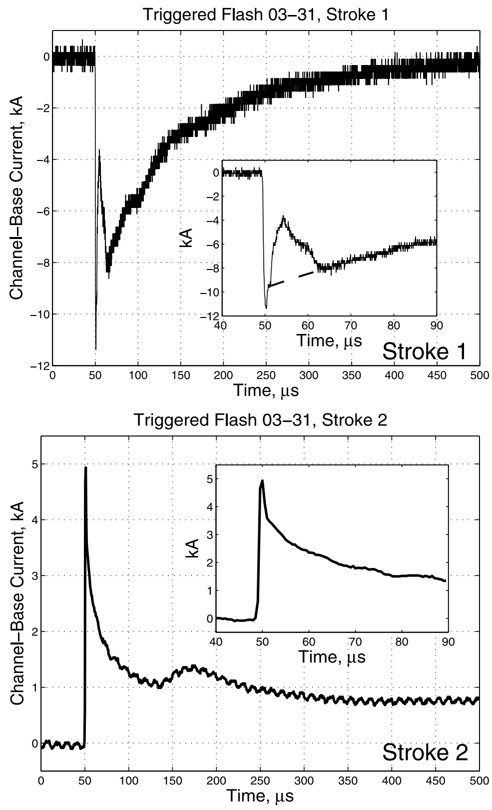

Figure 2. First (negative, top) and second (positive, bottom) return stroke current waveforms. The first stroke waveform was obtained from the high-bandwidth (5 MHz) record while the second stroke waveform was obtained from the low-bandwidth (500 kHz) record. The insets show the waveforms expanded on 50 μs time scales. The dotted line shown in the top inset is a hypothetical reconstruction of the current lost due to the flashover.

3. Data

[7] Video and still photographic records indicate that both strokes of the flash followed the same channel, at least for the bottom several hundred meters imaged above the launcher. The overall flash current waveform is shown in Figure 1. The initial stage lowered negative charge to ground. Near the point marked ICV (initial current variation [*Wang et al.*, 1999]), while the upward leader was still traversing the gap between the wire top and the cloud charge, the triggering wire was vaporized. The initial stage ends near time −0.05 s. The two return strokes are separated by about 58 ms. The return stroke current waveforms are shown on expanded time scales in Figure 2. The electric fields for both strokes, measured approximately 120 m from the channel, are shown in Figure 3. The magnetic fields for both strokes, measured approximately 240 m from the channel, are shown in Figure 4. Luminosity versus time waveforms for the first and second stroke channels, measured approximately 250 m away, are shown in Figure 5. Figure 6 shows plots of the dart-leader electric field change versus distance for both strokes, as measured at 5 stations.

[8] Stroke 1 lowered negative charge, a total of about −1 C with a peak current of −11.1 kA, while stroke 2 lowered positive charge, a total of about +24 C with a peak

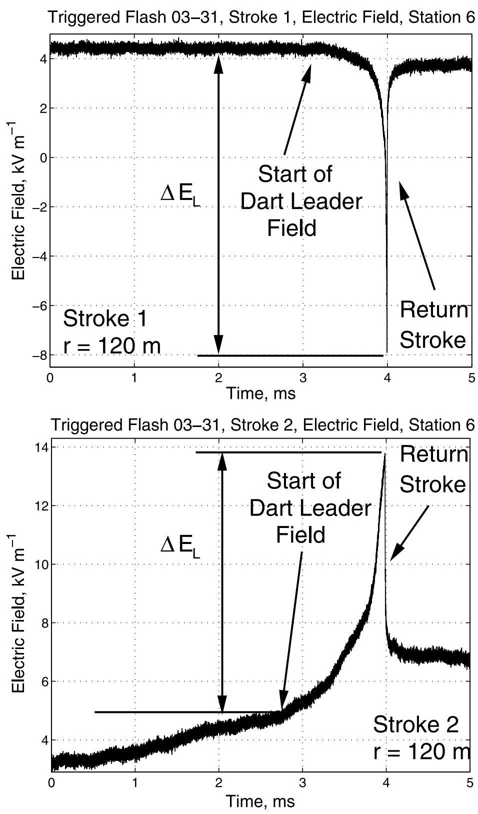

Figure 3. First (top) and second (bottom) stroke electric field waveforms, measured approximately 120 m from the channel. The start of the leader field and return stroke portion of the waveforms are labeled.

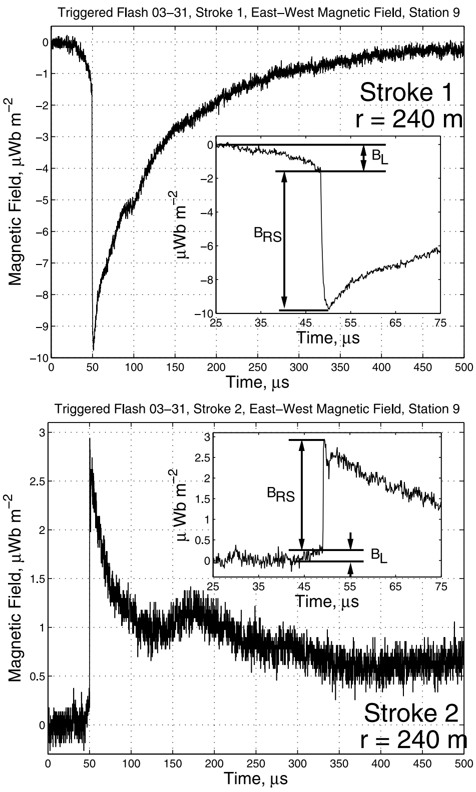

Figure 4. First (negative, top) and second (positive, bottom) stroke magnetic field waveforms, measured 240 m from the channel. Only the east-west component was measured, with the angle between the plane of the loop antenna and the direction to the launcher being approximately 20 degrees. The insets show the waveforms expanded on 50 µs time scales. The leader (B_L) and return stroke (B_{RS}) portions of the waveforms are labeled.

current of about +5 kA. A high-bandwidth (5 MHz) current record was obtained only for the first (negative) stroke, but low-bandwidth (500 kHz) records were obtained for both strokes. For the first stroke, the high-bandwidth record exhibits a peak of −11.1 kA whereas the low-bandwidth record has a peak of about −10.4 kA. The bandwidth distortion does not significantly affect the calculation of the charge transfer. The dip observed in the first-stroke current waveform (Figure 2, top), the bottom of which occurs about 4 µs after the return-stroke peak, but not seen in the magnetic field or luminosity waveforms (top plots of Figures 4 and 5, respectively), is likely due to a short-duration flashover (facilitated by the triggering wire from a previous unsuccessful launch), recorded on video, that allowed some current to bypass the current-measuring resistor. The dotted line, shown in the inset of the top plot of Figure 2, is a reconstruction of the missing current due to the flashover. The reconstruction results in a current waveshape similar to that observed for most other triggered strokes.

4. Discussion

[9] *Rakov* [2003] has identified three different types of "bipolar" lightning flashes. His Type 3 includes flashes that have return strokes of different polarities. Current waveforms indicating such flashes have been documented on tall towers by *McEachron* [1939, Figure 17] in the USA, *Berger and Vogelsanger* [1965, Figure 18] in Switzerland, *Janischewskyj et al.* [1999] in Canada, and *Schulz and Diendorfer* [2003, Figure 4.1] in Austria. The Canadian flash contained three strokes, the second of which was positive, following the same channel within at least 535 m above the tower top, that was initiated by an upward leader from the 553-m high Canadian National (CN) tower in Toronto. The three consecutive return stroke peak currents, in stroke order, were −10.6 kA, +6.5 kA, and −8.9 kA. Note that the first two strokes were of the same polarity and roughly the same peak current as the two strokes in the triggered flash studied in the present paper. The Austrian flash was initiated from the 100-m Gaisberg tower (on a mountain top) and contained a negative stroke having −15.7 kA peak current followed 17.2 ms later by a positive stroke having +8.3 kA peak current. This latter sequence is also very similar to the case under study here.

[10] *Crawford et al.* [2001] found that the distance dependence for triggered negative dart leader electric field changes was typically r^{-1} at distances (r) ranging from tens to hundreds of meters, implying a uniform charge density in the bottom kilometer or so of the leader channel. The data in Figure 6 are more or less consistent with *Crawford et al.* [2001] if the appropriate point is chosen for the start of the leader field change. The starting points chosen for the negative and positive dart leader electric fields are shown

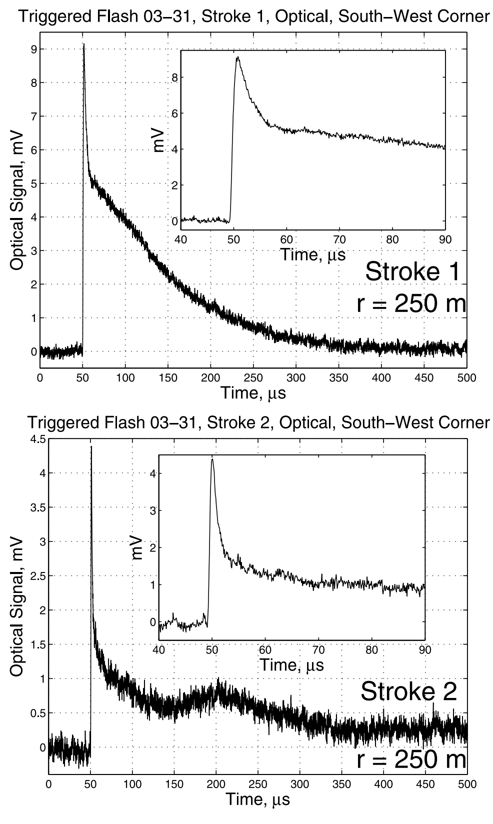

Figure 5. First (top) and second (bottom) stroke luminosity waveforms, measured at the south-west corner of the network, approximately 250 m from the channel. The insets show the waveforms expanded on 50 µs time scales.

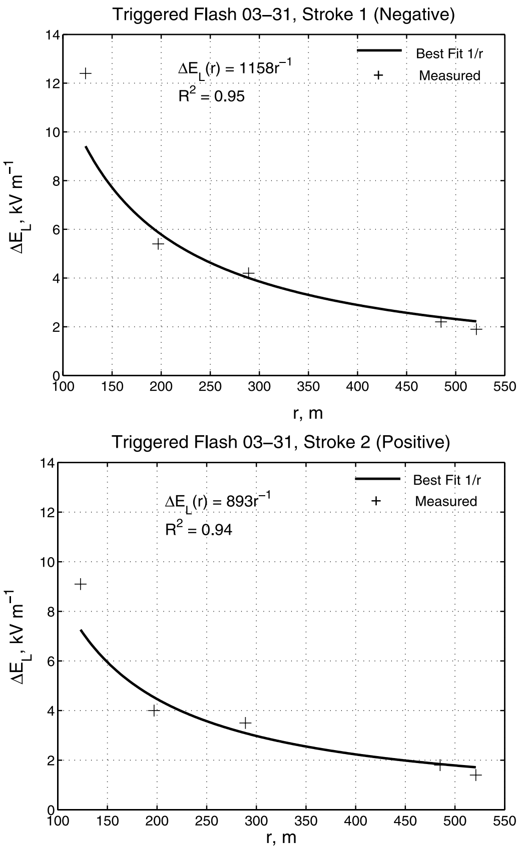

Figure 6. Plots of the first (top) and second (bottom) stroke leader electric-field change versus distance as measured from waveforms recorded at five stations located 120 to 520 m from the lightning channel. The best-fit inverse distance dependence curve (solid line) is plotted along with the measured data. The waveforms recorded at 120 m are shown in Figure 3.

in Figure 3. An assumed leader field starting point much earlier than those shown in Figure 3, for either leader, would result in an unreasonably long leader channel length (given a reasonable dart leader speed). The dart-leader charge density (ρ) was calculated for each stroke at each of the 5 electric-field measuring stations from the expression given by *Rubinstein et al.* [1995, equation 3] with an assumed leader channel height of 7.5 km. For the negative leader, the mean value of ρ, averaged over 5 stations, is -7.2×10^{-5} C m^{-1} with a standard deviation of 1.0×10^{-5} C m^{-1}. For the positive leader, the mean value of ρ is $+5.5 \times 10^{-5}$ C m^{-1} with a standard deviation of 0.80×10^{-5} C m^{-1}, again averaged over 5 stations.

[11] For each stroke, the magnetic field from the dart leader was measured in the magnetic field record prior to the return stroke (see Figure 4). Using Ampere's law for magnetostatics, the estimated first (negative) stroke dart leader current, just before the return stroke, is approximately -1.9 kA. The positive dart leader current, just prior to the return stroke, is estimated to be about +400 A (the positive dart leader magnetic field, and hence the positive dart leader current, was estimated to only one significant figure). Using the estimated dart leader currents and mean line charge densities, the dart leader speeds can be estimated with the approximation $I = \rho v$, where v is the dart leader speed and I is assumed to be a step-function current [*Kodali et al.*, 2004]. The negative dart leader speed, just prior to the beginning of the return stroke, is estimated to be 2.7×10^7 m s^{-1}. The estimated positive dart leader speed is 0.7×10^7 m s^{-1}. Hence the negative dart leader speed, near ground, is roughly a factor of 4 greater than the positive dart leader speed.

[12] Very rough estimates of the return stroke speeds can be made by again assuming $I = \rho v$ (I is the peak return stroke current and v is the return stroke speed), that is, assuming a step-function return stroke current and return-stroke line charge density equal to the dart leader line charge density. The estimated return stroke speeds are 1.6×10^8 and 0.92×10^8 m s^{-1}, for the negative and positive strokes, respectively. The event described by *Idone et al.* [1987] was estimated to have a positive return stroke speed of about 1×10^8 m s^{-1}, with similar speeds for the negative strokes in the flash, based on high-speed optical records. The positive stroke, however, was initiated by a positive stepped leader that departed from the previously-formed channel (from being a dart leader) about 150 m above ground, as noted earlier.

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