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A review of ten years of triggered-lightning experiments at Camp Blanding, Florida

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Abstract

The principal results of triggered-lightning experiments conducted at the International Center for Lightning Research and Testing (ICLRT) at Camp Blanding, Florida, from 1993 through 2002 are reviewed. These results include (a) characterization of the close lightning electromagnetic environment, (b) first lightning return-stroke speed profiles within 400 m of ground, (c) new insights into the mechanism of the dart-stepped (and by inference stepped) leader, (d) identification of the M-component mode of charge transfer to ground, (e) first optical image of upward connecting leader in triggered-lightning strokes, (f) electric fields in the immediate vicinity of the lightning channel, (g) inferences on the interaction of lightning with ground and with grounding electrodes, (h) discovery of X-rays produced by triggered-lightning strokes, (i) new insights into the mechanism of cutoff and reestablishment of current in rocket-triggered lightning. Selected results are discussed.

Keywords: Triggered lightning; Electromagnetic environment; Upward connecting leader; M-component

1. Introduction

The lightning-triggering facility at Camp Blanding, Florida was established in 1993 by the Electric Power Research Institute (EPRI) and Power Technologies, Inc. (PTI).

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Fig. 1. Photographs of lightning flashes triggered at the ICLRT at Camp Blanding, Florida. Top, a distant view of a strike to the test runway; middle, a strike to the test power system initiated from the tower launcher; bottom, a strike initiated from the underground launcher at the center of a 70×70 m^2 buried metallic grid.

Since September 1994, the facility has been operated by the University of Florida (UF). During 1995–2002, over 40 researchers (excluding UF faculty, students, and staff) from 13 countries representing 4 continents have performed experiments at Camp Blanding concerned with various aspects of atmospheric electricity, lightning, and lightning protection. Since 1995, the Camp Blanding facility has been referred to as the International Center for Lightning Research and Testing (ICLRT) at Camp Blanding, Florida. Photographs of lightning flashes triggered at the ICLRT are shown in Fig. 1, and a summary of the lightning triggering operations conducted for various experiments from 1997 to 2003 (the eleventh year of operation, 2003, is additionally included) is presented in Table 1. Over the 7-year period, the average number of triggered flashes is about 30 per year, with about 20 of them containing return-strokes. Out of a total of 208 flashes in Table 1, 205 transported negative charge and three either positive or both negative and positive charge to ground (Jerauld et al., 2004).

The principal results obtained from 1993 through 2002 at the ICLRT include

– characterization of the close lightning electromagnetic environment (Rakov et al., 1998, 2001; Uman et al., 2000, 2002; Crawford et al., 2001; Schoene et al., 2003a);
– first lightning return-stroke speed profiles within 400 m of ground (Wang et al., 1999b). (Additional results were obtained in 2003 (Olsen et al., 2004)).
– new insights into the mechanism of the dart-stepped (and by inference stepped) leader (Rakov et al., 1998; Wang et al., 1999b);
– identification of the M-component mode of charge transfer to ground (Rakov et al., 1995, 1998, 2001);
– first optical image of upward connecting leader in triggered-lightning strokes (Wang et al., 1999a);
– electric fields in the immediate vicinity of the lightning channel (Miki et al., 2002);
– inferences on the interaction of lightning with ground and with grounding electrodes (Rakov et al., 1998, 2002, 2003a; Bejleri et al., 2004);
– discovery of X-rays produced by triggered-lightning strokes (Dwyer et al., 2002, 2003; Al-Dayeh et al., 2002). [Additional results, outlined in Section 7, were obtained in 2003 (Dwyer et al., 2004a,b). Also, energetic radiation during the stepped leaders in

Table 1
1997–2003 Triggered-lightning experiments at the ICLRT at Camp Blanding, Florida

Year(s)	Rocket launchers used	Total flashes triggered	Flashes with return-strokes	Positive or bipolar flashes	Time period
1997	4	48	28	1	May 24–Sept. 26
1998	3	34	27	–	May 15, July 24–Sept. 30
1999	2	30	22	1	Jan. 23, June 26–Sept. 27
2000	2	30	27	–	June 12–Sept. 6
2001	2	23	11	–	July 13–Sept. 5
2002	2	19	14	–	July 9–Sept. 13
2003	2	24	12	1	June 30–Aug. 15
1997–2003		208	141	3	

natural lightning flashes in New Mexico and Florida was reported by Moore et al. (2001) and Dwyer et al. (2005), respectively);
- new insights into the mechanism of cutoff and reestablishment of current in rocket-triggered lightning (Rakov et al., 2003b).

Selected results are briefly discussed below. Further information is found in the references given as needed throughout the paper.

2. Characterization of the close lightning electromagnetic environment

A knowledge of close lightning electric and magnetic fields is needed for the evaluation of lightning-induced effects in various electric circuits and systems (e.g., Nucci and Rachidi, 1995) and for the testing of the validity of lightning models (e.g., Rakov and Uman, 1998; Schoene et al., 2003b). The close (within tens to hundreds of meters) lightning electromagnetic environment is most easily studied using rocket-

Table 2
Statistical characteristics of current, E-field, B-field, and their derivatives for triggered lightning, ICLRT, 1999 and 2000

Parameter	Unit	Sample size	Min.	Max.	Arithmetic mean	σ	Geometric mean	$\sigma_{\log}$
Current peak	kA	64	5	36.8	16.2	7.6	14.5	0.21
Current 30–90% risetime	ns	65	54	1751	260	316	191	0.29
Current HPW	μs	64	2.4	37.2	13.2	8.5	10.5	0.32
dI/dt Peak	kA/μs	64	8	292	117	65	97	0.31
dI/dt HPW	ns	29	49	149	92	25	89	0.12
ΔE_{RS}, 15 m	kV/m	86	30.2	197.2	104.6	41.0	96	0.19
ΔE_{RS}, 30 m	kV/m	86	16.3	116.2	60.0	22.9	55.3	0.19
E-field HPW, 15 m	μs	87	0.8	12.2	2.3	2.0	1.9	0.28
E-field HPW, 30 m	μs	84	1.4	13.9	4.2	2.8	3.5	0.26
dE/dt Peak, 15 m	kV/m/μs	80	37	657	313	140	273	0.26
dE/dt Peak, 30 m	kV/m/μs	64	19	234	114	53	95	0.27
dE/dt HPW, 15 m	ns	73	41	876	252	124	227	0.21
dE/dt HPW, 30 m	ns	49	138	899	319	159	294	0.16
B-field peak, 15 m	μT	93	53	466	203	95	182	0.21
B-field peak, 30 m	μT	88	27	239	109	50	98	0.21
B-field 30–90% risetime, 15 m	ns	92	212	2250	369	242	337	0.16
B-field 30–90% risetime, 30 m	ns	88	209	1890	387	220	357	0.16
B-field HPW, 15 m	μs	92	4.1	43.4	17.4	9.1	14.9	0.25
B-field HPW, 30 m	μs	88	3.4	37.1	14.6	7.9	12.5	0.25
dB/dt Peak, 15 m	T/s	90	108	2190	923	460	804	0.25
dB/dt Peak, 30 m	T/s	63	53	921	417	206	361	0.26
dB/dt HPW, 15 m	ns	71	44	317	134	56	124	0.18
dB/dt HPW, 30 m	ns	48	33	259	127	52	116	0.20

Adapted from Schoene et al. (2003a).
σ is the standard deviation, and $\sigma_{\log}$ is the standard deviation of the logarithm (base 10) of the parameter. HPW is the pulse width at half-peak value. 1 T = 1 Wb/m^2.

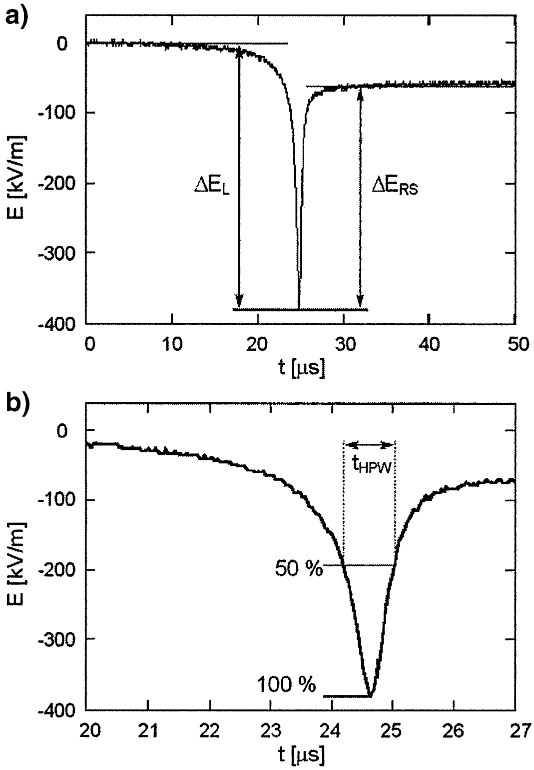

Fig. 2. Electric field at 15 m of return-stroke 1 of flash S9925 on (a) 50 μs and (b) 7 μs timescales. The electric field change due to the leader, ΔE_L, and electric field change due to the return-stroke, ΔE_{RS}, are illustrated in (a). The width of the electric field pulse measured at 0.5 E_L (half-peak width, HPW) is illustrated in (b). Atmospheric electricity sign convention. Taken from Schoene et al. (2003a).

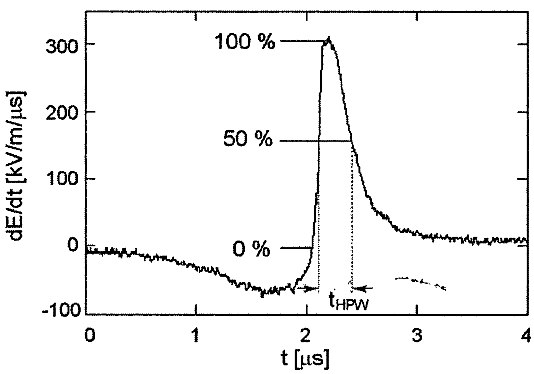

Fig. 3. Electric field derivative at 15 m of stroke 1 of flash S9932 on a 4 :s timescale. Half-peak width measurement is illustrated. Atmospheric electricity sign convention. Taken from Schoene et al. (2003a).

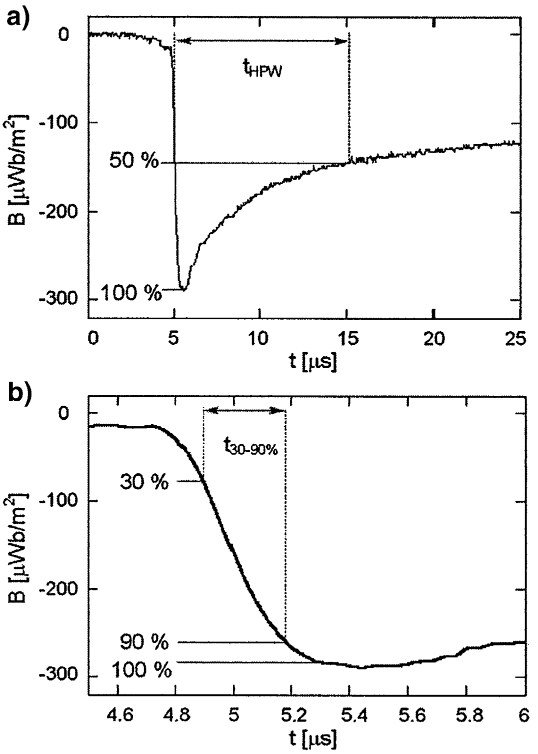

Fig. 4. Magnetic field at 15 m of return-stroke 3 of flash S9918 on (a) 25 :s and (b) 1.5 :s timescales. Half-peak width and 30–90% risetime measurements are illustrated in (a) and (b), respectively. Taken from Schoene et al. (2003a).

triggered lightning for which the termination point on ground is known (Leteinturier et al., 1990; Depasse, 1994; Rubinstein et al., 1995; Rakov et al., 1995, 1998, 2001; Uman et al., 2000, 2002; Crawford et al., 2001; Schoene et al., 2003a).

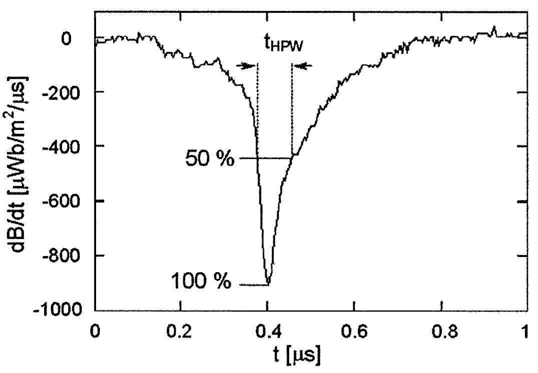

Fig. 5. Magnetic field derivative at 15 m of return-stroke 6 of flash S9933 on a 1 μs timescale. Half-peak width measurement is illustrated. Taken from Schoene et al. (2003a).

Here, we present measurements of the electric and magnetic fields and their time derivatives 15 and 30 m from the lightning channel made during the summers of 1999 and 2000. Lightning was triggered to a 1- or 2-m vertical rod mounted on the rocket launcher that was located below ground level in a pit in order to minimize the influence of the strike object on the measured fields. The strike rod was located in the center of and was electrically connected to a 70 m × 70 m buried metallic grid. The grid was installed to minimize the effects of field propagation and ground-surface arcing, the latter often otherwise occurring around the launcher. Only triggered flashes that transported negative charge to ground are included in the analysis presented here. Besides electric and magnetic fields and their derivatives, return-stroke currents and their derivatives were measured at the launcher. Statistical characteristics of measured field and current waveforms and their time derivatives are presented in Table 2, the definitions of the various characteristics being illustrated in Figs. 2–5. More detailed information about this experiment and associated data analysis is found in Schoene et al. (2003a).

3. M-component mode of charge transfer to ground

Fig. 6 schematically shows current profiles for three modes of charge transfer to ground in subsequent lightning strokes: (a) dart-leader/return-stroke sequence, (b) continuing current, and (c) M-component. The M-component, which can be viewed as a perturbation (or a surge) in the continuing current and in the associated channel luminosity, involves the superposition of two waves propagating in opposite directions. One wave moves toward the ground, and the other wave, reflected from the ground, moves toward the cloud. The amplitudes of these two waves are approximately equal, and the spatial front lengths are comparable with the distance between the lower cloud boundary and ground. The M-component mode of charge transfer to ground requires the

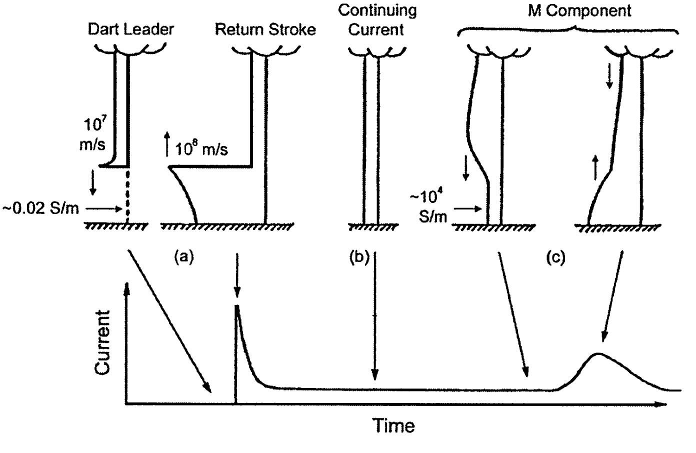

Fig. 6. Schematic representation of current profiles for three modes of charge transfer to ground in subsequent strokes of natural lightning or in rocket-triggered lightning strokes: dart-leader/return-stroke sequence, continuing current, and M-component (Rakov et al., 2001).

existence of a grounded channel carrying a current of typically some tens to some hundreds of amperes. In contrast, the leader/return-stroke mode of charge transfer to ground occurs only in the absence of such a well-conducting path to ground (Fisher et al., 1993). Thus, the primary distinction between the two modes is the availability of a well-conducting path to ground.

As shown by Rakov et al. (2001), the M-component electric field varies with distance considerably slower than the dart-leader electric field. The latter varies as r^{-1} (Crawford et al., 2001), while for the former the dependence in the distance range from 30 to 500 m is close to logarithmic, in support of the guided-wave mechanism described above. Besides "classical" M-components that occur during continuing currents following return-strokes in cloud-to-ground flashes, the M-component mode of charge transfer to ground, illustrated in Fig. 6, also occurs during the initial stage of both natural upward flashes initiated from tall grounded objects and rocket-triggered flashes.

4. First optical image of upward connecting leader in rocket-triggered lightning

Two dart-leader/return-stroke sequences, simultaneously recorded at the ICLRT by the high speed digital optical imaging system ALPS (Yokoyama et al., 1990) and by the electric field and current measuring systems, have been used for studying the lightning attachment process. The following new observations have been made: (1) an upward leader occurs in the dart-leader/return-stroke sequence; (2) the larger the leader electric field change and the larger the following return-stroke current, the longer the upward connecting leader; (3) the upward connecting leader is characterized by a light intensity about one order of magnitude lower than that of the corresponding downward leader and by a duration of several hundreds of nanoseconds; (4) the following return-stroke starts at the junction point of the downward and upward leaders and then travels in both

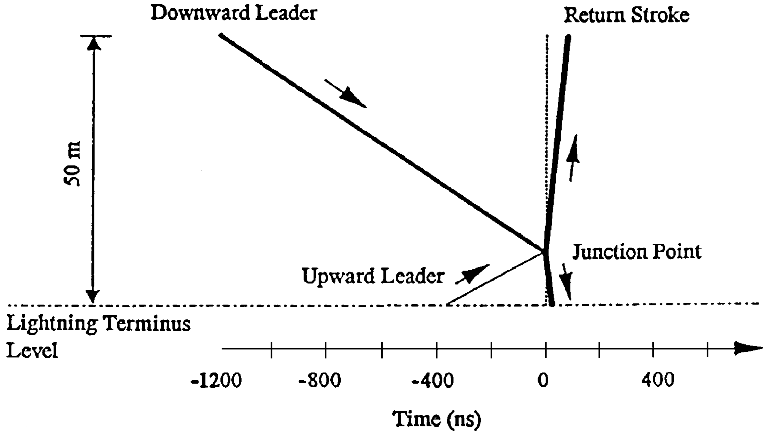

Fig. 7. A streaked image sketch of the attachment process of a dart-leader/return-stroke sequence in a lightning flash initiated using the rocket-and-wire technique at Camp Blanding, Florida. Taken from Wang et al. (1999a).

upward and downward directions. These findings have important implications for the understanding of the physics of the lightning discharge and for return-stroke modeling (e.g., Rakov and Uman, 1998). The results for one of the events, for which the length of the upward connecting leader was about 10 m, are schematically presented in Fig. 7. This is the first optically imaged upward connecting leader in rocket-triggered lightning, although unconnected upward leaders have been previously reported [see Rakov and Uman (2003) for a recent review]. Idone (1990), from streak-camera photographs, estimated the upper bound for lengths of inferred (none was imaged) upward connecting leaders to be of the order 10 to 20 m for nine strokes in four triggered lightning flashes.

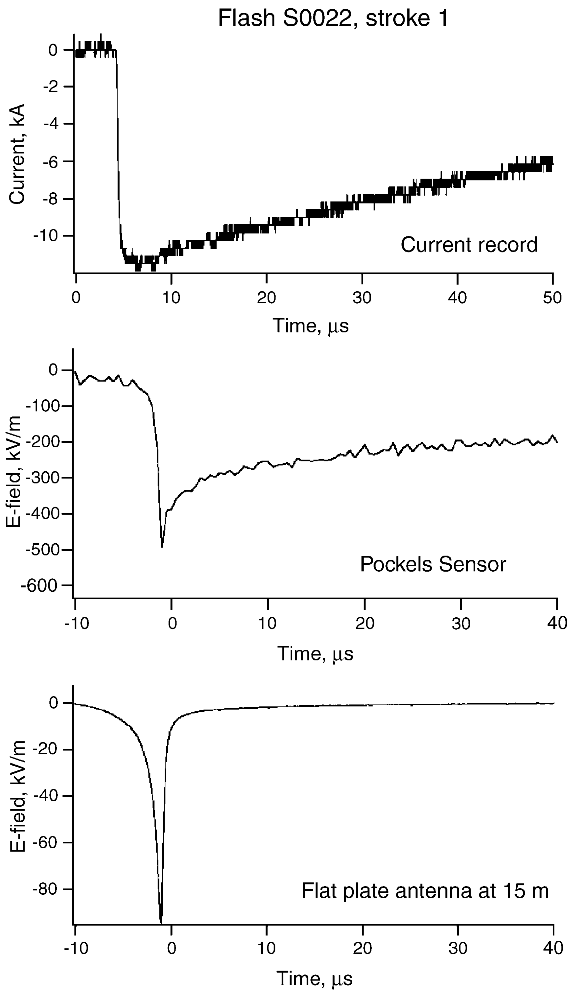

Fig. 8. Vertical electric field measured 0.1 m from the lightning channel attachment point (middle trace), channel-base current (top trace), and vertical electric field measured at 15 m for stroke 1 in triggered-lightning flash S0022. Taken from Miki et al. (2002).

5. Electric fields in the immediate vicinity of the lightning channel

The electric fields in the immediate vicinity of the triggered lightning channel were measured with Pockels sensors. Electric field waveforms produced by 36 leader/return-stroke sequences at horizontal distances from the channel attachment point ranging from 0.1 to 1.6 m were obtained. Vertical electric field pulse peaks are in the range from 176 kV/m to 1.5 MV/m (the median is 577 kV/m), and horizontal electric field pulse peaks are in the range from 495 kV/m to 1.2 MV/m (the median is 821 kV/m). Examples of electric field waveforms measured at 0.1 m for two strokes in two different triggered-lightning flashes are shown in Figs. 8 and 9. Additionally, vertical electric fields due to M-components were measured and compared to electric fields produced by leader/return-stroke sequences. For 8 out of 10 M-components having channel-base peak currents greater that 500 A, vertical electric fields at 0.1 to 1.6 m were below 20 kV/m, the lower measurement limit. For the remaining 2 of 10 M-

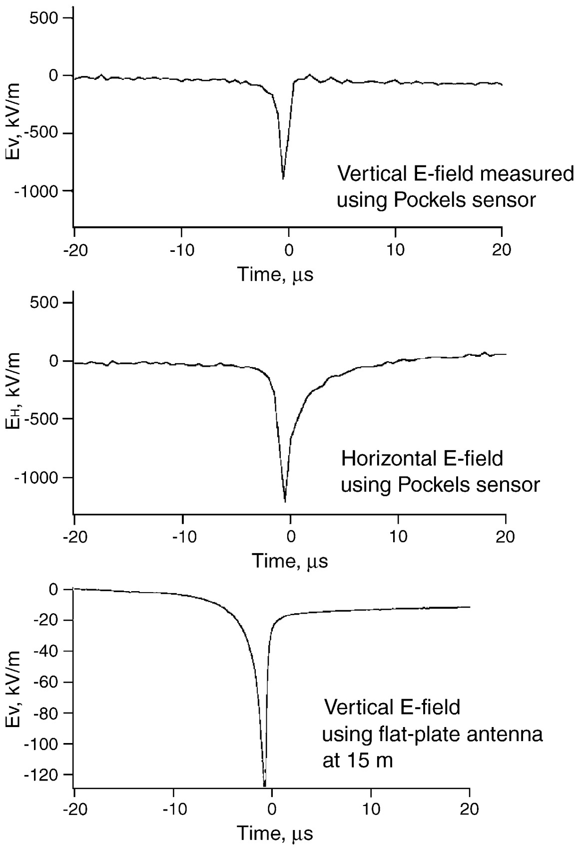

Fig. 9. Waveforms of the vertical and horizontal electric fields measured 0.1 m from the lightning channel attachment point along with the vertical electric field at 15 m for stroke 1 in triggered-lightning flash S0033. Taken from Miki et al. (2002).

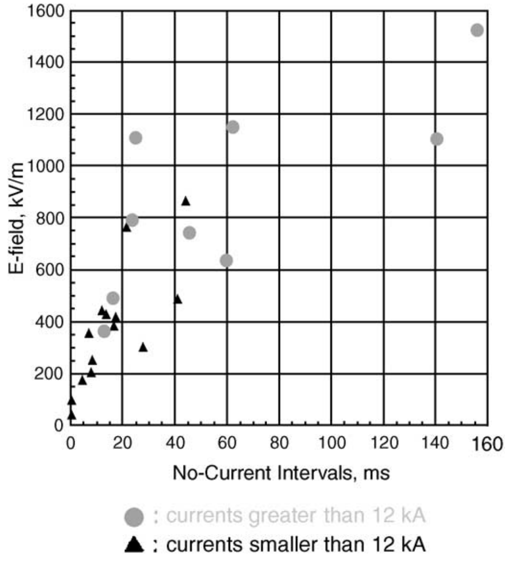

Fig. 10. Relationship between vertical electric field at 0.1 and 1.6 m and previous no-current interval. Two data points on the vertical axis (zero no-current interval) correspond to M-components. Taken from Miki et al. (2002).

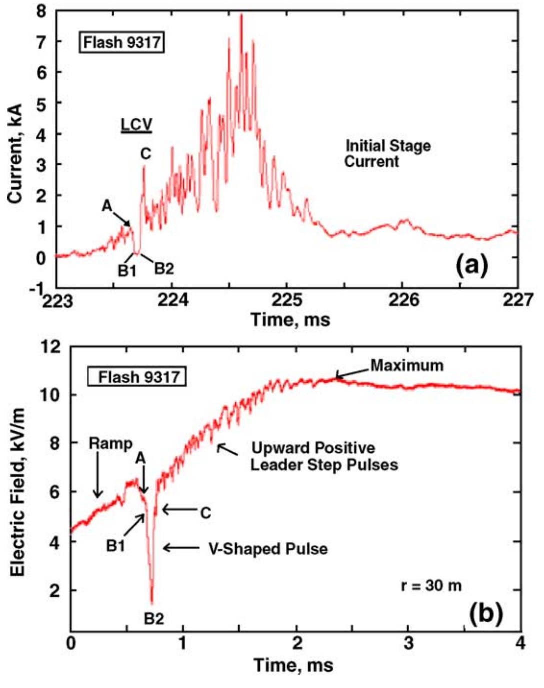

Fig. 11. (a) Current to ground and (b) electric field at a distance of 30 m from the lightning channel for flash 9317 triggered in 1993 at Camp Blanding, Florida. Taken from Rakov et al. (2003b).

components, whose current peaks were between 2.3 and 3.2 kA (exact values are unknown), vertical electric field peaks were about 100 and 48 kV/m at a distance of 0.1 m from the channel attachment point. It was found that the vertical electric field measured very close to the lightning channel tends to increase with an increase in the previous no-current interval (see Fig. 10), that is, in the time elapsed from the cessation of current of the preceding stroke (or of the initial-stage current).

6. Cutoff and reestablishment of current in triggered lightning

Measured channel-base current and the corresponding measured electric field at 30 m that exhibit features characteristic of the current cutoff (due to the disintegration of the lightning triggering wire) and the reestablishment of current are shown in Fig. 11a and b, respectively. The conceptual picture of such cutoff and reestablishment of current is shown in Fig. 12. Time instants A, B1, B2, and C indicated in Fig. 12 correspond to the similarly labeled features in Fig. 11a and b. Prior to A, 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, the wire is vaporized by the upward

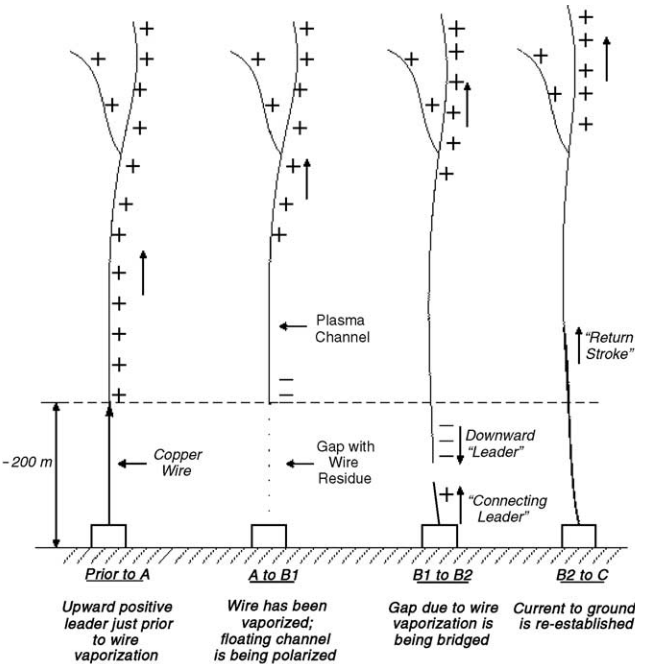

Fig. 12. Conceptual picture of current cutoff and reestablishment in classical rocket-triggered lightning. The lengths of the wire and the following gap are exaggerated relative to the plasma channel length (which is a kilometer or two) for illustrative purposes. Time instants A, B1, B2, and C are indicated in Fig. 11a and b. Taken from Rakov et al. (2003b).

positive leader current, and a 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. Thereafter, the triggering wire residue becomes a part of the conducting air-plasma channel that replaces the wire in the manner that is described below. The upward positive leader channel above 200-m altitude has a length of the order of a kilometer or two at the time of the wire vaporization and its upper end 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: an upward positive leader develops from the top of the ungrounded copper wire [see Fig. 2 of Rakov et al. (1998)] causing negative charge to accumulate at the bottom of the wire. At B1, 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), polarized by the cloud electric field, so 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 to meet the downward negative leader, possibly explaining in part the non-zero current from B1 to B2. From B1 to B2, the gap is bridged by a downward "leader" (and an upward "connecting leader") and at B2 an upward "return-stroke" is formed. This "return-stroke", whose current peak at ground occurs at C, traverses the newly formed (200 m or so in length) channel and then likely 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. The described process is probably similar to the formation of a downward leader after the channel current has been cut off near ground in natural lightning (e.g., Heckman and Williams, 1989), particularly when the time elapsed after the preceding return-stroke is a millisecond or less (Rakov and Uman, 1994; Idone and Davis, 1999).

7. Concluding remarks

Lightning research at the ICLRT at Camp Blanding, Florida, continues. New exciting results have been obtained during 2003 and 2004 (the eleventh and twelfth years of operation), and further experiments are planned for the Summer of 2005. In particular, from the experiments conducted at the ICLRT in 2003, Dwyer et al. (2004a) reported that the X-rays, with spectra extending up to about 250 keV, during rocket-triggered lightning were spatially and temporally associated with the dart-leaders, with the most intense bursts coming from the direction of the dart-leader front when it was within 50 m or so of the ground. Further, Dwyer et al. (2004b) reported the observation of an intense gamma-ray burst detected on the ground 650 m from the triggered-lightning channel, with gamma-ray energies extending up to more than 10 MeV. The gamma-ray burst was produced in coincidence with an extremely large current pulse (11 kA) occurring during the triggered-lightning initial stage, that is, before the first dart-leader/return-stroke sequence. From the experiments conducted in 2004, Dwyer et al. (2005) reported X-ray bursts associated with leader steps in natural lightning.

Acknowledgments

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