

Measurements of Radiation Field Signatures of Rocket-Triggered Lightning

S. Mallick, A. Nag, and V. A. Rakov

Department of Electrical and Computer Engineering
University of Florida
Gainesville, FL, USA
Email: smallick@ufl.edu

Abstract—In this paper, we describe the two-station measurements of triggered-lightning electromagnetic fields performed by the University of Florida Lightning Research Group in 2008-2009. Lightning is triggered at Camp Blanding, Florida, where near-field signals were recorded. Far-field signals were recorded at the Lightning Observatory in Gainesville, located about 45 km away from Camp Blanding.

I. INTRODUCTION

The random occurrence of natural lightning in space and time makes studying its characteristics difficult. The rocket-and-wire technique is used to artificially initiate (trigger) lightning from natural thunderclouds at a predetermined location and controlled time. A detailed discussion of this technique is found in chapter 7 of Rakov and Uman, 2003 [1]. Triggered-lightning strokes are similar to subsequent strokes in natural lightning.

The total electric field produced by a lightning discharge consists of the electrostatic, induction, and radiation components, while the total magnetic field consists of the induction and radiation components (Uman et al., 1975) [2]. Triggered-lightning fields are usually measured within the triggering facility, so that the distances are typically some tens to some hundreds of meters. At these distances, the electric field is dominated by its electrostatic component, and the magnetic field is dominated by its induction component. Triggered-lightning field measurements at larger distances, where the fields are dominated by their radiation components (at least at early times), are very rare.

Lin *et al.* (1979) [3] presented the electric and magnetic field waveforms produced by natural lightning return strokes for distances ranging from 1 to 200 km. This collection of field waveforms remains a major reference in studying the dependence of lightning electric and magnetic fields on distance.

Crawford *et al.* (2001) [4] studied the variation of leader electric field changes with distance for rocket-triggered lightning. In 1997-1999, they measured fields at multiple stations at Camp Blanding, Florida, which were 10 to 621 m away from the lightning channel. At these distances, the leader

electric field change is approximately equal to the return stroke field change. Crawford *et al.* concluded that, with a few exceptions, the measured leader electric field change varied as the inverse of the distance from the lightning channel.

Le Vine *et al.* (1989) [5] measured electric field waveforms produced by triggered lightning return strokes at a distance of 5.16 km from the triggering site, so that the initial portion of the waveform was essentially radiation. We are not aware of any other well-documented radiation-field measurements for triggered lightning. They compared the measured electric fields produced by subsequent return strokes of natural lightning with those in triggered lightning and found their waveforms to be similar.

In this paper, we describe two-station measurements of triggered-lightning electric fields performed by the University of Florida Lightning Research Group. The distance between the two field measuring stations is approximately 45 km.

II. CAMP BLANDING FACILITY

Rocket-triggered lightning experiments described here were conducted at Camp Blanding, Florida. The Camp Blanding facility (CB) occupies an area of roughly 1 km². Fig. 1 shows an overview of the CB. It has multiple rocket launchers. All launchers are equipped with resistive shunts to measure the lightning channel-base current. Multiple-station measurements of electric and magnetic fields, as well as X-rays are performed. Lightning channels are imaged using a variety of video and still cameras. The launcher controls and the data acquisition systems are located inside a “Launch Control” trailer. The trailer is protected by a system of well-grounded catenary wires. Fiber-optic links are used to transmit measured data from sensors to the data acquisition systems. Rakov *et al.* (2005) [6] have reviewed the triggered and natural lightning experiments done at CB in 1993-2003. More recent experiments at CB are described, for example, by Howard (2009) [7]. The return-stroke current and near-field waveforms presented here were recorded at CB.

III. LIGHTNING OBSERVATORY IN GAINESVILLE

Far-field signals, corresponding to the near-field signals measured at CB, were recorded at the Lightning Observatory in Gainesville (LOG), Florida. LOG is located on the roof of the five-storey New Engineering Building (NEB) on the University of Florida campus. The distance between CB and LOG is approximately 45 km. Fig. 2 shows the Google map of Florida with the locations of CB and LOG indicated.

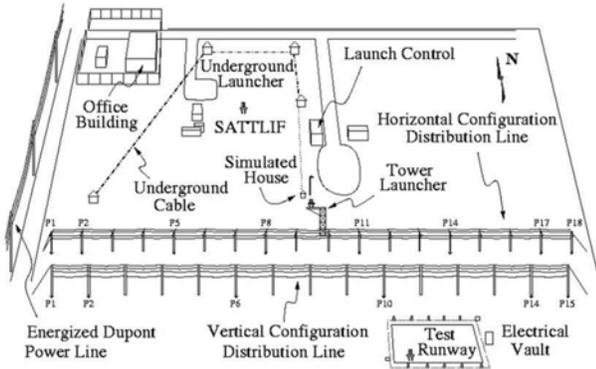


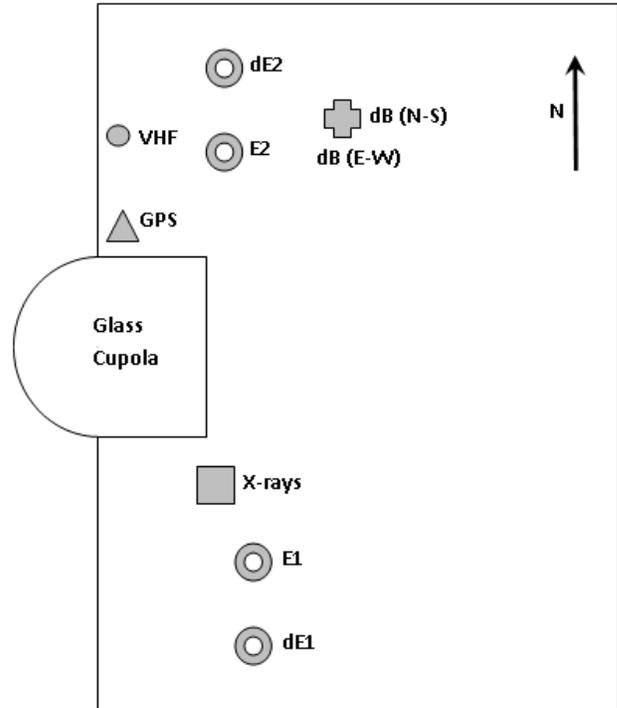
Figure 1. Overview of the Camp Blanding facility [1].



Figure 2. Google map of Florida showing locations of CB and LOG.

At present, two electric field sensors, two electric field derivative sensors, one X-ray detector, and one VHF sensor are operational at LOG. The electric field and electric field derivative sensors are elevated flat-plate antennas. The magnetic field derivative sensors are square loop antennas that measure the magnetic field derivative components in the east-west and north-south direction. The X-ray detector, provided by the Florida Institute of Technology, includes a NaI scintillator and a photomultiplier tube. The signals from sensors are relayed by fiber-optic links to the glass cupola, where they are recorded by digital storage oscilloscopes (DSO). The glass cupola provides an unobstructed view of 180° of the horizon, allowing optical observations of lightning. Fig. 3 shows the overview of LOG. A detailed description of LOG is given by Nag (2010) [8].

The LOG measures electromagnetic fields due to both thunderstorm activity in Gainesville and lightning discharges (natural and rocket-triggered) at CB. Accordingly, there are two modes of operation: single-station (for local measurements) and two-station (for recording CB events). For single-station measurements, the system is triggered when the electric field exceeds a set threshold value. For two-station measurements, a dedicated phone line is used to transmit a trigger signal from CB to LOG, in the event of a lightning discharge at CB. Table I gives record lengths, pre-trigger times, and sampling rates of the oscilloscopes used at LOG.



E1 and E2 – Wideband vertical electric field antennas
dE1 and dE2 – Electric field derivative antennas
dB (N-S) and dB (E-W) – Magnetic field derivative antennas (north-south and east-west components, respectively)

VHF – Narrowband (36 MHz) VHF radiation antenna
X-rays – NaI X-ray detector

Figure 3. Overview of the Lightning Observatory in Gainesville. E1, dE1, and X-ray detector are used in single-station experiments. E2 and dE2 are used in two-station experiments. dB (E-W) and dB (N-S) are used in both single-station and two-station experiments.

IV. RESULTS AND DISCUSSIONS

In 2008 and 2009, 64 rockets were launched at CB to trigger lightning. The number of triggered flashes was 37, so that the success rate was 58%. The number of triggered flashes with return strokes was 25 (68% of all triggered flashes), with the remaining 12 flashes being composed of the initial stage only. The total number of return-strokes in the 25 flashes was 111, so that the average number of strokes per flash was 4.4.

Synchronized near and far electromagnetic field waveforms were obtained for 15 flashes (preliminary result) with return strokes. No flashes composed of initial stage only were recorded at LOG. Table II gives a summary of the triggered lightning events simultaneously recorded at CB and LOG in 2008 and 2009.

TABLE I. DIGITAL STORAGE OSCILLOSCOPES (DSO) USED AT LOG

Experiment	DSO Type	Measurements	Record length (ms)	Pre-trigger time (ms)	Sampling rate (MHz)
Single-station	LeCroy 7100A	E, dE/dt, dB/dt	500	100	100
	LeCroy LT344L	E, X-rays	10	4	100
Two-station	LeCroy 7100	E, dE/dt	480	100	100
	Yokogawa DL716	E, dE/dt, dB/dt	3206	1280	10

Fig. 4 shows waveforms of the channel-base current and near electric field recorded at CB and far electric field recorded at LOG, all on a 1.4 s time scale, for flash UF 09-25 triggered on 06/29/2009. The flash consisted of initial stage and five negative leader/return strokes sequences. The fifth stroke occurred at a time beyond the record length of the Yokogawa DSO at CB, which recorded overall flash currents and fields at a lower sampling rate. Since Fig. 4 shows Yokogawa records from CB, the fifth stroke is not seen in the figure. However, the current waveforms for all the five return

strokes were recorded on a LeCroy DSO at CB, which operated in a segmented mode to record individual strokes at a higher sampling rate. The far-field signals of all the five return strokes were recorded at LOG, but only four are shown in Fig. 4 for consistency with CB records.

TABLE II. SUMMARY OF TRIGGERED LIGHTNING EVENTS RECORDED SIMULTANEOUSLY AT CB AND LOG IN 2008 AND 2009

Events	2008	2009	2008-2009
Number of rockets launched	21	43	64
Total number of triggered flashes	11	26	37
Number of flashes with initial stage only	4	8	12
Number of flashes with return strokes	7	18	25
Total number of strokes	36	75	111
Number of flashes with return strokes recorded at both CB and LOG	4	11	15
Total number of strokes recorded at both CB and LOG	20	45	65

Fig. 5 shows the current and electric field waveforms for the first stroke of flash UF 09-25 on an expanded time scale. The waveforms are manually aligned to account for different instrumentation delays. The leader field change and the return stroke field change are labeled in the near electric field waveform. Measurement of the initial electric field peak is illustrated for the far field waveform. The far field peak, E_P , was used to estimate the return-stroke peak current using the transmission line (TL) model (Uman and McLain, 1969) [9] and empirical formula of Rakov *et al.* (1992) [10].

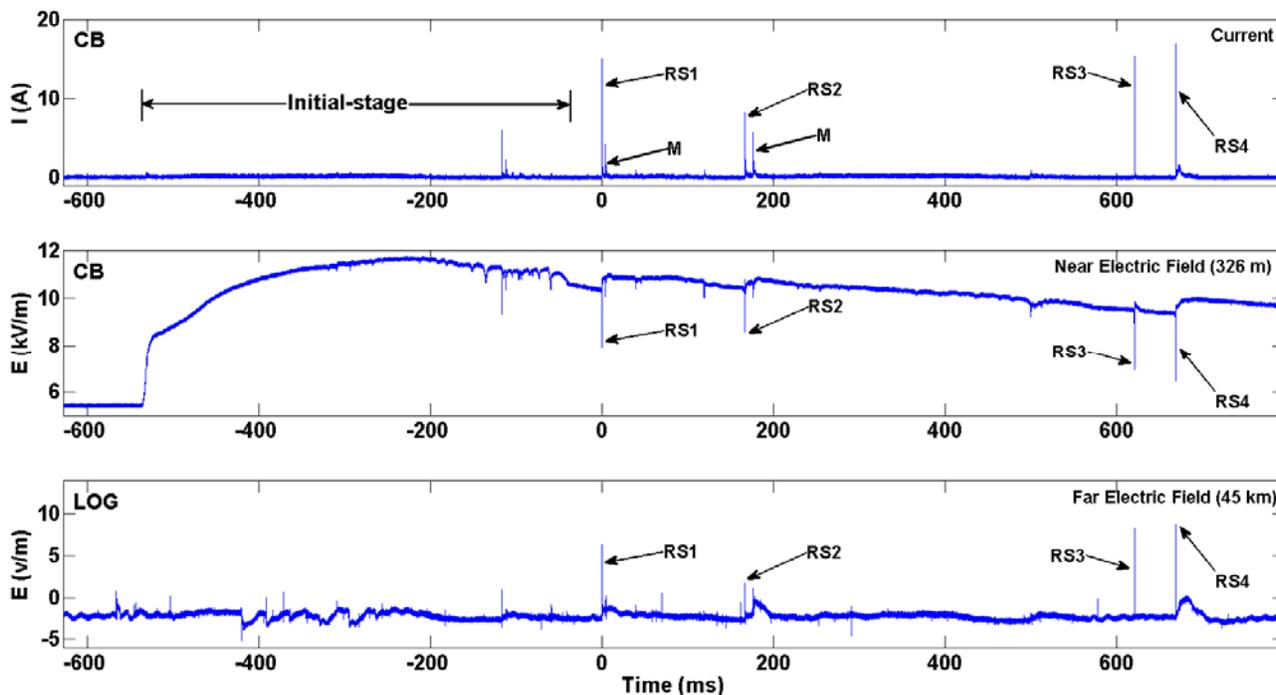


Figure 4. The current and electric field waveforms on a 1400 ms time scale recorded simultaneously at CB and LOG for flash UF 09-25. In this figure, RS stands for return stroke and M stands for M-component. The waveforms are aligned so that RS1 occurs at $t = 0$.

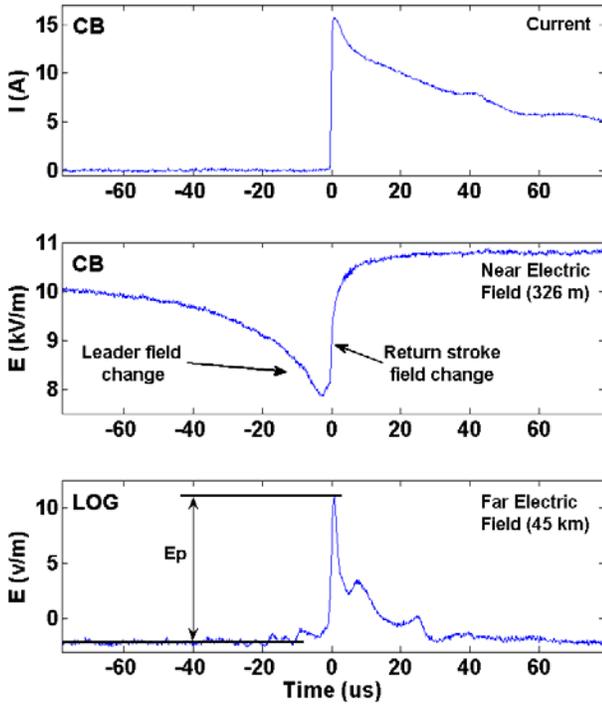


Figure 5. Current and electric field waveforms of the first return stroke of flash UF 09-25 on a 160 μ s scale. The waveforms are aligned so that the return stroke occurs at $t = 0$.

The results for flash UF 09-25 are summarized in Table III. The TL model peak current is given by

$$I_{TL} = \frac{2\pi\epsilon_0 c^2 r}{v} E_P, \quad (1)$$

where $\epsilon_0 = 8.85 \times 10^{-12}$ F/m (permittivity of free space), $c = 3 \times 10^8$ m/s (speed of light), r is the distance in m, and v is the return-stroke speed. The I_{TL} values are given for three different return-stroke speeds, $v = c/3$, $c/2$, and $2c/3$. The empirical-formula peak current is given by

$$I_{EF} = 1.5 - 0.037 E_P r, \quad (2)$$

where I_{EF} is in kA and taken as negative (absolute values are given in Table III), E_P is positive and in V/m, and r is the distance in km. Directly measured, I_{CB} , and US National Lightning Detection Network (NLDN) reported, I_{NLDN} , peak currents are also given.

It is seen in Table III that I_{EF} , I_{TL} for $v = c/2$, I_{NLDN} , and I_{CB} are all in reasonably good agreement with each other.

V. SUMMARY

Synchronized electric fields at CB and LOG (and their causative channel-base currents) were measured for 15 out of 25 triggered-lightning flashes with return strokes. The total

number of strokes observed at both CB and LOG (45 km apart) is 65. Parameters of field waveforms at both near and far distances are being examined.

TABLE III. ESTIMATION OF PEAK CURRENT FOR THE FIVE STROKES OF FLASH UF 09-25

Stroke order	E_P (V/m)	I_{TL} (kA)			I_{EF} (kA)	I_{CB} (kA)	I_{NLDN} (kA)
		$v = c/3$	$v = c/2$	$v = 2c/3$			
1	13.1	29.5	19.7	14.8	20.3	15.7	18.3
2	5.4	12.3	8.2	6.1	7.6	9.1	7.6
3	11.0	24.7	16.5	12.4	16.8	16.3	15.9
4	11.9	26.7	17.8	13.4	18.2	18.8	17.4
5	19.7	44.3	29.6	22.2	31.3	31.6	30.0

ACKNOWLEDGMENT

This work was supported in part by NSF Grant ATM-0852869 and by DARPA. The authors thank all members of the University of Florida Lightning Research Group for their help and support. Special thanks are due to Chris Biagi and Dustin Hill.

REFERENCES

- [1] V. A. Rakov and M. A. Uman, *Lightning: Physics and Effects*, New York, NY: Cambridge University Press, 2003.
- [2] M. A. Uman, D. K. McLain, and E. P. Krider, "The electromagnetic radiation from a finite antenna," *American Journal of Physics*, vol. 43, issue 1, pp. 33-38, Jan. 1975.
- [3] Y. T. Lin, M. A. Uman, J. A. Tiller, R. D. Brantley, W. H. Beasley, E. P. Krider, and C. D. Weidman, "Characterization of lightning return stroke electric and magnetic fields from simultaneous two-station measurements," *Journal of Geophysical Research*, vol. 84, no. C10, pp. 6307-6314, 1979.
- [4] Crawford *et al.*, "The close lightning electromagnetic environment: dart-leader electric field change versus distance," *Journal of Geophysical Research*, vol. 106, no. D14, pp. 14909-14917, 2001.
- [5] D. M. Le Vine, J. C. Willett, and J. C. Bailey, "Comparison of fast field changes from subsequent return strokes of natural and triggered lightning," *Journal of Geophysical Research*, vol. 94, no. D11, pp. 13259-13265, Sept. 30, 1989.
- [6] V. A. Rakov, M. A. Uman, and K. J. Rambo, "A review of ten years of triggered-lightning experiments at Camp Blanding, Florida," *Atmospheric Research*, vol. 76, issues 1-4, pp. 503-517, July-August 2005.
- [7] J. S. Howard, "Lightning propagation and ground attachment processes from multiple-station electric field and X-ray measurements," Ph.D. dissertation, University of Florida, Gainesville, FL, USA, 2009.
- [8] A. Nag, "Characterization and modeling of lightning processes with emphasis on compact intracloud discharges," Ph.D. dissertation, University of Florida, Gainesville, FL, USA, 2010.
- [9] M. A. Uman and D. K. McLain, "Magnetic Field of Lightning Return Stroke," *Journal of Geophysical Research*, vol. 74, no. 28, pp. 6899-6910, 1969.
- [10] V. A. Rakov, R. Thottappillil, and M. A. Uman, "On the empirical formula of Willett et al. relating lightning return-stroke peak current and peak electric field," *Journal of Geophysical Research*, vol. 97, no. D11, pp. 11527-11533, 1992.