

Observations of the initial, upward-propagating, positive leader steps in a rocket-and-wire triggered lightning discharge

Christopher J. Biagi,¹ M. A. Uman,¹ J. D. Hill,¹ and D. M. Jordan¹

Received 7 October 2011; revised 15 November 2011; accepted 17 November 2011; published 31 December 2011.

[1] We present high-speed video images (recorded at 300 kfps) of an upward positive leader developing stepwise from the top of a grounded triggering wire. The leader initiated from the wire top at a height of 123 m, and was imaged over a distance of 11 m in ten discrete steps. Unique current pulses were detected at the wire base corresponding to each optical step. Luminosity waves propagated downward from the leader tip. The step lengths ranged from 0.4 to 2.2 m; the interstep time intervals from 16.6 to 30.4 μs . The leader's upward development speed increased with height, from $5.5 \times 10^4 \text{ m s}^{-1}$ between heights of 123 m and 134 m, the bottom 11 m, to $2.1 \times 10^5 \text{ m s}^{-1}$ at a height of 350 m. The measured wire-base peak currents for the individual steps ranged from 17 to 153 A. After removing from the wire-base current measurements the effect of propagation on the triggering wire and the effect of reflection at the ground connection, we estimate that the peak currents at the wire top, the step current, ranged from 10 to 89 A. The charge lowered to ground following each step ranged from 22 to 107 μC . The leader channel contained, on average, 51 $\mu\text{C m}^{-1}$ of positive charge, a value that is similar to laboratory measurements of long positive polarity sparks. **Citation:** Biagi, C. J., M. A. Uman, J. D. Hill, and D. M. Jordan (2011), Observations of the initial, upward-propagating, positive leader steps in a rocket-and-wire triggered lightning discharge, *Geophys. Res. Lett.*, 38, L24809, doi:10.1029/2011GL049944.

1. Introduction

[2] Classical rocket-and-wire triggered lightning can be considered to originate when a sustained upward positive leader initiates from the top of the grounded triggering wire and develops upward toward the overhead cloud charge [Rakov and Uman, 2003]. There are few reports in the literature of observations of the development of upward positive leaders in artificially triggered lightning via highly time-resolved streak photography [Fieux *et al.*, 1978; Laroche *et al.*, 1988; Idone, 1992; Horii and Nakano, 1995; Lalande *et al.*, 2002] or high speed video framing [Kito *et al.*, 1985; Biagi *et al.*, 2009; Yoshida *et al.*, 2010]. The upward positive leader can apparently develop stepwise [e.g., Laroche *et al.*, 1988; Idone, 1992] or continuously [e.g., Horii and Nakano, 1995], and it sometimes alternates development modes [e.g., Idone, 1992]. The upward positive leader development speed increases with height, from as low as $\sim 10^4 \text{ m s}^{-1}$ near 100 m above ground level (AGL) [e.g., Fieux *et al.*, 1978; Yoshida *et al.*, 2010] to $3.3 \times 10^6 \text{ m s}^{-1}$

above a height of 1.5 km AGL (as observed using 3-D VHF interferometry by Yoshida *et al.* [2010]). When the upward positive leader develops stepwise, the leader step lengths apparently increase with height AGL [Yoshida *et al.*, 2010]. Laroche *et al.* [1988] reported that upward positive leader steps had a mean length of 14 m when the leader was at an altitude of about 1 km. Laroche *et al.* [1988] and Idone [1992] both reported mean interstep time intervals of 20 μs . A numerical model developed by Gallimberti *et al.* [2002] was used by Lalande *et al.* [2002] to predict stepping in upward positive leaders in classical triggered lightning, with an interstep time interval of 28 μs .

[3] The reports summarized above primarily describe the upward positive leader in triggered lightning at intermediate altitudes of several hundred meters to a few kilometers. No reports exist in the literature of optical observations of the leader developing stepwise from the triggering wire top, and, additionally, none with synchronized wire base current. In this paper, we present synchronized high-speed video and wire-base current of the lowest 11 m of an upward positive leader in a classical triggered lightning flash. The stepped development of the upward positive leader is resolved both temporally and spatially in the high-speed video images. Further, unique current pulses were measured at the wire base in association with each step. We present salient optical and current measurements of the upward positive leader steps. We relate our measurements to those of upward positive leaders at higher altitudes in triggered lightning, and to leaders in long positive laboratory sparks.

2. Experiment

[4] The observations presented in this paper are of a rocket-and-wire triggered flash, identified as UF09-30, that occurred at the International Center for Lightning Research and Testing (ICLRT), located in north-central Florida, at approximately 14:01:04.016 (GMT) on 30 June 2009. Note that Yoshida *et al.* [2010] tracked above a height of 1.5 km the upward positive leader of this flash using VHF interferometry. The rocket carrying the grounded triggering wire was launched from a 3-m launch tube assembly on top of an 11-m high launch tower located near the center of the experimental site. The triggering wire was Kevlar-reinforced, 0.2-mm diameter copper. Channel-base current was measured at the launch tower with a 1-m Ω current-viewing resistor (shunt) having a flat frequency response from DC to 3 MHz. The shunt output was fed in parallel to two different front-end electronics configurations that provided lower-range current data on two scales: designated "low" and "very-low" with effective dynamic ranges of about $\pm 6.3 \text{ kA}$, and, $\pm 21 \text{ A}$, respectively (an additional current scale not used here recorded higher currents up to $\pm 65 \text{ kA}$). Both

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

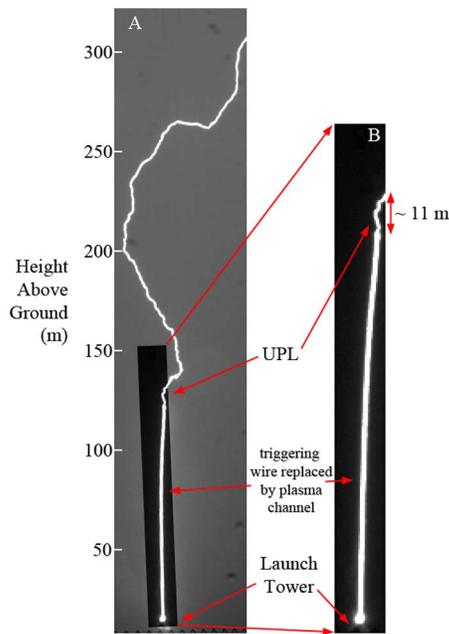


Figure 1. High-speed video images of the upward positive leader channel during the initial stage of UF09-30. (a) Image recorded by the Phantom camera at 8 kfps ($120 \mu\text{s}$ per frame) showing the destroyed triggering wire that has been replaced by a plasma channel, and the upward positive leader channel above it. The darker region of the image identifies the Photron's field of view. (b) Image recorded by the Photron camera at 300 kfps ($3.3 \mu\text{s}$ per frame) showing the plasma channel that replaced the destroyed triggering wire and about 11 m of the upward positive leader channel.

current measurements were digitized with 12-bit amplitude resolution at a sampling rate of 10 MHz. Positive current at the wire base corresponds to negative charge moving downward or positive charge moving upward.

[5] High-speed video frames were recorded by a Phantom v7.3 operating at a framing rate of 8 kfps (about $120 \mu\text{s}$ exposure time per frame) with 14-bit amplitude resolution, and a Photron SA1.1 operating at a framing rate of 300 kfps (about $3.3 \mu\text{s}$ exposure time per frame) with 12-bit amplitude resolution. Note that the video images recorded by the cameras are the integral of the channel luminosity over the duration of an exposure. Both cameras were co-located approximately 440 m from the launch tower. The Phantom viewed heights from ground to 320 m AGL with a spatial resolution of about 0.4 m per pixel. The Photron viewed heights from the launch tower top to approximately 150 m AGL with a spatial resolution of about 0.5 m per pixel.

3. Observation

[6] The grounded triggering wire was extended vertically when the ground-level quasi-static electric field was about 7.2 kV m^{-1} , indicating that predominately negative charge was overhead (physics sign convention). The upward positive leader that initiated triggered flash UF09-30 began its development when the triggering wire top was at a height of about 123 m. The lower 200 m or so of the upward positive leader channel that was imaged by the Phantom camera is shown in Figure 1a, and the lower 11 m of channel that was

imaged by the Photron camera is shown in Figure 1b. The Photron camera recorded a total of 60 images (about $200 \mu\text{s}$) before the upward positive leader propagated out of the camera's field of view. The upper right regions of these 60 images are arranged in a sequence of three rows in Figure 2, with time increasing from left to right and from top to bottom. The leader channel length after each new step is displayed in Figure 2, and given in Table 1. The wire-base current recorded by the very low measurement is also shown in Figure 2 (with a time scale that is aligned with the high-speed video frames). The very low measurement shown in Figure 2 saturated at about $\pm 21 \text{ A}$. Figure 3 shows the low current measurement on approximately the same time scale as the current plots in Figure 2. The leader steps in Figures 2 and 3, and Table 1, are identified by lower-case letters near the respective current pulses.

[7] Several interesting observations can be made from the data presented in Figures 2 and 3 and summarized in Table 1. The upward positive leader developed to a length of about 11 m in 8 distinct steps (steps a through h), with step lengths that ranged from 0.8 m to 2.2 m with a mean value of 1.5 m. Distinct channel brightening and wire-base current pulses were observed for steps nine and ten after the leader had extended beyond the camera's field of view. The channel diameter for the first step appears to overlap about two pixels, or a width of up to 0.9 m. It is difficult to resolve the channel diameter in successive steps, but it appears to never exceed two pixels. The channel appears to have lower luminosity on each side extending out 1 pixel, or about 0.5 m. This luminosity may be due to camera blooming, or it may be evidence of a corona sheath. The leader developed upward with an average speed of $5.5 \times 10^4 \text{ m s}^{-1}$ in its first 11 m of development, and by the time the leader exited the Phantom field of view at an altitude of about 310 m, the average speed had increased fourfold to $2.1 \times 10^5 \text{ m s}^{-1}$. Steps e, f, g, and h developed in two high-speed video frames. In the first frames for Steps f, h, and h, luminosity appears first at the top of previously formed channel segment (with no spatial separation between the two), followed by a re-illumination of the previously established channel in the following frame, indicating that a current wave was generated at the leader tip that subsequently traveled down the channel. The bottom end of the newly formed steps was always at the upper end of the previously established leader. The interstep time interval (determined from the time between current pulses) ranged from 16.6 to $30.4 \mu\text{s}$ with a mean value of $21.1 \mu\text{s}$.

[8] It is evident in Figures 2 and 3 that a corresponding current pulse is detected at the wire base for each step observed in the high-speed video images. This current pulse contains a negative charge that is equivalent to the positive charge deposited on the new section of leader channel, assuming that no charge is deposited on the triggering wire (C. J. Biagi et al., Transient current pulses in rocket-extended wires used to trigger lightning, submitted to *Journal of Geophysical Research*, 2011). The incident current pulse that is injected into the leader and wire by each step is likely unipolar with a full width on the order of several microseconds, as shown in the modeling of Biagi et al. (submitted manuscript, 2011) for similar current pulses produced by precursors (non-sustained leader channels that usually stop developing after a few meters). What is measured at the wire base is a single current pulse exhibiting a

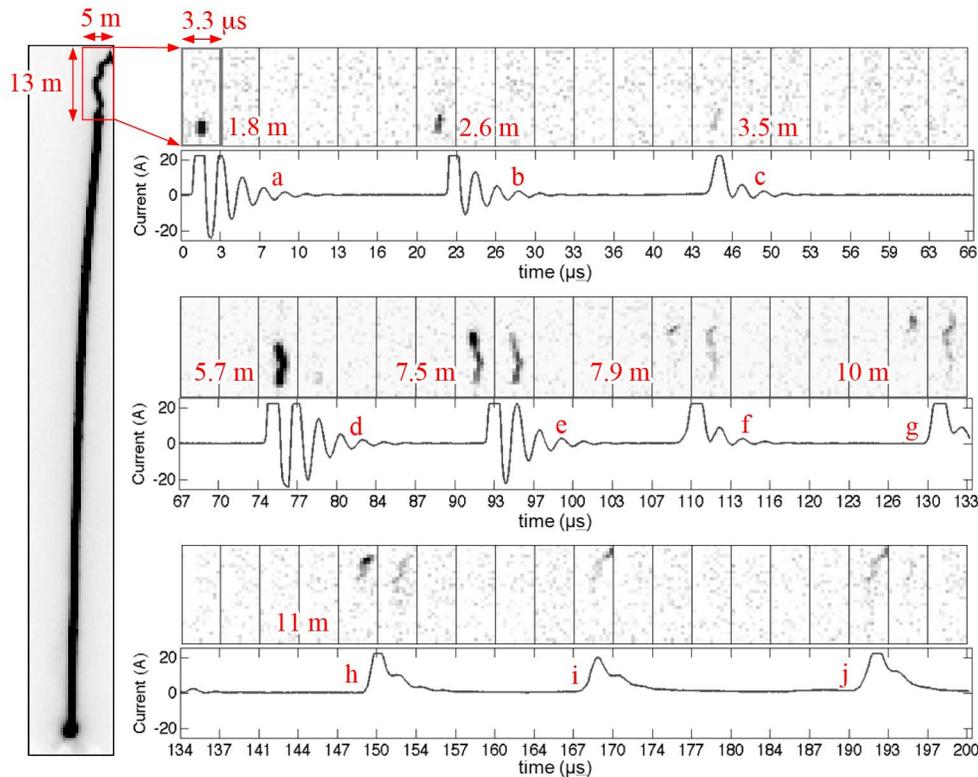


Figure 2. The sequence of 60 Photron images containing the upward positive leader of UF09-30, and the synchronized wire-base current. The part of the Photron image containing lightning channel is shown on the left for reference. All of the images are intensity inverted and contrast enhanced. Each image in the sequence views the same 13×5 m of space, and is an integration of luminosity over a time of $3.3 \mu\text{s}$. The numbers next to the leader channel give the total length of the leader channel after each step. The leader develops outside the field of view with step i when it is approximately 11 m in length. The very low current measurement at the wire base saturated at about 21 A (also shown in Figure 3b).

more or less damped-oscillatory behavior. The first peak of the damped-oscillatory signature that is measured at the wire base is the superposition of (1) the current pulse that was generated at the wire top and propagated down the wire, and (2) a reflected current pulse of the same polarity from the approximately short-circuit termination at the ground rod. During the time when the first current pulse is flowing at the

wire base, there are several sequences of current pulse reflections from the ground and wire top, reversing polarity with each wire/leader top reflection (the wire top or leader tip constitutes an open circuit termination). These reflected current pulses superimpose with the original unipolar pulse, yielding the oscillatory behavior. The magnitude of successive reflected current pulses are increasingly smaller due to

Table 1. Salient Information for the Stepped Upward Positive Leader of UF09-30

Step	Step Length (m)	Total Leader Length (m)	Interstep Time Interval (μs)	Measured Peak Current (A)	Scaled Peak Current ^a (A)	Step Charge (μC)	Ratio of Step Charge to Step Length ($\mu\text{C m}^{-1}$)
a	1.8	1.8	n/a	123	71	47	26
b	0.8	2.6	21.4	37	21	22	28
c	0.9	3.5	21.7	25	14	n/a ^b	n/a ^b
d	2.2	5.7	30.4	153	89	107	49
e	1.8	7.5	18.6	122	71	99	55
f	0.4	7.9	17	32	19	44	110
g	2.1	10	20.5	41	24	70	33
h	n/a ^c	11	19.0	17	10	n/a	n/a ^b
i	n/a	n/a	16.6	23	14	60 ^d	n/a ^b
j	n/a	n/a	24.9	20	12	n/a	n/a ^b
arithmetic mean	n/a	1.4	21.2	59	34	64	51

^aThe measured peak current is scaled to take account of reflections at ground and attenuation along the wire (using Equation 6–16 in Section 6.4.3).

^bOnly the first peak of these current pulses was resolved, the rest of the pulse was below the noise floor so the charge could not be determined.

^cThe leader was developing outside of the camera's field of view for Steps h, i and j.

^dThe charge for Step i was determined from the very low shunt measurement (the others were determined from the low measurement).

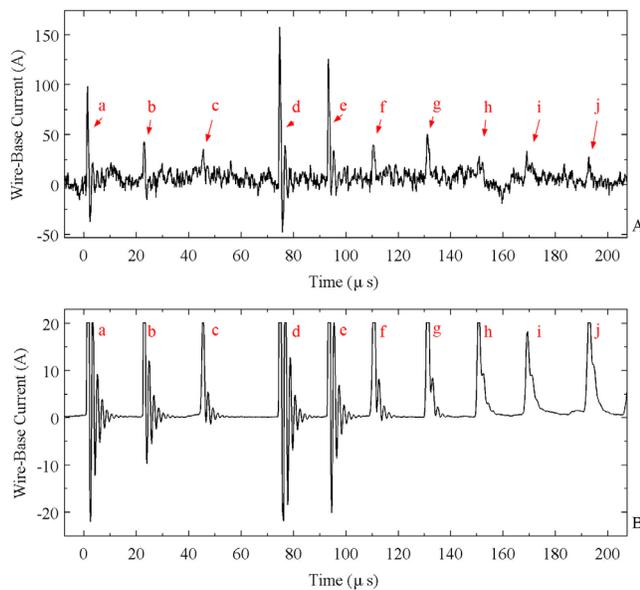


Figure 3. The wire-base current associated with the ten upward positive leader steps in UF09-30 that were imaged with high-speed video. (a) The low current measurement. (b) The very low current measurement (also shown in Figure 2).

energy losses from propagation on the resistive wire and leader channel, and charge absorption by the leader and ground.

[9] The current pulses measured at the wire base become smoother and less oscillatory as the leader grows in length, with the exceptions of steps d and e. It is reasonable to assume that the electrical characteristics of the triggering wire did not change in the 200 μs during which the steps occurred, nor does the wire length or the grounding impedance. Thus, the change in the current pulses measured at ground can be reasonably attributed to the upward developing leader channel increasingly attenuating successive current pulse reflections (see Biagi et al. (submitted manuscript, 2011) for a full discussion of these processes).

[10] The measured peak currents for Steps a through j, determined from the low current measurement shown in Figure 3, are given in Table 1; they ranged from 17 to 153 A with a mean of 59 A. The incident current peaks can be estimated by accounting for (1) the transmission line effects of the triggering wire; that is, scaling the measured wire-base current peaks to account for the propagation losses in the wire and (2) the current reflection from ground. The following equation from Biagi et al. (submitted manuscript, 2011) provides a scaling factor:

$$G = [(1 + \Gamma_G) \exp(\alpha l)]^{-1} \quad (1)$$

with the attenuation constant for current propagation on the triggering wire being $\alpha = 8.2 \times 10^{-4} \text{ Np m}^{-1}$, and the ground reflection coefficient being $\Gamma_G = 0.9$. Using these values, and a wire length, l , of 123 m, the wire base current should be scaled by a factor $G = 0.58$ to account for the transmission line effects. The scaled peak current amplitudes are given in Table 1; they ranged from 10 to 89 A with a mean of 34 A.

[11] The charges associated with steps a, b, d, e, f and g were estimated by computing the time integral of the current signature in the low current measurement. The charge for step i was computed from the very low current measurement. The charge cannot be computed for steps c, h, and i because their signal to noise ratio is too low. It is assumed that, by the end of the damped oscillatory signature measured at ground, a charge is lowered to ground that is equal to the charge deposited by the new leader step (but of opposite polarity). This computation is similar to what is done for precursors of Biagi et al. (submitted manuscript, 2011). The charges for the current pulses associated with the ten steps in Figure 2 and 3 are given in Table 1; they ranged from 22 to 107 μC with a mean of 64 μC. The ratio of the step charges to the step lengths ranged from 26 to 110 μC m⁻¹ with a mean of 51 μC m⁻¹. The steps with higher currents that lowered more charge to ground tended to have higher integrated luminosity, but there was no clear relationship between the luminosity and scaled peak current or step charge, perhaps owing to the low signal to noise ratio of the optical and current measurements.

4. Discussion

[12] Other researchers, using streak photography, have observed that upward positive leaders in triggered lightning develop intermittently [e.g., Laroche et al., 1988; Idone, 1992; Rakov et al., 2003]. The high-speed video images presented in Figure 2 are the first images from a framing camera of a positive leader clearly stepping as it first develops from the triggering wire top, additionally coordinated precisely with wire-base current pulses. The luminosity waves that appear to propagate downward from the leader tip are consistent with similar observations by Idone [1992] and Rakov et al. [2003]. The currents determined for each leader step, both measured and scaled (on average 59 and 34 A, respectively), are consistent with other reports of current pulses associated with the initiation of upward positive leaders [e.g., Laroche et al., 1988; Lalande et al., 1998; Willett et al., 1999; Biagi et al., 2009], but are up to two orders of magnitude less than the peak currents (on average 1.6 kA) reported for individual steps in an upward positive leader at higher altitudes between 300 to 500 m by Rakov et al. [2003]. The individual steps of the upward positive leader examined by Rakov et al. [2003] transferred on average 31 mC of charge, or about a factor of 500 more than the average charge per step, 64 μC, for the upward positive leader in UF09-30. It is worth noting that Rakov et al. [2003] defined a step as an “impulsive process that periodically illuminates the extending leader channel...regardless of the mechanism involved”, and that the tip of the upward positive leader was not observed optically.

[13] The upward positive leader developed from the wire top at a height of about 123 m with an average speed of $5.5 \times 10^4 \text{ m s}^{-1}$, which increased fourfold to $2.1 \times 10^5 \text{ m s}^{-1}$ when the leader tip reached a height of 310 m. These average speeds are consistent with those reported by other [e.g., Fieux et al., 1978; Laroche et al., 1988; Idone, 1992; Biagi et al., 2009]. Yoshida et al. [2010], who presented a detailed description of the same upward positive leader in

UF09-30 as it developed to higher altitudes using 3-D interferometric images, reported that the leader developed from 1.5 to 3.7 km with a three-dimensional speed of $3.3 \times 10^6 \text{ m s}^{-1}$.

[14] The lengths of the leader's first steps between heights of 123 and 134 m (0.8 to 2.2 m), were smaller than those measured by *Laroche et al.* [1988] (14 m) for a leader at a height of about 1 km. The mean interstep time intervals for the upward positive leader in UF09-30 was about 21 μs , which is consistent with the average interstep time interval reported by *Laroche et al.* [1988] of 20 μs , but less than the average interstep time of 50 μs that *Rakov et al.* [2003] inferred from current and electric field records for an upward positive leader at a height of 300 to 500 m.

[15] Intermittent development of positive leaders has also been observed in long laboratory sparks [e.g., *Gorin et al.*, 1976; *Les Renardieres Group*, 1977; *Gallimberti*, 1979; *Domens et al.*, 1991; *Bazelyan and Raizer*, 1998; *Bazelyan and Raizer*, 2000; *Gu et al.*, 2010]. The measured charges for the upward positive leader steps in UF09-30 are consistent with charge measurements for long positive laboratory sparks [e.g., *Les Renardieres Group*, 1972, 1974, 1977; *Domens et al.*, 1991]. *Domens et al.* [1991], who studied the 3-D development and charges of positive leaders in a 16.7-m spark gap, determined that 50 μC of charge flowed through the high voltage electrode for each meter of leader growth. For the upward positive leader of UF09-30, the charge per unit length was computed for each step by dividing the total charge per step by the step's length. The computed charge per unit length ranged from 26 to 110 $\mu\text{C m}^{-1}$ with a mean of 51 $\mu\text{C m}^{-1}$, which is essentially the same value determined for the long laboratory spark by *Domens et al.* [1991].

5. Summary

[16] We have presented images from a high-speed video framing camera showing an upward positive leader developing stepwise from the triggering wire top, additionally with synchronized unique current pulses observed at the triggering wire base. We have provided measurements of the leader step currents, charges, lengths, and interstep time intervals, and these measurements are, by and large, consistent with those reported by most others, with the notable exception of *Rakov et al.* [2003]. We have determined that the charge per unit length of the upward positive leader near the wire top is essentially the same as for positive leaders in long laboratory sparks.

[17] **Acknowledgments.** This research was supported in part by DARPA grants HR0011-08-1-0088 and HR0011-1-10-582 1-0061, and NASA grant NNK10MB02P.

[18] The Editor thanks the two anonymous reviewers for their assistance in evaluating this paper.

References

Bazelyan, E. M., and Y. P. Raizer (1998), *Spark Discharge*, CRC Press, Boca Raton, Fla.

- Bazelyan, E. M., and Y. P. Raizer (2000), *Lightning Physics and Lightning Protection*, Inst. of Phys., Bristol, U. K., doi:10.1887/0750304774.
- Biagi, C. J., D. M. Jordan, M. A. Uman, J. D. Hill, W. H. Beasley, and J. Howard (2009), High-speed video observations of rocket-and-wire initiated lightning, *Geophys. Res. Lett.*, *36*, L15801, doi:10.1029/2009GL038525.
- Domens, P., A. Gilbert, J. Dupuy, and B. Hutzler (1991), Propagation of the positive streamer-leader system in a 16.7 m rod-plane gap, *J. Phys. D Appl. Phys.*, *24*, 1748–1757, doi:10.1088/0022-3727/24/10/009.
- Fieux, R. P., C. H. Gary, B. P. Hutzler, A. R. Eybert-Berard, P. L. Hubert, A. C. Meesters, P. H. Perroud, J. H. Hamelin, and J. M. Person (1978), Research on artificially triggered lightning in Fance, *IEEE Trans. Pow. Appar. Syst.*, *PAS-97*, 725–733.
- Gallimberti, I. (1979), The mechanism of the long spark formation, *J. Phys.*, *7*(40), 7–193.
- Gallimberti, I., G. Bacchiega, A. Bondiou-Clergerie, and P. Lalande (2002), Fundamental processes in long air gap discharges, *C. R. Phys.*, *3*, 1335–1359, doi:10.1016/S1631-0705(02)01414-7.
- Gorin, B. N., V. I. Levitov, and A. V. Shkilev (1976), Some principles of leader discharge of air gaps with a strong non-uniform field, *IEE Conf. Publ.*, *143*, 274–278.
- Gu, S., W. Chen, J. Chen, H. He, and G. Qian (2010), Observations of the streamer-leader propagation processes of long air-gap positive discharges, *IEEE Trans. Plasma Sci.*, *38*(2), 214–217, doi:10.1109/TPS.2009.2037004.
- Horii, K., and M. Nakano (1995), Artificially triggered lightning, in *Handbook of Atmospheric Electrodynamics*, vol. 1, edited by H. Volland, pp. 151–166, CRC Press, Boca Raton, Fla.
- Idone, V. P. (1992), The luminous development of Florida triggered lightning, *Res. Lett. Atmos. Electr.*, *122*, 23–28.
- Kito, Y., K. Horii, Y. Higashiyama, and K. Nakamura (1985), Optical aspects of winter lightning discharges triggered by the rocket-wire technique in Hokuriku district of Japan, *J. Geophys. Res.*, *90*, 6147–6157.
- Lalande, P., A. Bondiou-Clergerie, P. Laroche, A. Eybert-Berard, J.-P. Berlandis, B. Bador, A. Bonamy, M. A. Uman, and V. A. Rakov (1998), Leader properties determined with triggered lightning techniques, *J. Geophys. Res.*, *103*(D12), 14,109–14,115, doi:10.1029/97JD02492.
- Lalande, P., A. Bondiou-Clergerie, G. Bacchiega, and I. Gallimberti (2002), Observations and modeling of lightning leaders, *C. R. Phys.*, *3*, 1375–1392, doi:10.1016/S1631-0705(02)01413-5.
- Laroche, P., A. Eybert-Berard, L. Barret, and J. P. Berlandis (1988), Observations of preliminary discharges initiating flashes triggered by the rocket and wire technique, paper presented at the 8th International Conference on Atmospheric Electricity, Uppsala Univ., Swed. Nat. Sci. Res. Council, Uppsala, Sweden, 13–16 June.
- Les Renardieres Group (1972), Research on long air gap discharges at Les Renardieres, *Electra*, *23*, 53–157.
- Les Renardieres Group (1974), Long air gap discharges at Les Renardieres: 1973 results, *Electra*, *35*, 49–156.
- Les Renardieres Group (1977), Positive discharge in long air gaps at Les Renardieres: 1975 results and conclusions, *Electra*, *53*, 31–153.
- Rakov, V. A., and M. A. Uman (2003), *Lightning: Physics and Effects*, Cambridge Univ. Press, New York.
- 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.
- Willett, J. C., D. A. Davis, and P. Laroche (1999), An experimental study of positive leaders initiating rocket-triggered lightning, *Atmos. Res.*, *51*, 189–219, doi:10.1016/S0169-8095(99)00008-3.
- Yoshida, S., C. J. Biagi, V. A. Rakov, J. D. Hill, M. V. Stapleton, D. M. Jordan, M. A. Uman, T. Morimoto, T. Ushio, and Z.-I. Kawasaki (2010), Three-dimensional imaging of upward positive leaders in triggered lightning using VHF broadband digital interferometers, *Geophys. Res. Lett.*, *37*, L05805, doi:10.1029/2009GL042065.

C. J. Biagi, J. D. Hill, D. M. Jordan, and M. A. Uman, Department of Electrical and Computer Engineering, University of Florida, Gainesville, FL 32611, USA. (biagi@ufl.edu)