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The close lightning electromagnetic environment: Dart-leader electric field change versus distance

David E. Crawford, Vladimir A. Rakov, Martin A. Uman, George H. Schnetzer, Keith J. Rambo, Michael V. Stapleton, and Richard J. Fisher

Department of Electrical and Computer Engineering, University of Florida, Gainesville, Florida

Abstract. Net electric field changes due to dart leaders in triggered lightning from experiments conducted in 1997, 1998, and 1999 at the International Center for Lightning Research and Testing at Camp Blanding, Florida, are analyzed and compared with similar data obtained in 1993 at Camp Blanding and at Fort McClellan, Alabama. In 1997–1999 the fields were measured at 2-10 stations with distances from the lightning channel ranging from 10 to 621 m, while in 1993 the fields were measured at three distances, 30, 50, and 110 m, in Florida and at two distances, about 10 and 20 m, in Alabama. With a few exceptions, the 1997–1999 data indicate that the distance dependence of the leader electric field change is close to an inverse proportionality (r^{-1}), in contrast to the 1993 data in which a somewhat weaker distance dependence was observed. The typically observed r^{-1} dependence is consistent with a uniform distribution of leader charge along the bottom kilometer or so of the channel.

1. Introduction

Rubinstein et al. [1992, 1995] analyzed vertical electric field waveforms for 31 leader/return-stroke sequences at 500 m and two leader/return-stroke sequences at 30 m from the lightning channel. The lightning flashes were triggered using the classical rocket-and-wire technique at the Kennedy Space Center, Florida, in 1986 and 1991, respectively. *Rubinstein et al.* [1995] found that at tens to hundreds of meters from the lightning channel the combined leader/return-stroke vertical electric field waveforms appear as asymmetric V-shaped pulses, with the trailing (return-stroke) edge of the pulse being sharper than the leading (leader) edge. The bottom of the V is associated with the transition from the leader to the return stroke. The first multiple-station electric field measurements within a few hundred meters of the triggered-lightning channel were performed in 1993 at Camp Blanding, Florida [*Uman et al.*, 1994], and in the same year at Fort McClellan, Alabama [*Fisher et al.*, 1994]. Electric fields were measured at 30, 50, and 110 m from the lightning channel at Camp Blanding and at 9.3 and 19.3 m at Fort McClellan. Detailed analyses of these two data sets have been presented by *Rakov et al.* [1998]. At these ranges, typically the leader electric field change ΔE_L is not much different from the return-stroke field change ΔE_{RS}. From the 1993 Camp Blanding experiment, the geometric mean width at half-peak value (T_{HPW}) is 3.2 μs at 30 m, 7.3 μs at 50 m, and 13 μs at 110 m, a distance dependence close to linear. In both Florida and Alabama, the variation with distance r from the channel of leader electric field change ΔE_L was found to be somewhat slower than an inverse proportionality (r^{-1}).

In this paper we present multiple-station measurements of ΔE_L for strokes in lightning flashes triggered in 1997, 1998, and 1999 at Camp Blanding, Florida. The fields were measured at 2-10 stations with distances from the lightning channel ranging from 10 to 621 m. With a few exceptions, these data indicate that the distance dependence of ΔE_L is close to r^{-1}. The results are compared with the 1993 data from Florida and Alabama.

2. Research Facilities

The lightning-triggering site at Camp Blanding, Florida, is referred to as the International Center for Lightning Research and Testing (ICLRT). The ICLRT is located on a Florida Army National Guard Base at 30°N, 82.2°W. This location is approximately 45 km northeast of the University of Florida (UF) in Gainesville. The ICLRT occupies approximately 1 km² of mostly open, flat area at an elevation of about 75 m above mean sea level and is surrounded by pine forest. The soil is sandy and mostly covered with grass. Measured ground conductivity at the site is approximately 2.5×10^{-4} S m^{-1} [*Rakov et al.*, 1998]. Research and testing facilities on the site are shown in Figure 1. Up to three rocket launchers were used in the experiments discussed here. Launch operations were conducted from the UF Launch Control Trailer (UF-LC) in 1993 and from UF-LC and the Sandia Transportable Triggered-Lightning Instrumentation Facility (SATTLIF) in 1997–1999.

The lightning-triggering site used for 1993 experiments in Alabama was located at Fort McClellan, at an elevation

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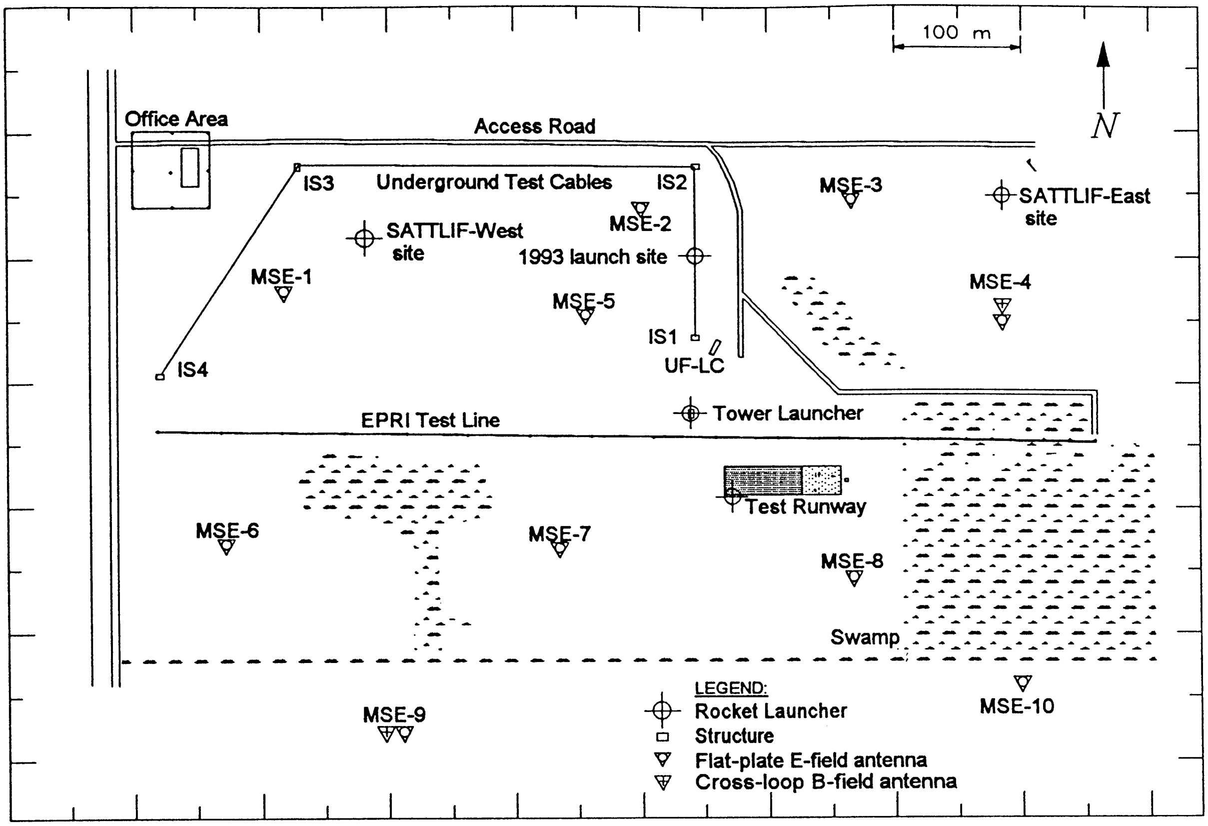

Figure 1. Research facilities at the International Center for Lightning Research and Testing (ICLRT) at Camp Blanding, Florida. Abbreviations are as follows: MSE, antennas of the multiple-station electric and magnetic field measuring system in 1998; SATTLIF, Sandia Transportable Triggered-Lightning Instrumentation Facility; UF-LC, University of Florida Launch Control; IS, instrument station. See text for details.

of about 200 m above mean sea level. The soil was heavy red clay. Measured ground conductivity at the site was about 1.8×10^{-3} S m^{-1} [*Fisher et al.*, 1994].

2.1. The 1993 Experiments

The 1993 launch operations at Camp Blanding were conducted by personnel from the Centre d'Études Nucléaires de Grenoble (CENG), Grenoble, France. The rocket launcher had a height of about 4.5 m and was positioned, approximately equidistant from instrument stations IS1 and IS2 (see Figure 1), over three power cables buried at a depth of about 1 m. The launcher had no grounding electrode. During this experiment, triggered-lightning electric fields were recorded at three locations, 30, 50, and 110 m from the lightning channel. The 30-m system included a flat-plate antenna (0.2 m^2), placed essentially flush with the ground, and a passive integrator. It was operated by UF. The UF system was calibrated theoretically [e.g., *Uman*, 1987, Appendix C]. The output signal from the integrator was transmitted to UF-LC via a Nicolet ISOBE 3000 fiber-optic link with a 3-dB bandwidth of 15 MHz and digitally recorded using a Nicolet Pro90 oscilloscope. Data were recorded at either 20-MHz sampling rate with 8-bit resolution or 10-MHz sampling rate with 12-bit resolution, with the corresponding record length being 25.6 or 52.2 ms, respectively [*Versaggi*, 1994; *Rakov et al.*, 1998]. The electric field measuring systems at 50 and 110 m were operated by CENG personnel and consisted of two identical Thomson E31 spherical electric field sensors, each with a built-in active integrator. The CENG electric field sensors had a passband of 1 kHz to 150 MHz and were calibrated by the manufacturer prior to field use. The output signal from each sensor was transmitted, via a Thomson CV-40 signal conditioner and MM100/P100 fiber-optic link, to UF-LC, where it was recorded on 8-bit LeCroy 9314 digital oscilloscopes at a sampling rate of 50 MHz [*Berlandis et al.*, 1994; *Rakov et al.*, 1998].

In the 1993 experiment at Fort McClellan, Alabama, electric fields were measured by Sandia National Laboratories personnel at about 10 (9.3) and 20 (19.3) m from the lightning channel using flat-plate antennas with active integrators. Signals from the integrators were transmitted via fiber-optic links to 8-bit, 25-MHz LeCroy 9400a digitizers. The overall upper frequency bandwidth of the electric field systems was 10 MHz. The electric field antennas were calibrated by Sandia personnel in the laboratory prior to field use, and the gain was adjusted using an additional capacitor at the input of the electronic circuit [*Fisher and Schnetzer*, 1994]. Systematic calibration error was estimated to be about 30%. The rocket launcher had a height of 4.5 m and was grounded using a single 0.3-m- or 1.3-m-long vertical ground rod. The measured low-frequency, low-current grounding resistance was 260 Ω.

2.2. The 1997 Experiment

The 1997 experiment was designed specifically to study in detail the dependence of ΔE_L on the distance from the lightning channel. The launcher was located at the SATTLIF-East site (see Figure 1). It was 5 m in height and was earthed through three 2.5-m ground rods with an overall measured low-frequency, low-current resistance of 220 Ω. A total of seven UF flat-plate antennas were deployed at distances ranging from 5 to 500 m from the rocket launcher. Similar to the 30-m antenna used in 1993, all UF antennas were calibrated theoretically [e.g., *Uman*, 1987, Appendix C]. Additionally, distant lightning was used for relative calibration of the electric field measuring systems [*Crawford*, 1998], and the resultant corrections to the theoretical calibration were found to be negligible. Output signals from each antenna were transmitted via fiber-optic links to digitizers located at SATTLIF and UF-LC (see Figure 1). Fiber-optic links used were Nicolet ISOBE 3000 and Meret units followed by antialiasing filters with overall 3-dB bandwidths of 10 MHz. A more detailed description of the 1997 measuring systems is given by *Crawford* [1998].

At SATTLIF, five LeCroy 9400 digital oscilloscopes (having two channels each) and one Nicolet MultiPro 150 digitizer were used to record the incoming analog signals. The 8-bit LeCroy oscilloscopes were operated at a sampling rate of 25 MHz and were configured to record up to eight events per lightning flash. The MultiPro 150 is a displayless card crate controlled via a GPIB bus by a personal computer. It had four channels per card, 12 bit resolution, and was operated at a sampling rate of 10 MHz for a total record length of 51.2 ms for each channel. One card (for a total of four channels) was installed for this experiment. Only one trigger per lightning flash was possible. Additionally, a 14-channel AMPEX PR2230 analog tape drive was used to record selected data as a backup to the digitizers and to obtain the overall flash records.

At UF-LC, five Nicolet Pro90 digital oscilloscopes were used to record incoming signals. The Pro90 oscilloscopes had two 12-bit and two 8-bit channels. The oscilloscopes were configured for a 10-MHz sampling rate with a 51.2-ms total record length for each measurement. As with the MultiPro, only one trigger per flash was possible. In the 1997 experiment, only one stroke per flash was recorded with Nicolet digitizers.

A triggering signal for all digitizers in this experiment was generated whenever the lightning current flowing through the current-viewing resistor installed at the base of the rocket launcher exceeded ±4 kA. This signal was routed to the external trigger inputs of the LeCroy oscilloscopes and MultiPro 150 digitizer located at SATTLIF. From the MultiPro 150 the triggering signal was transmitted via digital fiber-optic link to UF-LC, where it triggered the Pro90 oscilloscopes.

2.3. The 1998 Experiment

In 1998 an experiment was designed to record the electric fields produced by the first strokes in natural cloud-to-ground lightning flashes terminating within a kilometer or so of the center of the ICLRT. Fields produced by triggered-lightning flashes were also recorded. A total of 10 flat-plate electric field antennas were deployed in the field, distributed widely throughout the test range over an area of about 0.5 km² (see Figure 1). Output signals from each antenna were transmitted to a MultiPro 150 digitizer installed at UF-LC via Nicolet ISOBE 3000 fiber-optic links. Four cards were installed in the MultiPro, for a total of 16 channels with a sampling rate of 10 MHz. The record duration for each channel was 51.2 ms, with a pretrigger delay of 40 ms to facilitate recording of natural stepped-leader electric fields. Two sets of dual orthogonal loop antennas for measuring magnetic fields were installed at nearly opposite corners of the field measuring network (see Figure 1); their signals were used to trigger the digitizer and provide rudimentary direction-finding capability for locating natural lightning flashes. The digitizer was set to trigger when the signal level from any of the four loop antennas exceeded that expected from a return stroke with a peak current of 20 kA at a distance of 1 km from the antenna. The system was designed to run unattended, and magnetic field triggering allowed the recording of events initiated from any of the ICLRT launch facilities. Only data for triggered lightning are presented here.

In 1998, electric fields were recorded for lightning flashes triggered from the following three launchers (see Figure 1): (1) the tower launcher (4.5-m-tall launcher placed on an 11-m tower) grounded through a 25-m vertical ground rod with a low-frequency, low-current grounding resistance of approximately 20 Ω; (2) a 7-m-tall (including lightning attachment rod) launcher positioned near the southwest corner of the test runway, ungrounded but positioned directly over the test runway lighting system counterpoise (6 AWG, bare-copper, horizontal conductor extending around the runway perimeter and buried at a depth of a few tens of centimeters [*Bejleri*, 1999]); and (3) a 10-m-tall launcher (including a 5-m lightning attachment rod) at the SATTLIF-West site, grounded through three 2.5-m vertical ground rods.

2.4. The 1999 Experiment

In 1999 an experiment was designed to measure close triggered-lightning electric fields over a buried wire-mesh metallic grid, which surrounded the launcher located at the SATTLF-West site (see Figure 1). The grid was installed to minimize field propagation effects and ground-surface arcing, which often otherwise occurs around the launcher base [*Fisher and Schnetzer*, 1994; *Rakov et al.*, 1998].

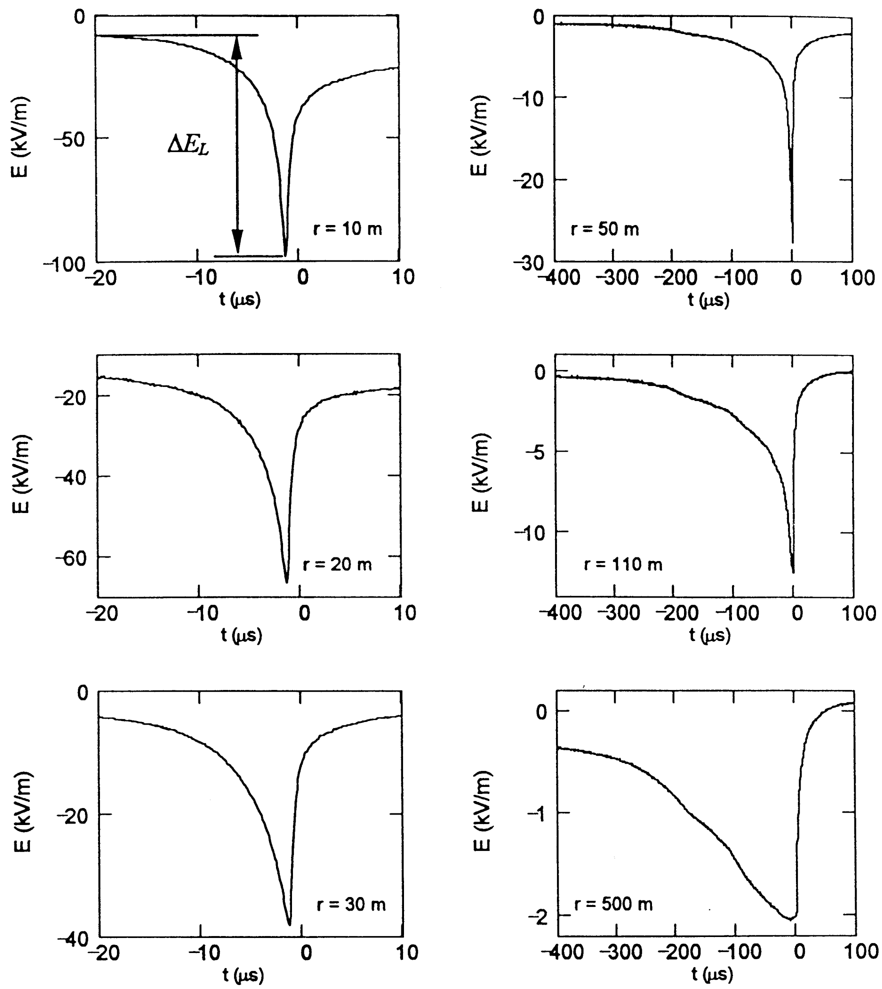

Figure 2. Electric field waveforms recorded in 1997 at 10, 20, 30, 50, 110, and 500 m from the lightning channel for dart-leader/return-stroke sequence S9721-1. ΔE_L is the leader electric field change.

Further, in order to minimize the influence of the launcher on the measured fields, the launcher was placed completely underground within a wooden-frame-reinforced cubical pit approximately 4 m on each side, located in the center of the buried grid. The buried grid had a mesh size of 5 × 10 cm^2 and overall dimensions of 70 × 70 m. The grid was buried in clean sand at a depth of up to 20 cm. The measured low-frequency, low-current grounding resistance of the buried grid was 6 Ω. The top of the launcher was approximately flush with the ground surface, and bonded to the buried grid via four symmetrically arrayed metal straps. The base of the launcher was connected through two straps to a single 16 m vertical rod, driven into the earth at the bottom of the pit. This rod had a low-frequency, low-current grounding resistance of 40 Ω. A galvanized-steel lightning attachment rod was mounted on the top of the launcher. The rod initially protruded 1 m above the ground surface (during flashes S9915 and S9918), and later it was lengthened 2 m (flashes S9930–S9935) to increase the likelihood that the lightning channel would terminate on the rod and that the lightning current would flow through the instrumented launcher.

Electric fields over the buried metallic grid were measured using UF flat-plate antennas located 15 and 30 m from the strike rod. The electric field antenna housings were electrically bonded to the buried grid. Meret fiber-optic transceivers (with a 35-MHz bandwidth) were utilized to transmit output signals from the antennas to 10-MHz antialiasing filters followed by LeCroy 9400 digital oscilloscopes. A TTL-level external trigger signal for the oscilloscopes was generated whenever the lightning current through the current viewing resistor installed at the launcher exceeded ±5 kA. Additionally, in 1999, electric fields were recorded, for lightning flashes triggered from the underground launcher (SATTLIF-West) and from the tower launcher (see Figure 1), by the multiple-station field measuring system described above.

3. Data Presentation

3.1. General Information

The electric field waveforms recorded at six distances ranging from 10 to 500 m from the lightning channel, for a typical dart-leader/return-stroke sequence in triggered lightning, are plotted as an example in Figure 2. Note that

Table 1. Dart-Leader Electric Field Change as a Function of Distance From the Lightning Channel for Events Recorded at the International Center for Lightning Research and Testing in 1993–1999[a]

Flash	Stroke	Number of Stations	I_p, kA	$\Delta E_L = f(r)$, kV m^{-1}	Distances, m	Launch Site
				1993		
9313	2	3	9.7	$61r^{-0.28}$	30,50,110	between IS1 and IS2
	3	3	11	$69\,r^{-0.30}$	30,50,110	between IS1 and IS2
	4	3	13	$76\,r^{-0.30}$	30,50,110	between IS1 and IS2
	5	3	11	$56\,r^{-0.25}$	30,50,110	between IS1 and IS2
9320	1	3	9.6	$1.7\times10^2\,r^{-0.51}$	30,50,110	between IS1 and IS2
	2	3	8.4	$1.0\times10^2\,r^{-0.42}$	30,50,110	between IS1 and IS2
				1997		
S9711	1	3	6.5	$1.6\times10^3\,r^{-1.1}$	50,110,500	SATTLIF-East
S9712	1	3	5.3	$1.4\times10^2\,r^{-0.59}$	10,20,30	SATTLIF-East
S9718	1	5	12	$2.1\times10^3\,r^{-1.1}$	20 – 500	SATTLIF-East
		3		$1.4\times10^3\,r^{-1.0}$	30,50,110	SATTLIF-East
S9720	1	4	21	$2.6\times10^3\,r^{-1.1}$	30 – 500	SATTLIF-East
		3		$1.7\times10^3\,r^{-0.99}$	30,50,110	SATTLIF-East
S9721	1	6	11	$1.3\times10^3\,r^{-1.0}$	10 – 500	SATTLIF-East
		3		$9.9\times10^2\,r^{-0.93}$	30,50,110	SATTLIF-East
		3		$7.1\times10^2\,r^{-0.84}$	10,20,30	SATTLIF-East
				1998		
U9801	1	10	8.7	$2.8\times10^3\,r^{-1.2}$	102 – 410	runway
U9822	1	10	11	$2.6\times10^3\,r^{-1.1}$	92 – 380	tower
U9824	1	10	17	$5.1\times10^3\,r^{-1.2}$	102 – 410	runway
U9825	1	10	NR	$5.8\times10^3\,r^{-1.2}$	102 – 410	runway
U9827	1	9	41	$7.1\times10^3\,r^{-1.2}$	92 – 380	tower
S9806	1	10	9.1	$1.5\times10^3\,r^{-0.96}$	67 – 619	SATTLIF-West
				1999		
U9901	1	10	8.2	$3.3\times10^3\,r^{-1.2}$	91 – 380	tower
U9902	1	10	12	$2.1\times10^3\,r^{-1.1}$	91 – 380	tower
S9915	1	9	11	$1.0\times10^3\,r^{-0.98}$	15 – 621	SATTLIF-West
S9918	1	9	26[b]	$5.3\times10^3\,r^{-1.2}$	15 – 621	SATTLIF-West
S9930	1	3	39	$4.0\times10^3\,r^{-1.0}$	15 – 507	SATTLIF-West
S9932	1	4	19	$3.6\times10^3\,r^{-1.1}$	15 – 507	SATTLIF-West
S9934	1	4	30	$3.0\times10^3\,r^{-1.0}$	15 – 507	SATTLIF-West
S9935	1	3	21[b]	$2.1\times10^3\,r^{-1.0}$	15 – 507	SATTLIF-West

[a] NR, not recorded. I_p, return-stroke peak current. Launch site locations are indicated in Figure 1. SATTLIF, Sandia Transportable Triggered-Lightning Instrumentation Facility.
[b] Peak current estimated from peak magnetic field recorded at 15 m from the channel using Ampere's law for magnetostatics.

the amplitude of the V-shaped waveform decreases and its duration increases with increasing distance from the lightning channel.

In the following, we present relations between the measured leader electric field change ΔE_L and distance r from the lightning channel for triggered-lightning events recorded during 1993, 1997, 1998, and 1999. The definition of ΔE_L is shown in Figure 2. The relation between leader field change and distance was assumed to be of the power form $\Delta E_L = ar^b$. A logarithmic transformation was applied, and an unweighted linear regression equation was obtained of the form $\ln \Delta E_L = \ln a + b \ln r$. The coefficient of determination R^2 (the square of correlation coefficient) was calculated and was found to be between 0.9 and 1 for every event except U9825-1, for which it was 0.84. The value of determination coefficient of, say, 0.95 indicates that 95% of the variation in $\ln \Delta E_L$ is due to variation in $\ln r$ and 5% is due to variation in other factors. The resulting values of a and b were rounded to two significant figures. The power form equations relating ΔE_L and r are presented in Table 1. For the 1997 experiment, when possible, two equations are given, one for all data available and the other for measurements at 30, 50, and 110 m (for direct comparison with the 1993 data). Additionally, for flash S9721, an equation for measurements at 10, 20, and 30 m is included.

3.2. The 1993 Experiments

In 1993 at Camp Blanding, electric field changes for a total of six strokes in two flashes were recorded simultaneously at three distances, 30, 50, and 110 m, from the launcher. These are the same data previously reported by *Rakov et al.* [1998]. The electric field variation with distance from the lightning channel is appreciably weaker than the inverse proportionality predicted by the uniformly charged leader model [e.g., *Rubinstein et al.*, 1995]. For flash 9313 the fields vary as $r^{-0.25}$ to $r^{-0.30}$, and for flash 9320, the observed distance dependences are $r^{-0.42}$ and $r^{-0.51}$. Except for stroke 9320-1, these data are all for triggered strokes of order 2 or higher, while only first strokes were recorded in the 1997, 1998, and 1999 experiments discussed below. Note that all strokes in classical triggered lightning, including the first, are similar

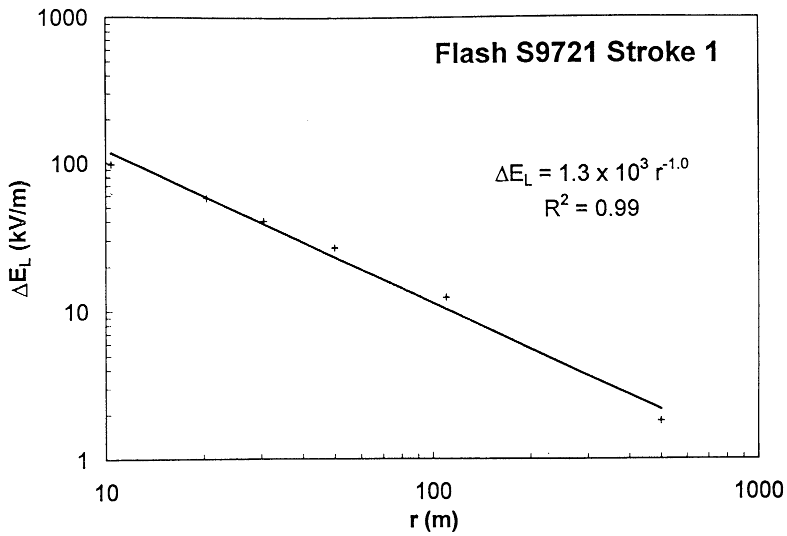

Figure 3. Dart-leader electric field changes versus distance from the lightning channel for event S9721-1, as recorded at six stations in 1997.

to subsequent strokes in natural lightning. In 1993 at Fort McClellan, a total of three flashes, 93-02, 93-03, and 93-15, were analyzed. The ratio of electric fields measured at about 10 and 20 m was of the order of 1.2 [*Fisher et al.*, 1994; *Rakov et al.*, 1998, Figure 5], indicating a distance dependence weaker than r^{-1}. The sample sizes for the measurements at 10 and 20 m were 15 and 8, respectively.

3.3. The 1997 Experiment

In 1997, five triggered-lightning strokes were recorded. As noted in section 2.2, the total number of antennas used was seven. However, the electric field recorded at 5 m (and sometimes at greater distances) from the channel in all cases was corrupted, apparently due to ground surface discharges and/or current flowing in a residual triggering wire on the ground in the vicinity of the affected antennas. As seen in Table 1, ΔE_L for each event varies with distance as $r^{-0.99}$ to $r^{-1.1}$ (based on all available data), with the exception of stroke S9712-1 for which it varies more slowly, as $r^{-0.59}$. It appears that the variation with distance at closer ranges may be weaker than that for the overall 10- to 500-m range. For the range 10 to 30 m, the equation for stroke S9721-1 (the only stroke other than S9712-1, for which measurements at 10, 20, and 30 m are available) is found to be $\Delta E_L = 7.1 \times 10^2\ r^{-0.84}$. A plot of ΔE_L versus distance for a typical 1997 stroke, S9721-1, is shown in Figure 3. Stroke S9712-1, which exhibited the relatively weak $r^{-0.59}$ distance dependence, differed from the other strokes in the 1997 data set in that the 10-90% risetime of the measured return-stroke current was unusually long, 4 μs; for the remaining return strokes recorded during 1997,

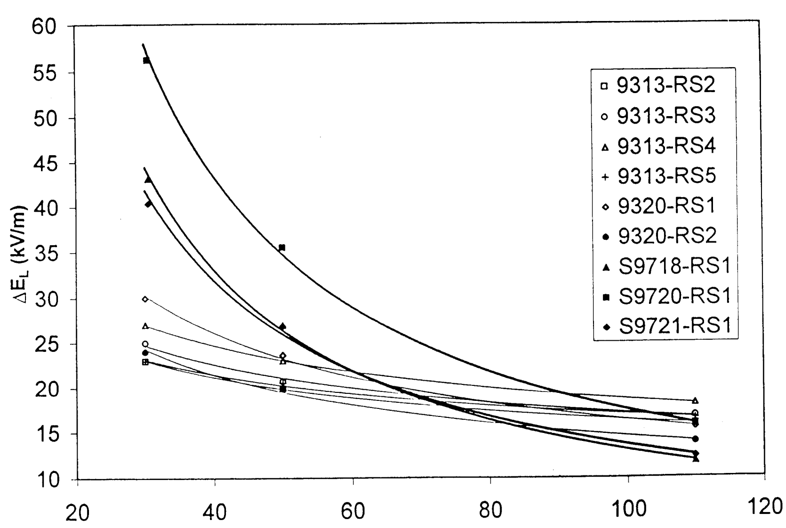

Figure 4. Dart-leader electric field changes versus distance from measurements at 30, 50, and 110 m from the lightning channel for direct comparison of 1993 and 1997 data. See also Table 1.

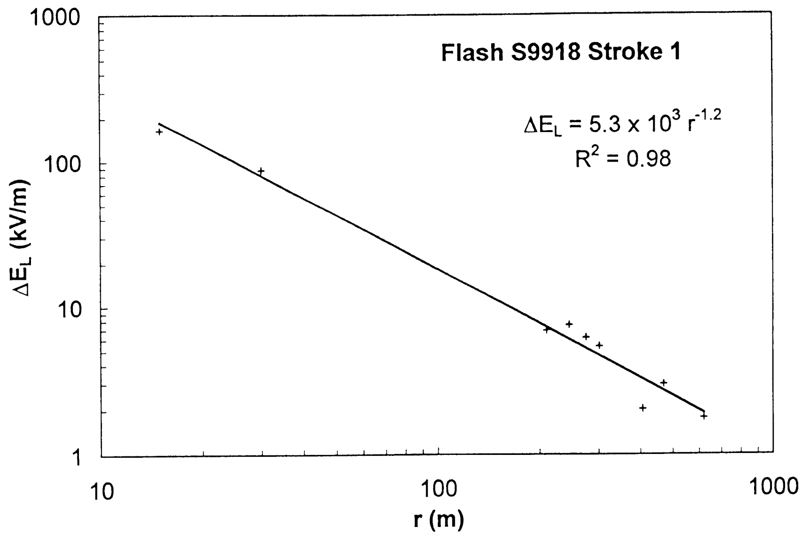

Figure 5. Dart-leader electric field changes versus distance from the lightning channel for event S9918-1, as recorded at nine stations in 1999.

the rise times varied from 0.3 to 2.2 μs, with a median value of 0.4 μs and a mean of 0.9 μs. Further, the S9712-1 peak current was relatively small, 5.3 kA; the 1997 mean was 13 kA and geometric mean was 12 kA.

Figure 4 depicts ΔE_L measured at 30, 50, and 110 m from the channel versus distance for both 1993 and 1997, to allow direct comparison of the two data sets. For the three-station 1997 data, the variation of ΔE_L with distance from the channel is somewhat slower, from $r^{-0.93}$ to $r^{-1.0}$, than for all available data (10-500 m), but remains close to r^{-1}.

3.4. The 1998 Experiment

During 1998, 10-station data were obtained for six triggered-lightning strokes. Three were triggered from the runway launcher, two from the tower launcher, and one from the SATTLIF-West launcher (see Figure 1). As seen in Table 1, ΔE_L for 1998 events varies with distance from the channel as $r^{-0.96}$ to $r^{-1.2}$.

3.5. The 1999 Experiment

During the 1999 campaign, electric field changes for eight triggered-lightning strokes were recorded at different distances from the channel. Six of these were from flashes triggered from the SATTLIF-West launcher; they were recorded at three to nine distances from the channel. The remaining two, recorded at 10 distances, were from flashes triggered from the tower launcher. As seen in Table 1, ΔE_L for 1999 events varies with distance from the lightning channel as $r^{-0.98}$ to $r^{-1.2}$, consistent with the results from the 1997 and 1998 experiments. A plot of ΔE_L versus distance for a typical 1999 stroke, S9918-1, is shown in Figure 5.

In addition to the events in Table 1, electric fields for a total of 38 events were recorded simultaneously at 15 and 30 m from the underground launcher at SATTLIF-West. The ratio of the recorded leader electric field change at 15 m to that at 30 m is close to 2 (the mean was 2.0, the geometric mean was 1.9, and the range of variation was from 1.5 to 2.4). This result is reasonably consistent with the r^{-1} distance dependence.

4. Discussion

At distances within hundreds of meters of the lightning channel, the electric field due to the descending leader is primarily electrostatic. If the fully developed leader channel is modeled as a vertical, uniformly charged line extending between the cloud and a perfectly conductive ground, the vertical electric field change at the Earth's surface due to the leader process will vary with distance from the channel as r^{-1} [*Rubinstein et al.*, 1995]. For this model, 90% of the leader electric field change measured at 30 m is determined by the charge on the channel below 280 m, while at 500 m the corresponding contributing channel length is 2.5 km, according to calculations by *Rubinstein et al.* [1995].

The data obtained in 1997, 1998, and 1999 indicate that with a few exceptions the variation of magnitude of the dart-leader electric field change with distance within several hundred meters from the channel is not much different from r^{-1}. For a vertical lightning channel this is consistent with a leader-deposited charge per unit length that is more or less constant within the bottom kilometer or so of the channel. The 1997 data suggest that the variation with distance of the leader electric field change is slightly weaker at closer ranges, that is, within a few tens of meters of the channel. This decrease may be due to the influence of the metallic launcher, although the 1999 data obtained at 15 and 30 m from the underground launcher with the strike rod protruding only 1 or 2 m above ground are reasonably consistent with data obtained with ground-based launchers up to 10 m in height. Other potentially influencing factors include lightning channel geometry, variation of charge density with height, and limited sample sizes.

We now discuss the potential influence of channel geometry. A uniformly charged channel inclined toward a field measuring station will appear to exhibit a charge density which increases with altitude and will cause the field to vary with distance more slowly than r^{-1}; for a channel inclined away from the observer, the opposite is true. At sufficient distance away, a tortuous section of a uniformly charged leader channel contributes to the leader electric field change as more highly charged than a straight section with the same line charge density. In a triggered lightning the lower portion of the channel (formed along the trace of the vaporized triggering wire) typically exhibits less tortuousity and is often more nearly vertical than the upper portion of the channel. This less tortuous channel section typically extends from the launcher to a height of 200–300 m [*Rakov et al.*, 1998]. From this height up to the cloud base, the channel typically is considerably more tortuous [e.g., *Idone et al.*, 1984; *Wang et al.,* 1999].

We now compare the 1997-1999 data with the 1993 data. Most of the 1997, 1998, and 1999 data (all obtained in Florida) indicate that ΔE_L varies as r^{-1}. This result differs from results based on data obtained in 1993 in Florida and Alabama [*Rakov et al.,* 1998]. The latter indicated that the measured leader electric field change varied more slowly than inverse distance from the channel. The reasons for this discrepancy are unknown, but some possibilities are discussed below.

In 1993 at Camp Blanding, five of the six recorded dart-leader field changes were associated with triggered-lightning strokes of order 2 or higher. Similarly, in 1993 at Fort McClellan, most of the strokes were of order 2 or higher. On the other hand, in 1997, 1998, and 1999 only first strokes (dart-leader/return-stroke sequences) were recorded. As seen in Table 1, the field variation with distance changed little with stroke order in the 1993 Camp Blanding data for both recorded flashes. As mentioned above, in general, there is essentially no difference between strokes of different order in triggered lightning, but additional measurements might still prove instructive in this respect.

As seen in Figure 4, the electric field changes measured at 110 m from the channel during 1993 are similar in magnitude to those measured in 1997, and the trends diverge as the distance to the channel decreases. The largest discrepancy between the 1993 and 1997 data shown in Figure 4 is seen at 30 m. Measuring systems used at Camp Blanding in 1993 and in 1997 at 110 m were different (see section 2.1), while at 30 m they were similar and were calibrated in the same manner. Thus there appears to be no evidence that the observed discrepancy between the 1993 and 1997 data seen in Figure 4 is due to different instrumentation used in those years.

As noted above, the distance dependence of the leader electric field change can be influenced by lightning channel geometry. From multiple-station photographic and video records, the lightning channel of Camp Blanding flash 9320 appears to be more or less straight and vertical (its inclination does not appear to exceed 20° or so from the vertical) for the bottom hundreds of meters. The channel shape of Camp Blanding flash 9313 below the cloud base resembled a question mark [*Rakov et al.,* 1995]. Thus there appears to be no evidence that the lightning channel geometry has influenced the 1993 Camp Blanding data.

Perhaps 1993 Camp Blanding flashes 9313 and 9320 and 1993 Fort McClellan flashes 93-02, 93-03, and 93-15, for which appreciably slower than r^{-1} distance dependences were observed, were not typical triggered-lightning events. Measurements for stroke S9712-1 from the 1997 experiment confirm that the variation of ΔE_L with distance may occasionally be appreciably slower than r^{-1} (see Table 1).

We now estimate the dart-leader line charge density, ρ_L, for a typical triggered-lightning stroke, stroke 1 in flash S9721. For this event, electric field waveforms are shown in Figure 2, with $\Delta E_L = 1.3 \times 10^3 r^{-1.0}$ kV m^{-1} for r ranging from 10 to 500 m (see Table 1 and Figure 3). The return-stroke peak current I_p is 11 kA. Since very close to the channel the net leader electric field change is $\Delta E_L = \rho_L/(2\pi\varepsilon_o r)$ [*Rubinstein et al., 1995*], where ε_o is the electrical permittivity of free space, we find that $\rho_L = 7.2 \times 10^{-5}$ C m^{-1}. This value of dart leader charge density characterizes the bottom kilometer or so of the channel and is consistent with the values of ρ_L previously estimated by *Rubinstein et al.* [1995]. The dart-leader charge is effectively neutralized by the following return stroke. The ratio, I_p/ρ_L, of the measured return-stroke peak current and the estimated dart-leader line charge density is 1.5×10^8 m s^{-1}. This ratio has the dimension of speed and its value is of the order of typically measured speed for return strokes, a result consistent with similar estimates reported by *Rakov et al.* [1998].

5. Summary

Dart-leader electric field changes due to triggered-lightning strokes from experiments conducted in 1997, 1998, and 1999 at Camp Blanding, Florida, were analyzed. The fields were measured at 2-10 stations with distances from the lightning channel ranging from 10 to 621 m. With a few exceptions, the 1997–1999 data indicate that the distance dependence of the leader electric field change is close to an inverse proportionality (r^{-1}). This result is compared with the distance dependences based on similar measurements performed in 1993 in Florida and Alabama. In the 1993 experiments the fields were measured at three distances, 30, 50, and 110 m, in Florida and at two distances, about 10 and 20 m, in Alabama. The 1993 data indicated a distance dependence that was somewhat slower than r^{-1}. The analysis of data in their entirety suggests that although the leader electric field change at distances ranging from tens to hundreds of meters from the lightning channel typically varies as r^{-1}, appreciably weaker distance dependence may be occasionally observed. The r^{-1} dependence is consistent with a more or less uniform distribution of dart-leader charge along the bottom kilometer or so of the channel. A knowledge of the distribution of charge along the leader channel is needed for better understanding of the physics of the lightning discharge and for testing the validity of return-stroke models [see *Thottappillil et al.,* 1997].

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D. E. Crawford, R. J. Fisher, V. A. Rakov, K. J. Rambo, G. H. Schnetzer, M. V. Stapleton, and M. A. Uman, Department of Electrical and Computer Engineering, University of Florida, 553 Engineering Building 33, Gainesville, FL 32611. (rakov@ece.ufl.edu)

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