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M-component mode of charge transfer to ground in lightning discharges

Vladimir A. Rakov, David E. Crawford, Keith J. Rambo, George H. Schnetzer, and Martin A. Uman
Department of Electrical and Computer Engineering, University of Florida, Gainesville, Florida, USA

Rajeev Thottappillil
Institute of High Voltage Research, Uppsala University, Uppsala, Sweden

Abstract. The *M*-component mode of charge transfer to ground is examined using (1) multiple-station measurements of electric and magnetic fields at distances ranging from 5 to ~ 500 m from triggered-lightning channels and (2) measured currents at the channel base. Data have been obtained in 1997, 1999, and 2000 at the International Center for Lightning Research and Testing at Camp Blanding, Florida, for (1) "classical" *M*-components that occur during the continuing currents following return strokes and (2) impulsive processes that occur during the initial stage of rocket-triggered lightning and are similar to the "classical" *M* components. All lightning events considered here effectively transported negative charge to ground. For one triggered-lightning event the electric field 45 km from the lightning channel was measured together with the current and close fields. The shapes and magnitudes of the measured close electric and magnetic fields are generally consistent with the guided-wave mechanism of the lightning *M* component. Specifically, the *M*-component electric field peak exhibits logarithmic distance dependence, $\ln(kr^{-1})$, which is indicative of a line charge density that is zero at ground and increases with height. Such a distribution of charge is distinctly different from the more or less uniform charge density that is characteristic of the dart leaders in triggered lightning, as inferred from close electric field measurements. The M-component magnetic field peak decreases as the inverse distance (i.e., r^{-1}), which is generally consistent with a uniform current within the lowest kilometer or so of channel. The M-component electric field at 45 km appeared as a bipolar, microsecond-scale pulse that started prior to the onset of the *M*-component current at the channel base. *M*-component-type processes can produce acoustic signals with peak pressure values of the same order of magnitude as those from the leader/return stroke sequences in triggered lightning.

1. Introduction

There are three possible modes of charge transfer to ground associated with the subsequent strokes in negative lightning discharges: (1) the dart leader/return stroke sequence, (2) the continuing current, and (3) the *M* component. Figure 1 shows schematically the current profiles corresponding to these three modes.

1. In the dart leader/return stroke mode, a descending leader creates a conductive path between the cloud charge source and the ground (the conductivity along the channel increases from about 0.02 to 10^4 S/m [*Rakov*, 1998, Table 1]) and deposits negative charge along this path. The following return stroke traverses this path, moving from the ground toward the cloud charge source, and neutralizes the negative leader charge. Thus both leader and return stroke processes (also an upward connecting leader if any) serve to effectively transport negative charge from the cloud to the ground. The dart leader progresses downward at a typical speed of 10^7 m/s [e.g., *Orville and Idone*, 1982], while the typical upward return stroke speed is about 10^8 m/s [e.g., *Idone and Orville*, 1982]. The dart leader and return stroke have peak currents of the order of 1 and 10 kA, respectively [*Idone and Orville*, 1985; *Berger et al.*, 1975]. The typical charge transfer to ground by a dart leader/return stroke sequence is about 1 C [e.g., *Berger et al.*, 1975; *Fisher et al.*, 1993].

2. The continuing current that follows a return stroke can be viewed as a quasi-stationary arc between the cloud charge source in the cloud and ground. The typical arc current is tens to hundreds of amperes, and the duration is up to hundreds of milliseconds [e.g., *Berger and Vogelsanger*, 1965; *Thottappillil et al.*, 1995]. The resultant charge transfer to ground is up to tens of coulombs. *Latham* [1980] has estimated, using a model of a free vertical arc in air at atmospheric pressure, that for currents of the order of hundreds of amperes the temperature of the arc core is about 12,000°K. Using the calculations of *Yos* [1963] and *Plooster* [1971], we estimate that at 12,000°K the electrical conductivity in the channel should be between 10^3 and 10^4 S/m. For comparison, the conductivity of solid carbon is 3 x

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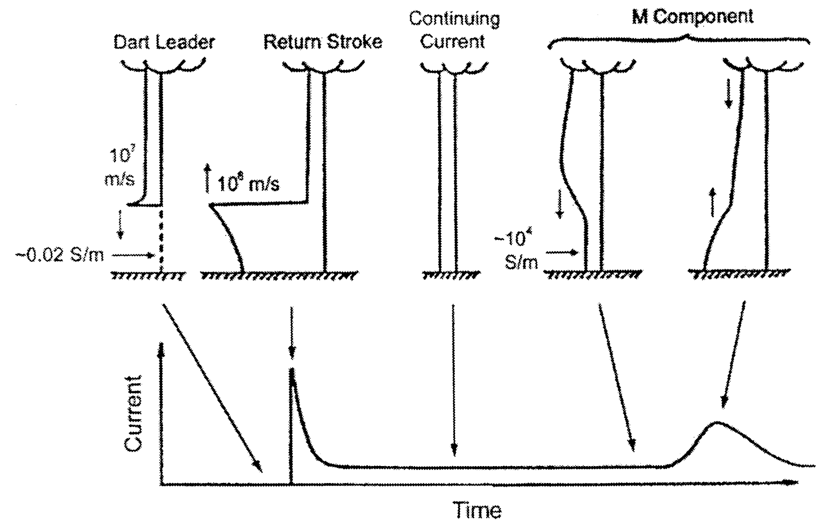

Figure 1. Sketch of the physical mechanisms and current profiles for three modes of charge transfer to ground during lightning subsequent strokes: dart-leader/return-stroke sequence, continuing current, and *M* component. The spatial fronts in dart-leader and return-stroke waves are of the order of 10 and 100 m, respectively. The fronts in *M*-component waves are of the order of 1 km (shown shorter for illustrative purposes). For all these processes the lightning channel conductivity is of the order of 10^4 S/m, except for the channel section between the dart-leader tip and the ground which is shown by a dashed line. For the dashed portion, the conductivity is about 0.02 S/m. The current versus time, which would be measured at the ground, is shown in the bottom graph.

10^4 S/m. For currents of a few tens of amperes the temperature of the arc core is about 7,000°K [*Latham*, 1980], and the corresponding conductivity is 390 S/m [*Yos*, 1963], which is more than 4 orders of magnitude higher than the conductivity of the pre-dart-leader channel [*Rakov*, 1998].

3. Lightning *M* components are perturbations or transient enhancements in the continuing current [*Fisher et al.*, 1993; *Thottappillil et al.*, 1995] and in the associated channel luminosity [*Malan and Collens*, 1937; *Jordan et al.*, 1995]. A typical *M* component is characterized by a more or less symmetrical current pulse at the channel base with an amplitude of 100-200 A (2 orders of magnitude lower than that of a return-stroke current pulse), a rise time of 300-500 μs (3 orders of magnitude longer than for a return stroke), and a charge transfer of 0.1 to 0.2 C (1 order of magnitude smaller than that for a subsequent return-stroke pulse) [*Thottappillil et al.*, 1995]. The *M* components in the triggered-lightning data of *Thottappillil et al.* [1995] outnumbered the leader/return stroke sequences by 4 to 1. Some *M* components have current peaks in the kiloamperes range, comparable to the peaks of the smaller return strokes [e.g., *Rakov et al.*, 1998, Figure 14].

The physical mechanism of the lightning *M* component has been inferred by *Rakov et al.* [1995] from a comparison of the electric fields 30 m from the triggered-lightning channel and the channel-base currents for this lightning process in conjunction with modeling. It appears from their analyses that the *M* component can be viewed as the superposition of two guided waves (the wave-guiding structure is discussed in the next paragraph) which propagate in opposite directions (see Figure 1). The downward moving wave is analogous to a leader, and the upward moving wave, which is a reflection of the downward moving wave from the ground, is analogous to a return stroke. The amplitudes of these waves are approximately equal, their expected propagation speeds are between 10^7 and 10^8 m/s [*Rakov et al.,* 1995], and their spatial front lengths are comparable to the distance between the lower cloud boundary and the ground. When the downward wave reaches ground it "sees" essentially a short circuit and is reflected with a reflection coefficient for current that is close to +1 and with a reflection coefficient for the associated charge density that is close to −1. At each vertical section of channel the two waves are shifted in time, the amount of the shift being small near the ground and increasing toward the cloud. The two waves are usually optically indistinguishable below cloud base, but their existence can be detected by examining the *M*-component electric and magnetic fields observed at ranges from tens to hundreds of meters. Because the reflection coefficients for the traveling waves of current and charge density are different, the incident and reflected waves of current (which determine the close magnetic fields) add at each channel section, while the incident and reflected waves of charge density (which determine the close electric fields) subtract. As a result, at close ranges, the *M*-component magnetic field has an overall waveshape similar to that of the channel-base current, whereas the *M*-component electric field has a waveform that appears to be the time derivative of the channel base current. These characteristic features, in addition to the presence of background continuing current immediately prior to the current pulse, allow *M* components to be distinguished from leader/return stroke sequences.

The M-component mode of charge transfer requires the existence of a grounded channel, carrying a current of typically some tens to some hundreds of amperes, which can act as a conducting, wave-guiding structure. In contrast, the dart leader/return stroke mode of charge transfer requires the absence of such a conducting path, as discussed by *Fisher et al.* [1993]. In the latter mode, the wave-guiding structure is not available and is created by the leader (breakdown processes at the leader tip), which increases the conductivity along the channel by 5 to 6 orders of magnitude, from about 0.02 (essentially a nonconductor) to 10^4 S/m [*Rakov*, 1998, Table 1]. Thus the primary distinction between return/return stroke and the *M*-component modes is the availability of a conducting path to ground (see Figure 1).

"Classical" *M* components occur during the continuing current that follows return strokes in both triggered and natural lightning. Since continuing currents in natural lightning [*Shindo and Uman,* 1989; *Rakov and Uman,* 1990] are primarily associated with subsequent strokes, we assume that *M* components in rocket-triggered lightning are similar to those in natural lightning. *Wang et al.* [1999b] studied the current pulses associated with the initial stage of rocket-triggered lightning, sometimes called ICC (initial continuous current) pulses (Figure 2), and found them to be similar to "classical" M-component current pulses. Thus the *M*-component mode of charge transfer to ground also occurs during the initial stage of rocket-triggered lightning. It is also likely to occur during the initial stage of upward natural lightning that is initiated from tall objects. *Rakov* [2000] has argued that the very large positive currents (many in excess of 100 kA) measured by K. Berger on instrumented towers were produced by *M*-component type processes. In this paper we will term both "classical" *M* components and the ICC pulses "*M*-components." ICC pulses were recorded only in 1999 and 2000, and "classical" *M* components were recorded in 1997, 1999, and 2000.

The guided-wave mechanism of *M* components predicts that at close ranges (1) the *M*-component magnetic field

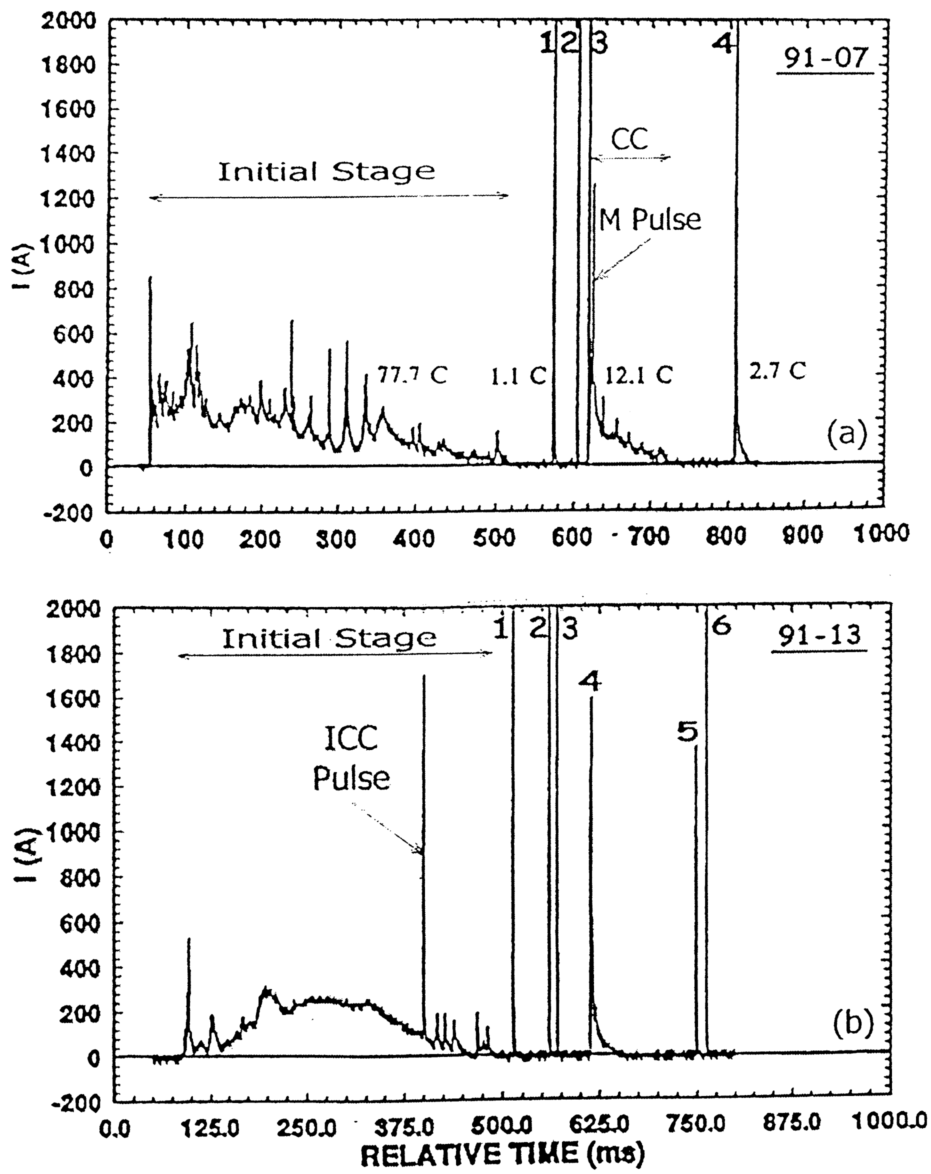

Figure 2. Examples of the overall current records of negative rocket-triggered lightning flashes at Fort McClellan, Alabama. (a) Flash 91-07, (b) flash 91-13. The records are intentionally clipped at 2000 A. All return-stroke pulses are numbered. Charge transfers are indicated in Figure 2a. The largest *M*-component pulse after stroke 3 in 97-07 and the largest ICC pulse in 91-13 are labeled in Figures 2a and 2b. ICC, initial continuous current; CC, continuing current. Note that the largest ICC pulse in 91-13 has a greater peak than return-stroke pulses 4 and 5. Adapted from *Schnetzer and Fisher* [1992].

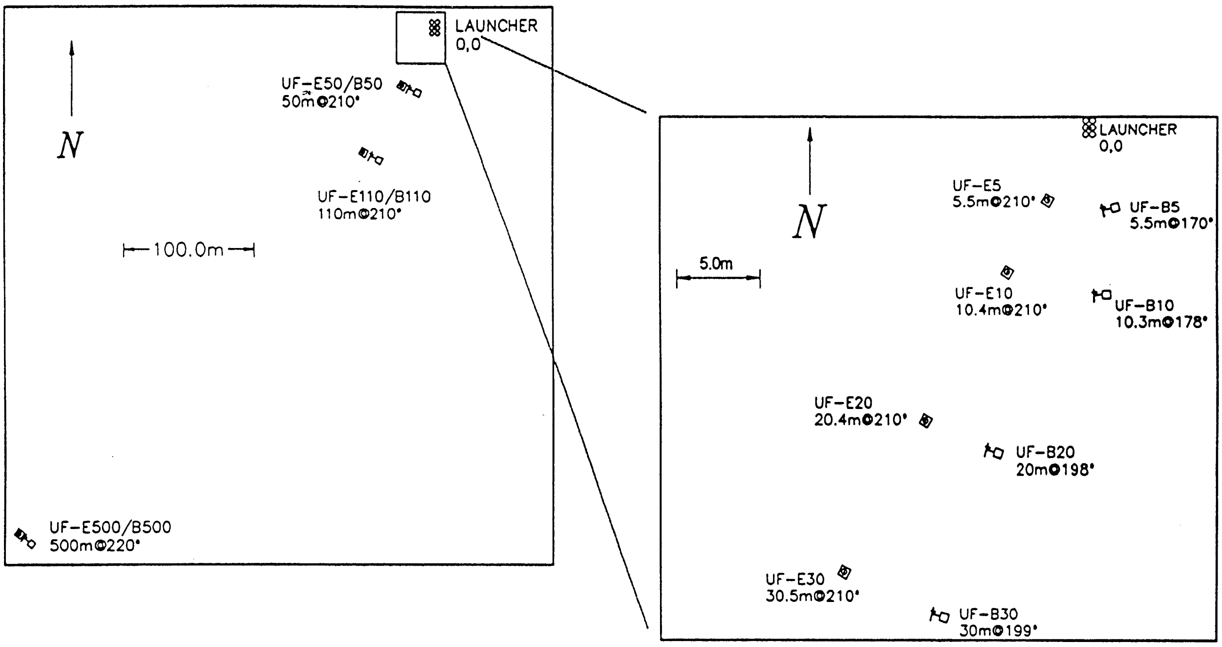

Figure 3. Positions of field measuring stations with respect to the rocket launcher at the International Center for Lightning Research and Testing (ICLRT) at Camp Blanding, Florida, in 1997.

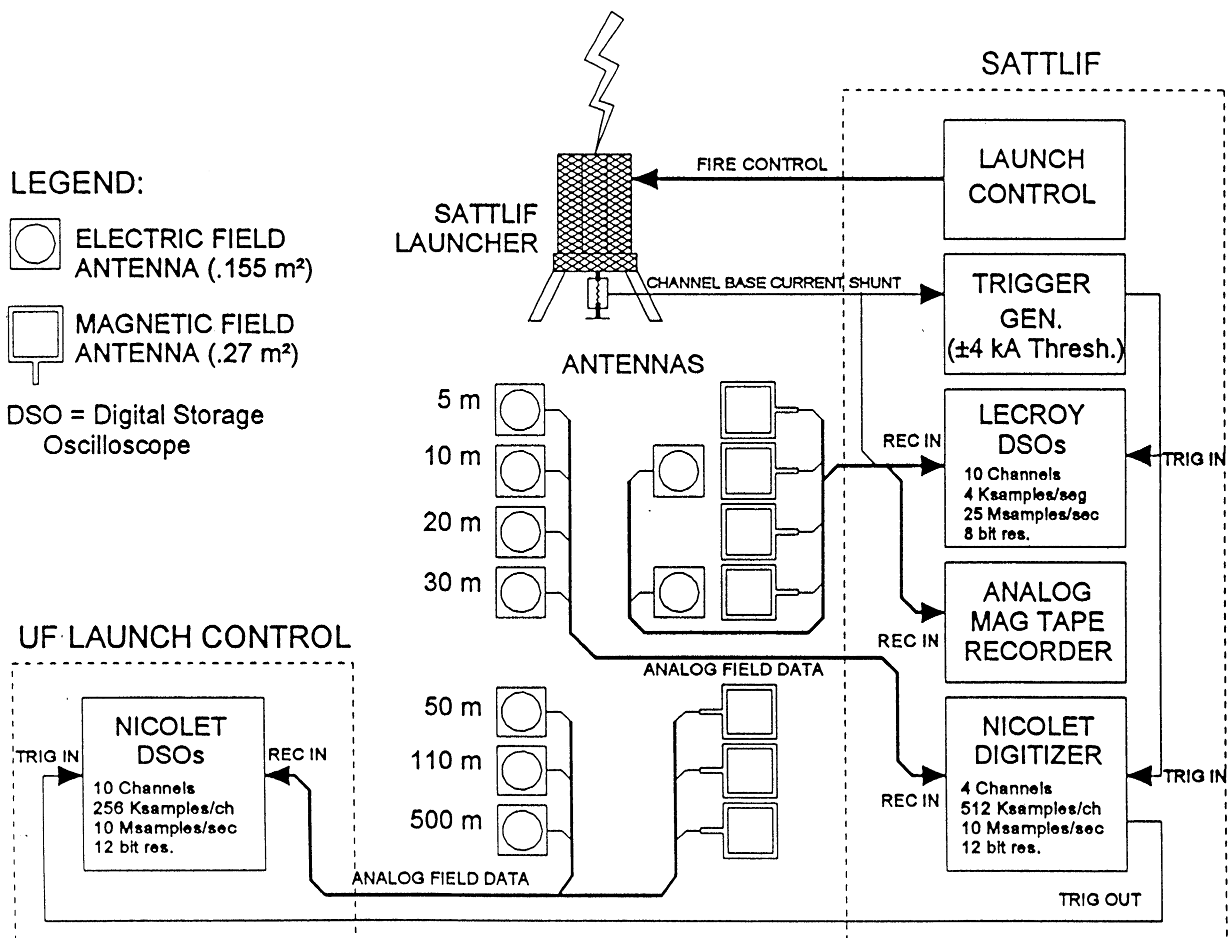

Figure 4. Block diagram of data acquisition system used at the ICLRT in 1997. See also Figure 3.

should vary as the inverse distance from the channel base, and (2) the *M*-component electric field magnitude should be relatively insensitive (compared to leader electric field magnitude) to variations in distance from the channel base. We have tested these predictions using multiple-station electric and magnetic field measurements at distances from 5 to about 500 m from the triggered-lightning channel at Camp Blanding, Florida. Preliminary results, based on data acquired in 1995, have been presented by *Rakov et al.* [1998]. In this paper we present more comprehensive measurements obtained in 1997, 1999, and 2000 which support the guided-wave mechanism of the lightning *M* component.

2. Data

Most of our experimental data were acquired at the International Center for Lightning Research and Testing (ICLRT) at Camp Blanding, Florida. A description of the ICLRT, including the lightning-triggering facilities and the instrumentation is found in the works of *Rakov et al.* [1995, 1998, 2000], *Uman et al.* [1997, 2000], and *Crawford et al.* [2001]. Lightning was triggered using the classical rocket-and-wire technique [e.g., *Rakov et al.*, 1998, Figure 1]. For one triggered lightning event, in addition to the current and close fields, the electric field was measured at the University of Florida Campus in Gainesville, 45 km from the lightning channel.

2.1. 1997 Experiment

In 1997, electric and magnetic fields due to triggered lightning were measured using flat-plate antennas and loop antennas, respectively, at seven distances, 5, 10, 20, 30, 50, 110, and 500 m from the rocket launcher. The relative positions of the field-measuring stations and the launcher are shown in Figure 3. The upper frequency response of the flat-plate measuring system was 10 MHz, and its lower-frequency response was determined by the integrator RC decay time constant which was from 5.1 to 55 ms. Magnetic field waveforms were distorted by an instrumentation decay time constant of 1 ms or so and therefore are not considered here. Lightning currents were measured using a current-viewing resistor (low inductance, resistive shunt) installed at the base of the rocket launcher. The bandwidth of the current measuring system was from 10 Hz to 8 MHz. A block diagram of the data acquisition system is shown in Figure 4. More information on this system, including its calibration, can be found in the work of *Crawford* [1998]. The rocket launcher was 5 m in height and was grounded, through three interconnected 2.5-m ground rods, in sandy soil with measured conductivity of about 2.5 x 10^{-4} S/m. The measured low-frequency, low-current resistance of the grounding system was 220 Ω. A total of five strokes in five different triggered-lightning flashes were recorded, three of which contained pronounced *M* components following leader/return stroke sequences. A total of six *M* components are analyzed here. Electric field waveforms recorded at the closer ranges were often (in all cases at 5 m) corrupted. The corruption was apparently caused by ground surface discharges [*Fisher et al.*, 1994; *Rakov et al.*, 1998] and/or currents flowing in the triggering wires from previous unsuccessful triggering attempts that were lying on the ground near the field measuring station. We did not include corrupted records in our analyses, although in some cases it was possible to identify *M* components in the corrupted electric field records. [The electric field peak at 20 m for S9720-M2 is shown in Figure 9 as an exception even though the overall record was corrupted.] Characteristics of the six *M* components are summarized in Table 1. Current and electric fields at 50, 110, and 500 m from the lightning channel for four *M* components, *M*3a, *M*3b, *M*4, and *M*4a, which occurred in the same flash (S9711) are shown in Figure 5. A more detailed characterization of the six 1997 *M* components can be found in the work of *Crawford* [1998].

2.2. 1999 Experiment

From 1993 to 1998 the rocket-launching systems used at the ICLRT had a height of typically 3 to 7 m (including the lightning strike rod) and were placed on the ground or on top of a wooden tower. Electric and magnetic fields produced by triggered lightning were measured after they had propagated over sandy soil. To minimize the influence of the triggering structure and the effects of propagation over a soil of finite conductivity, we constructed in 1999 a new triggering facility at the ICLRT. In this facility the launcher was placed below ground level and was surrounded by a buried metallic grid having dimensions of 70 m by 70 m. The grid had a mesh size of 5 cm by 8 cm and was buried at a depth of up to 20 cm. The top of the underground launcher (about 4 m tall) was nearly flush with the ground surface and was connected via four symmetrically placed metal straps to the buried grid. The base of the launcher was connected to a single 16-m vertical ground rod. The measured low-frequency, low-current grounding resistances of the buried grid and the vertical ground rod were 6 and 40 Ω, respectively. To increase the probability of lightning attachment to the instrumented launcher, a lightning strike rod was mounted on top of the launcher. The height of this rod was 1 m above ground initially and, later, was increased to 2 m. Electric and magnetic fields and their time rates of change (time derivatives) were measured at distances of 15 and 30 m from

Table 1. Characteristics of Six *M* Components Recorded at the ICLRT in 1997

Flash	*M* Component	Peak Current, A	Electric Field Peak, kV/m						Remark
			10 m	20 m	30 m	50 m	110 m	500 m	
S9711	*M*3a	890	-	-	-	1.1	0.86	0.39	
	*M*3b	520	-	-	-	0.54	0.49	0.22	
	*M*4	890	-	-	-	1.5	1.3	0.52	
	*M*4a	240	-	-	-	0.71	0.63	0.29	
S9712	M2	1800-4000	9.9	6.2	5.0	-	-	-	
S9720	M2	1800-4000	-	-	2.1	1.6	1.3	0.69	see Figures 5 and 9

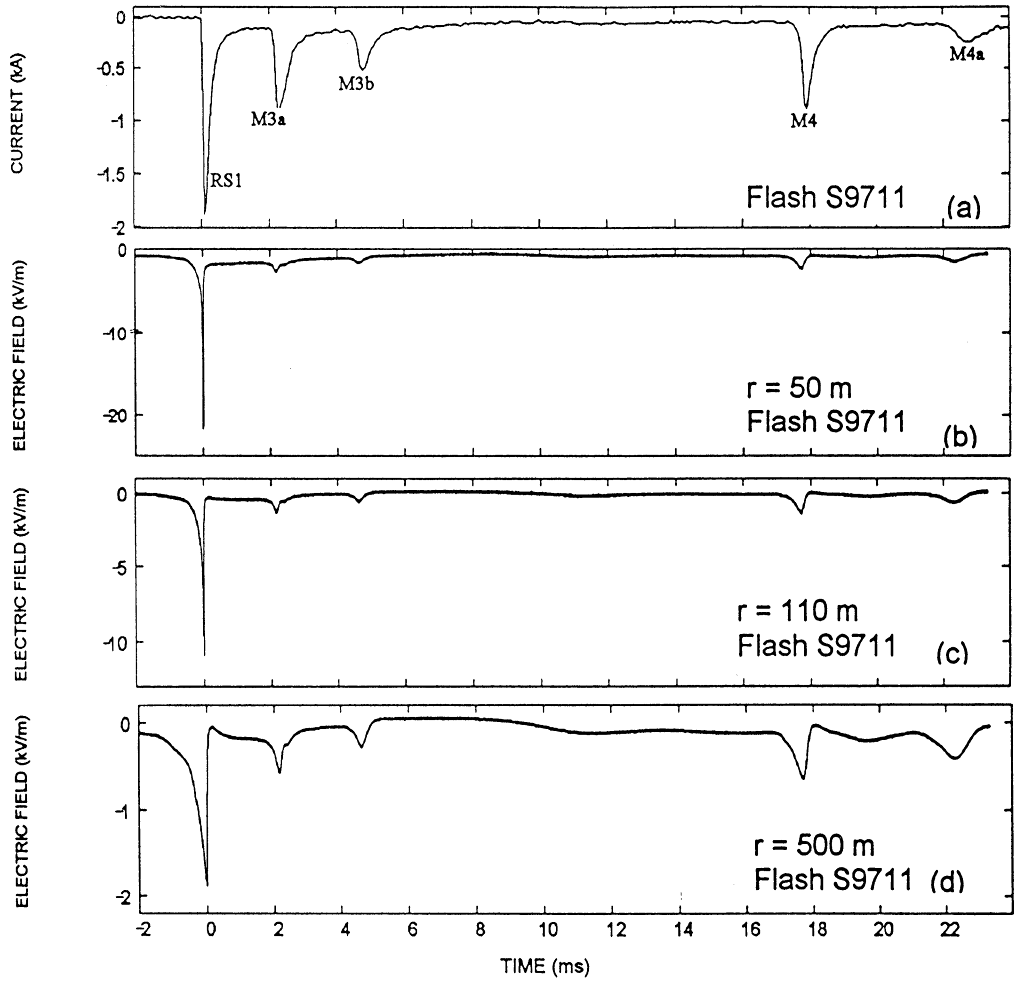

Figure 5. A leader/return stroke (RS1) sequence followed by four pronounced *M*-components (*M*3a, *M*3b, *M*4, and *M*4a) in flash S9711 initiated using the classical rocket-and-wire technique at the ICLRT in 1997: (a) current (clipped at about 1.8 kA), (b) electric field at 50 m, (c) electric field at 110 m, and (d) electric field at 500 m. Note that the magnitude of the *M*-component electric field pulses relative to the magnitude of return/return stroke electric field pulse increases with distance.

the lightning strike rod. The positions of field-measuring stations with respect to the underground launcher are shown in Figure 6a. Also shown in Figure 6a (in the northwest quadrant) are acoustic shock-wave sensors labeled Sh. Considered here are data from the electric-field-measuring systems labeled E(15) and E(30), from magnetic-field-measuring systems labeled B(15) and B(30), and from shock-wave sensors labeled Sh(5), Sh(15), and Sh(30). Electric fields were measured using flat-plate antennas, similar to those used in 1997, whose housings were electrically connected to the buried metallic grid. Magnetic fields were measured using loop antennas oriented so as to maximize the signal from a vertical lightning channel attached to the launcher. The bandwidth of the magnetic-field-measuring system was from about 100 Hz to 10 MHz. Lightning currents flowing through the launcher to the buried grid and to the vertical ground rod were measured using six current transformers (110A Pearson coils) whose bandwidth was from about 3 Hz to 18 MHz. Four current transformers were used to measure a current into the grid and two to measure a current through the ground rod. The total lightning current was obtained by digital summation of these two currents. Kistler-type-211B piezoelectric pressure transducers with type-5114 couplers were used for the acoustic signal measurements. High-gain amplifiers were used to increase output signals from these sensors up to the normal input level of the fiber-optic transmitters. The transducers were mounted in the center of 23 cm by 23 cm aluminum plates with the face of the transducer flush with the surface of the plate. The aluminum plates were mounted approximately 0.8 m above the ground on wooden stands and oriented so they faced the lightning channel.

Two *M*-components whose current peaks exceeded the system's trigger threshold level of 5 kA were recorded. These were event 5 in flash S9915 and event 1 in flash S9933, whose characteristics are summarized in Table 2. Event 5 (*M*-component) in flash S9915 occurred about 27 ms after the preceding return stroke (event 4 in flash S9915). Both the return stroke and the *M*-component were observed to produce acoustic signals. The peak overpressure measured by a sensor in the center of a vertical aluminum plate (see above) at a distance of about 5 m from the rocket launcher was about 23

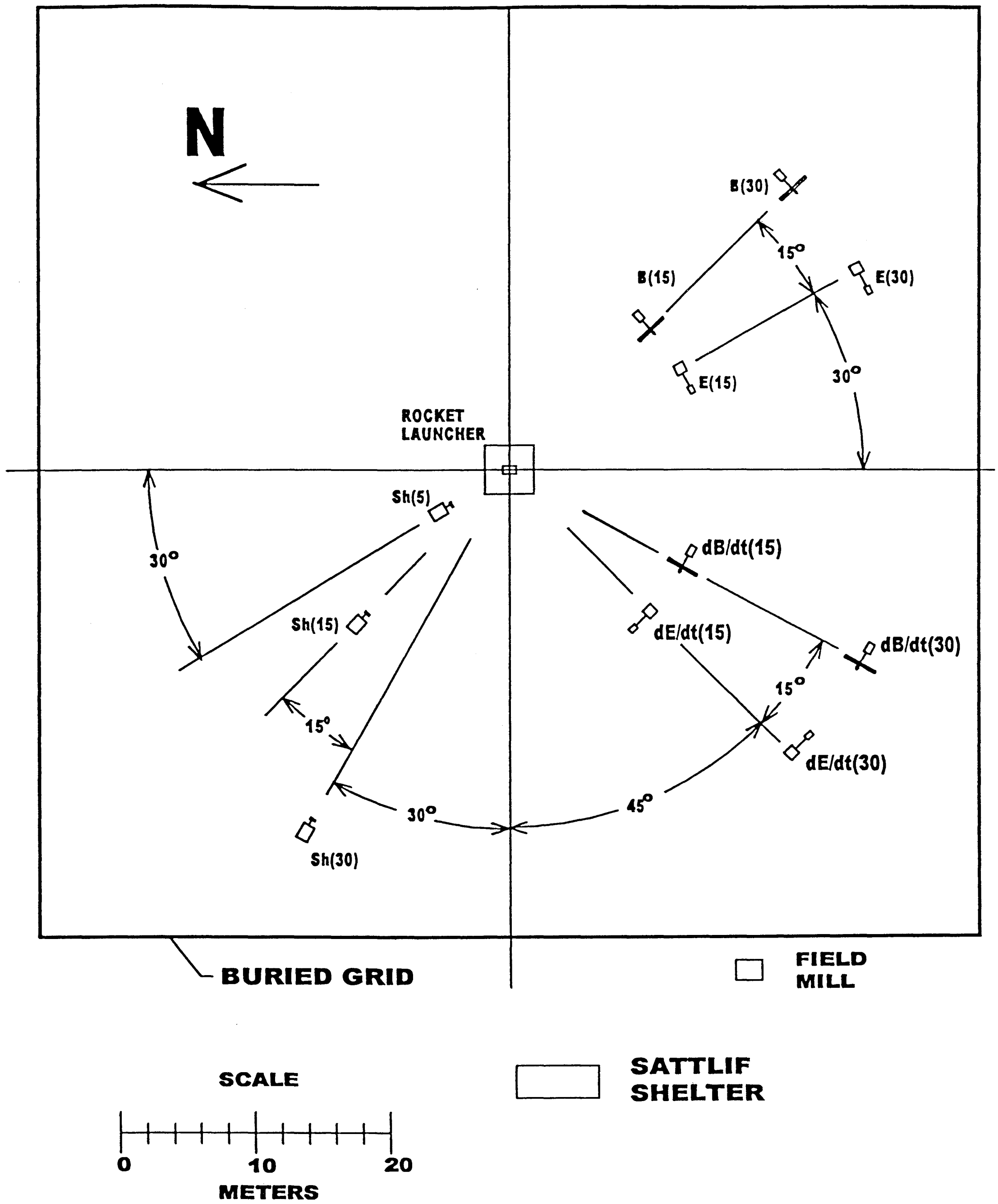

Figure 6a. Positions of field-measuring stations with respect to the underground launcher at the ICLRT in 1999.

Table 2. Characteristics of Two *M* Components Recorded at the ICLRT in 1999

Flash - Event	Peak Current, kA	Magnetic Field Peak, μWb/m², 15 m	Magnetic Field Peak, μWb/m², 30 m	$\frac{B15m}{B30m}$	Electric Field Peak, kV/m, 15 m	Electric Field Peak, kV/m, 30 m	Electric Field Peak, kV/m, 65 m	Electric Field Peak, kV/m, 507 m	$\frac{E15m}{E30m}$	Remark
S9915 - 5	5*	69	38	1.8	11	8.8	-	-	1.2	acoustic signal observed
S9933 - 1	8.1	122	67	1.8	14	11	8.3	3.8	1.3	ICC pulse; see Figure 10

Asterisk, estimated from magnetic field measured at 15 m from the launcher (lightning channels did not attach to the strike rod).

x 10^{-3} atm for the return stroke and 9.5 x 10^{-3} atm for the *M*-component. The corresponding peak currents (estimated from the magnetic fields measured at 15 m from the rocket launcher) were about 16 and 5 kA, respectively.

Additionally, acoustic signals were observed at 5, 15, and 30 m from the rocket launcher for an initial-stage pulse in flash S9908 that contained no downward leader/upward return stroke sequences. The peak overpressure values were about 17 x 10^{-3}, 6.8 x 10^{-3}, and 4.8 x 10^{-3} atm at 5, 15, and 30 m, respectively. It appears that all "impulsive" processes in lightning discharges produce acoustic signals.

2.3. 2000 Experiment

The same underground launcher was used as in 1999. Electric fields were measured using flat-plate antennas at 5, 15, and 30 m from the lightning channel, and magnetic fields were measured using loop antennas at 15 and 30 m from the channel. The upper frequency response of the flat-plate measuring system in 2000 was 15 MHz. The bandwidth of the magnetic field measuring system was from about 10 Hz to 15 MHz. The antennas were located in the northeast quadrant (see Figure 6b), except for the 5-m electric field antenna, which was located west of the launcher. (The antennas shown in the southeast and southwest quadrants in Figure 6b were used in other experiments.) To increase the probability of lightning attachment to the launcher, a metallic ring concentric with the 2-m lightning strike rod and electrically connected to the base of the strike rod was installed. The radius of the ring was 1.5 m. The height of the ring above ground was 1.5 m, so the tip of the strike rod was 50 cm

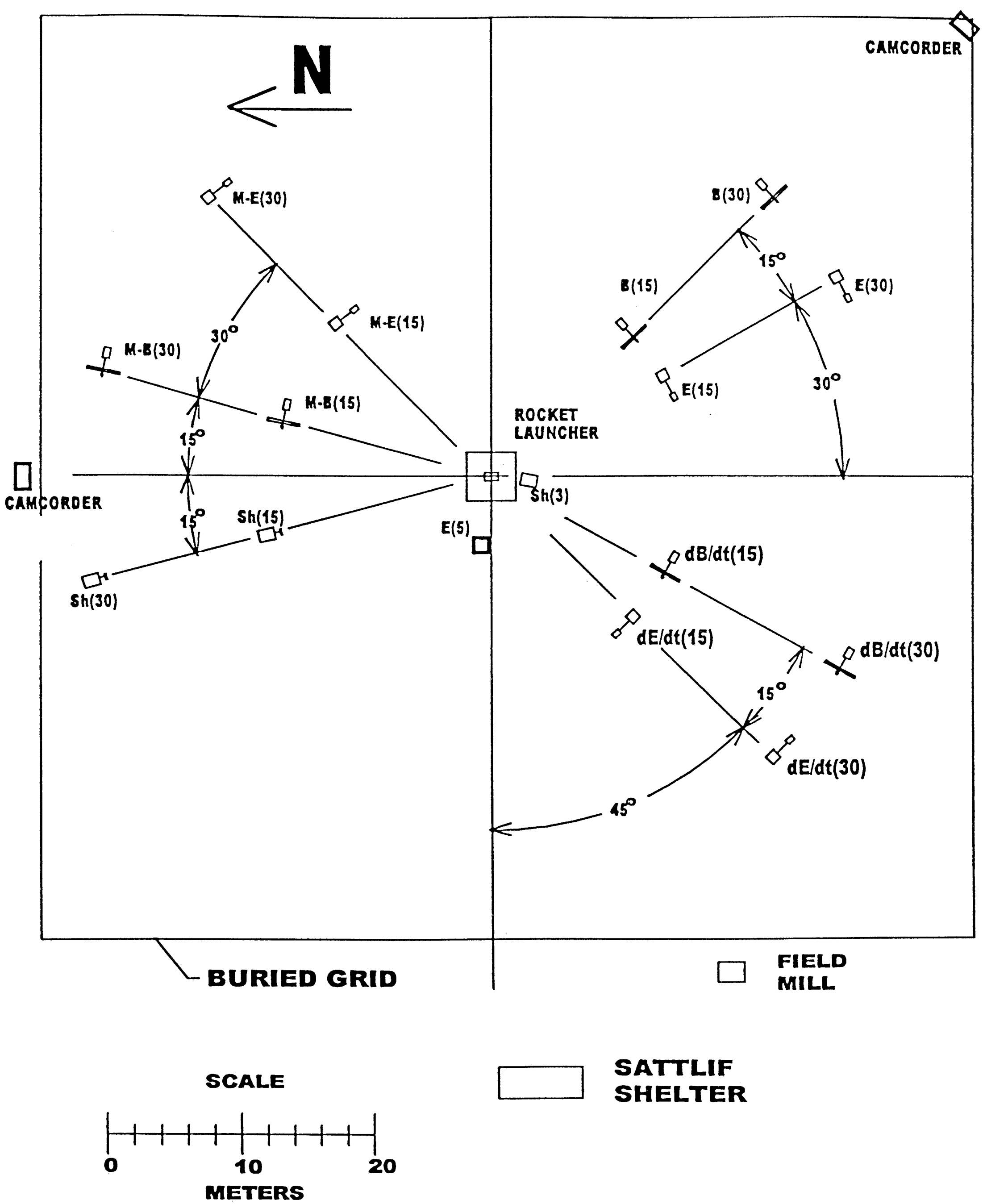

Figure 6b. Same as Figure 6a but in 2000.

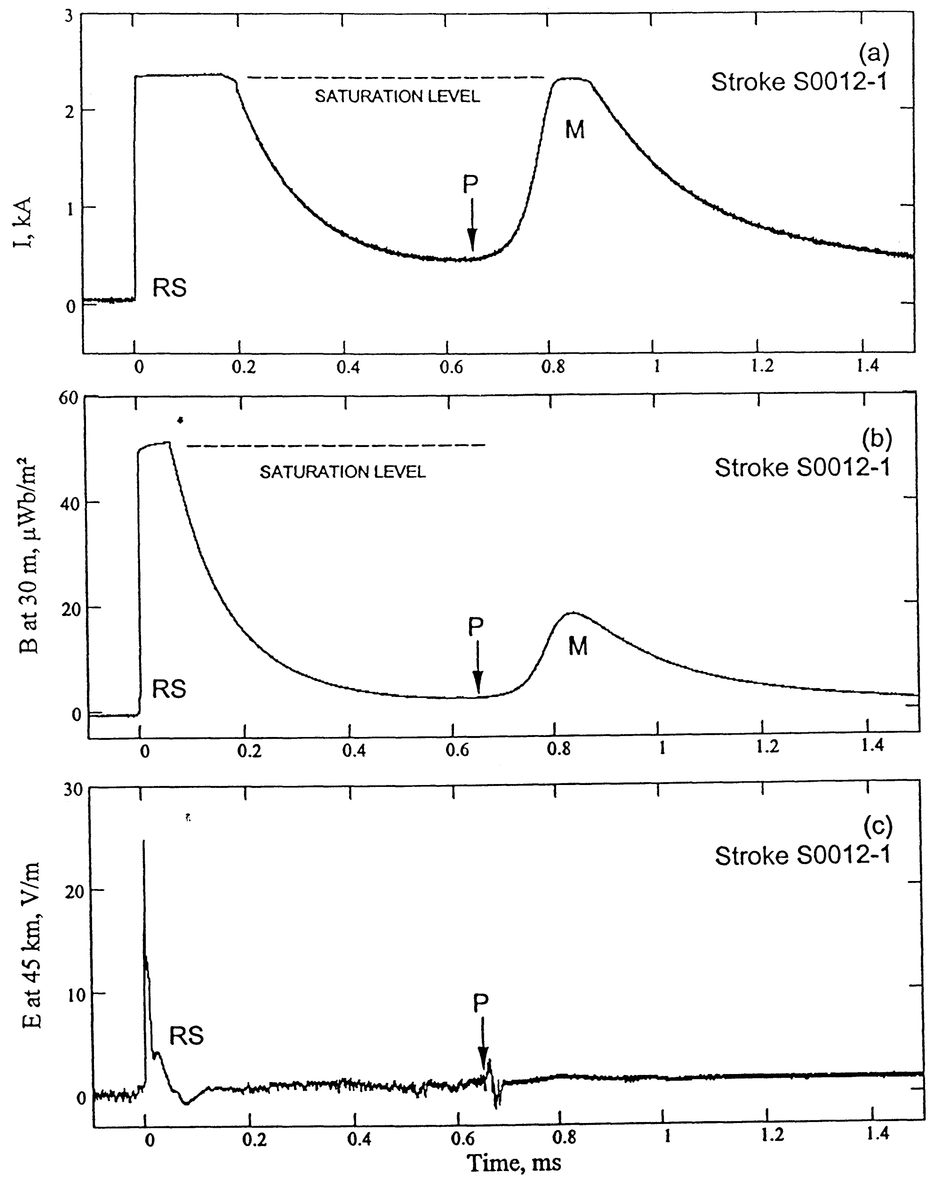

Figure 7. A return stroke (RS) followed by an *M* component (*M*) in flash S0012 initiated using the classical rocket-and-wire technique at the ICLRT in 2000: (a) current (inverted relative to current waveforms in Figs. 5, 8, 12, and 13; both return-stroke and *M*-component waveforms are clipped at 2.3 kA); (b) magnetic field at 30 m (return-stroke waveform is clipped); and (c) electric field at 45 km. *M*-component current peak is estimated from the measured magnetic fields to be about 2.4 kA. The onset of the pulse (P) seen in the 45-km electric field record is indicated by vertical arrows in the current and 30-m magnetic field records.

above the plane of the ring. The total lightning current was measured using a current-viewing resistor installed between the lightning strike rod and the top of the launcher. The overall frequency bandwidth of the current-measuring system was from dc to 8 MHz. The current trigger threshold in 2000 was 3.2 kA.

In addition to electric fields at 5, 15, and 30 m we also measured the electric field 45 km from the lightning channel for one event. This measurement was made using a 1.5-m whip antenna on the roof of the five-story Engineering Building at the University of Florida Campus in Gainesville. The measuring system was calibrated using (1) distant-lightning electric fields simultaneously measured using the whip antenna in Gainesville and a flat-plate antenna (placed flush with ground) at the ICLRT, (2) corresponding lightning locations reported by the U.S. National Lightning Detection Network (NLDN), and (3) an assumption that the distance variation of far electric fields is close to an inverse proportionality. The electric field waveform at 45 km is shown in Figure 7 together with the current and 30-m magnetic field waveforms. Note that the *M*-component electric field at 45 km appears to be a bipolar microsecond-scale pulse that begins prior to the onset of the *M*-component current at the channel base.

In 2000, simultaneous current, electric field, and magnetic field measurements were obtained for 10 *M*-components. Characteristics of these 10 events are summarized in Table 3. The most complete set of records obtained in 2000, for *M*1 in flash S0013, is shown in Figure 8. It includes current, magnetic fields at 15 and 30 m, and electric fields at 5, 15,

Table 3. Characteristics of *M* Components Recorded at the ICLRT in 2000

Flash	*M* Component	Peak Current, A	B15m, μWb/m^2	B30m, μWb/m^2	B15m/B30m	E5m, kV/m	E15m, kV/m	E30m, kV/m	Remarks
S0008	*M*1	3200	37	20	1.9	27	20	15	ICC pulse; see Fig. 11
S0012	*M*1	>2300	33	16	2.0	1.7	0.9	0.9	see Figs. 7 and 11
S0013	*M*1	>2300	44	22	2.0	7.5	4.5	4.1	see Figs. 8 and 11
S0013	*M*2	100	1.5	0.7	2.1	-	0.3	0.3	E15m/E30m = 1
S0022	*M*2	925	12	5.7	2.1	1.4	1.1	-	E5m/E15m = 1.3
S0022	*M*3	605	8.0	3.6	2.2	1.2	1.0	-	E5m/E15m = 1.2
S0023	*M*1	720	4.1	2.0	2.1	-	0.3	-	
S0023	*M*3	2250	35	17	2.1	3.3	2.2	-	E5m/E15m = 1.5
S0027	*M*1	980	15	6.7	2.2	-	1.6	1.7	E15m/E30m = 0.94
S0027	*M*3	990	13	5.7	2.2	-	1.1	0.9	E15m/E30m = 1.2

Not included in this table are several *M* components that appeared only in current and magnetic field records (electric field records are either unavailable or insufficiently resolved).

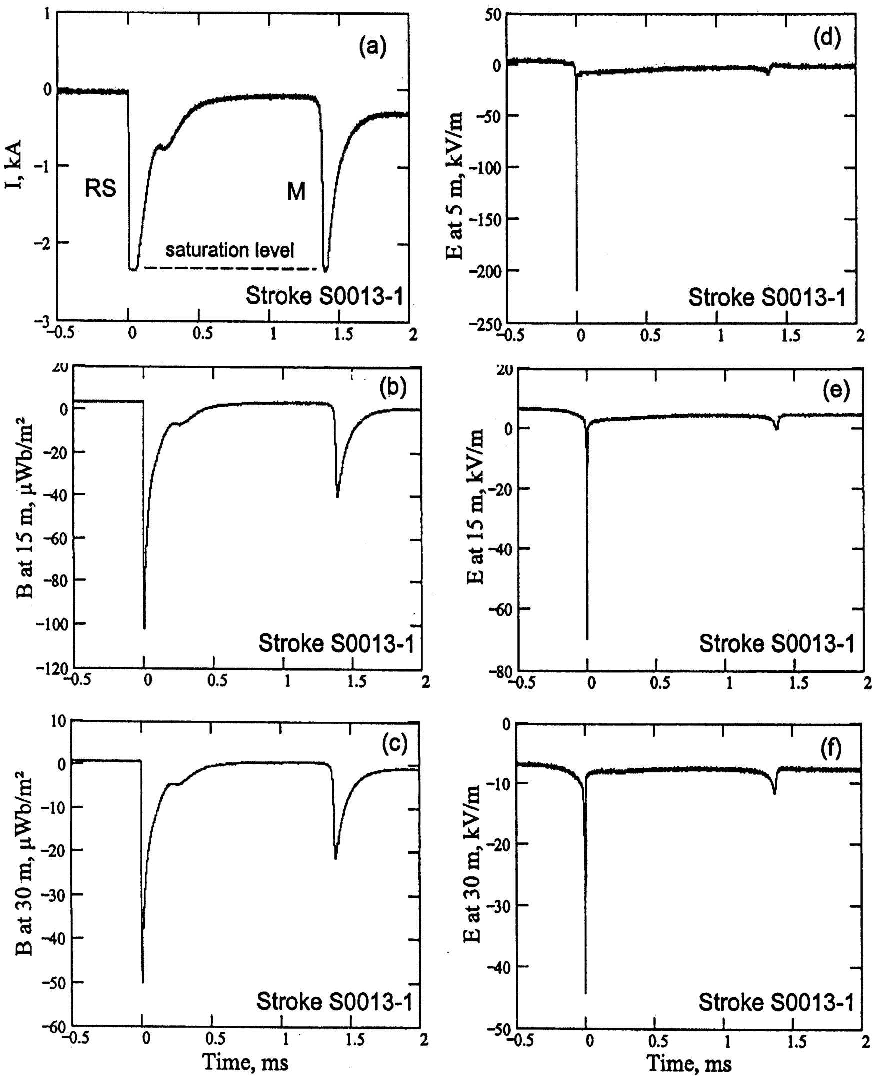

Figure 8. A leader/return stroke (RS) sequence followed by an *M*-component (*M*) in flash S0013 initiated using the classical rocket-and-wire technique at the ICLRT in 2000: (a) current (both return stroke and *M*-component waveforms are clipped at 2.3 kA); (b) magnetic field at 15 m; (c) magnetic field at 30 m; (d) electric field at 5 m; (e) electric field at 15 m; and (f) electric field at 30 m. *M*-component current peak is estimated from the measured magnetic fields to be about 3.3 kA.

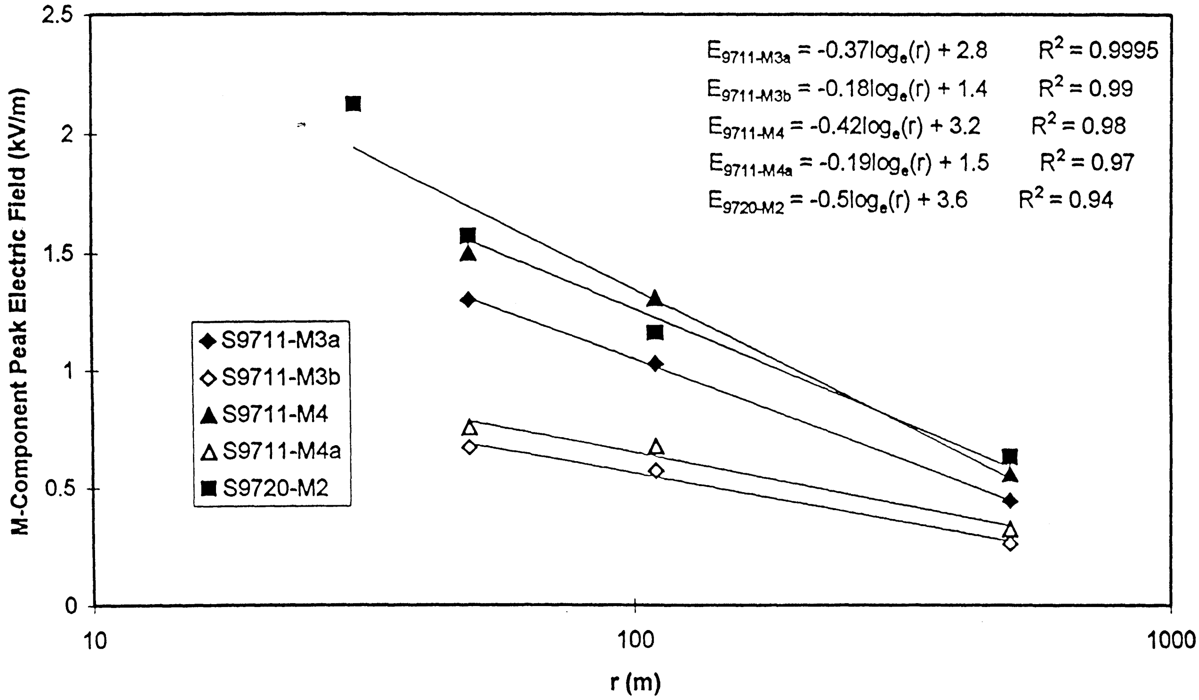

Figure 9. *M*-component electric field peak as a function of distance from the lightning channel for data obtained at the ICLRT in 1997. One data point, a square at r = 20 m, is obtained from the corrupted electric field record and therefore is unreliable. Note that the distance dependence is close to logarithmic. R^2 here and in Figures 10 and 11 is the determination coefficient (the square of the correlation coefficient). See also Table 1.

and 30 m. Note that the ICC pulse in flash S0008 occurred at the very end of the initial stage, when the initial continuous current dropped below the noise level of about 3 A of the low-level current record. The lowest continuing current level prior to an *M*-component reported by *Thottappillil et al.* (1995) was about 20 A.

3. Analysis and Discussion

The dart leader electric field changes at tens to hundreds of meters from the lightning channel are expected to have an inverse distance dependence [*Crawford et al.*, 2001], whereas the distance dependence of the *M*-component electric field change is expected to be considerably weaker. Indeed, it is clear from Figure 5, that the magnitudes of *M*-component electric field waveforms relative to the magnitude of the leader/return stroke field waveform increase with distance. Figure 9 shows the *M*-component electric field peak as a function of distance from 20 to 500 m for the five *M* components recorded in 1997. As expected, the distance dependence is weaker than an inverse distance proportionality (r^{-1}); in fact, it is close to logarithmic, which can be shown [e.g., *Bazelyan,* 1995] to be consistent with a charge density on the lightning channel that increases linearly with height, starting from zero at ground level. Note that the latter condition is dictated by the boundary condition at ground such that the reflection coefficient for the charge density wave is close to −1. In contrast, the typically observed r^{-1} distance dependence for dart leaders [*Crawford et al.*, 2001] is consistent with a more or less uniform distribution of charge over the lower kilometer or so of channel [*Rubinstein et al.*, 1995].

As noted in section 2.1, most of the 1997 electric field measurements at distances less than 30 m were corrupted due to surface arcing and/or the presence of triggering wires on ground. The installation of a buried metallic grid in 1999 (see section 2.2) was, in part, motivated by the desire to measure electric fields within 30 m of the lightning channel with the potential influence of surface arcing being minimized. *M*-components recorded in 1999 and 2000 exhibited electric field peaks that varied within 30 m appreciably slower than r^{-1}, and in the case of four-station and three-station measurements in 1999 and 2000, respectively, could be approximated by a logarithmic function (see Figures 10 and 11).

M-component *M*4 in flash S9711 (see Figure 5) and *M*-component *M*1 in flash S0013 (see Figure 8) were modeled using the same simplified approach as that used by *Rakov et al.* [1995]. In this approach the lightning channel, carrying a steady current, is viewed as a straight and vertical transmission line. The M-component current measured at the channel base is assumed to be a superposition of a downward incident current wave and an upward reflected current wave. The current reflection coefficient at ground is equal to unity (which corresponds to the grounding resistance being much smaller than the characteristic impedance of the lightning channel). The incident and reflected waves are assumed to propagate along the channel (downward and upward, respectively) without either attenuation or distortion and at the same constant speed, the latter being the only adjustable parameter in this simple model.

The results of modeling for S9711-*M*4 for the adjusted speed value of 10^7 m/s are shown in Figure 12. Also Figure 12 shows the measured channel-base current waveform

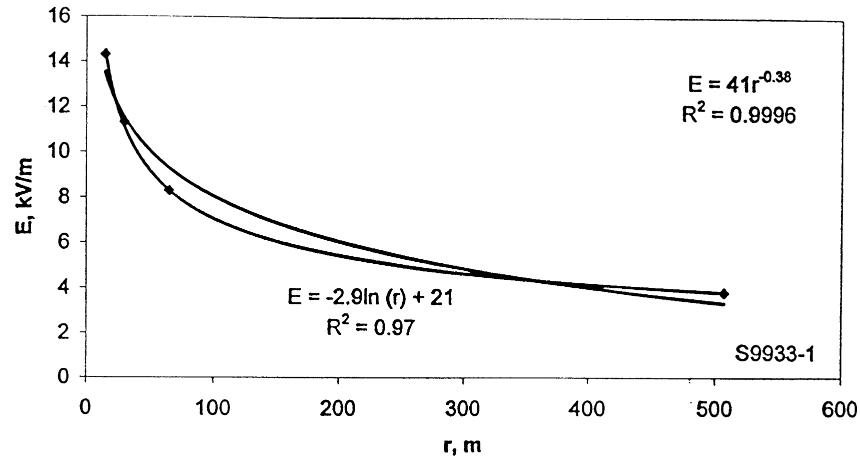

Figure 10. Electric field peak as a function of distance (15 to 507 m) from the lightning channel for an *M* component in flash S9933 recorded at the ICLRT in 1999. Approximations by both logarithmic and power functions are shown. Note that the distance dependence is appreciably slower than an inverse proportionality. See also Table 2.

(digitized at a sampling interval of 80 μs). The model-predicted electric field peaks at 50, 110, and 500 m are 1.3, 1.1, and 0.46 kV/m, respectively, while the corresponding measured values are 1.5, 1.3, and 0.52 kV/m (see Table 1). There is a reasonable agreement between the calculated and the measured electric field waveforms in terms of the pulse width at all three distances. However, model-predicted field variations after the main pulse are not consistent with measurements, particularly at larger distances.

The results of modeling for S0013-*M*1 for the adjusted speed value of 4.6 x 10^7 m/s along with measured field waveforms are shown in Figure 13 and in Table 4. Also shown in Figure 13 is the current waveform at the channel base used for modeling. The high-current record and magnetic field records were used to reconstruct the waveform below the negative saturation level indicated in the low-current record shown in Figure 8a. The peak values of measured electric and magnetic fields at all distances are well reproduced by the model (see Table 4). The overall field waveshapes are reasonably reproduced for magnetic fields and for electric field at 5 m. Computed electric field waveforms at 15 and 30 m are appreciably narrower than measured ones. Note that the apparent positive polarity overshoot in the computed electric field waveforms at 15 and 30 m, not seen in the measured waveforms, can be made negligible by slightly reducing the current reflection coefficient at ground to 0.96-0.99. The agreement in terms of the electric field pulse width at 15 and 30 m apparently cannot be improved within the framework of the simple model used.

As noted in section 2.3, the *M*-component electric field at 45 km is a bipolar microsecond-scale pulse (see Figure 7) which begins prior to the onset of the *M*-component current at the channel base. We infer that this microsecond-scale pulse is associated with establishing the contact between an in-cloud leader and the current-carrying channel to ground. This

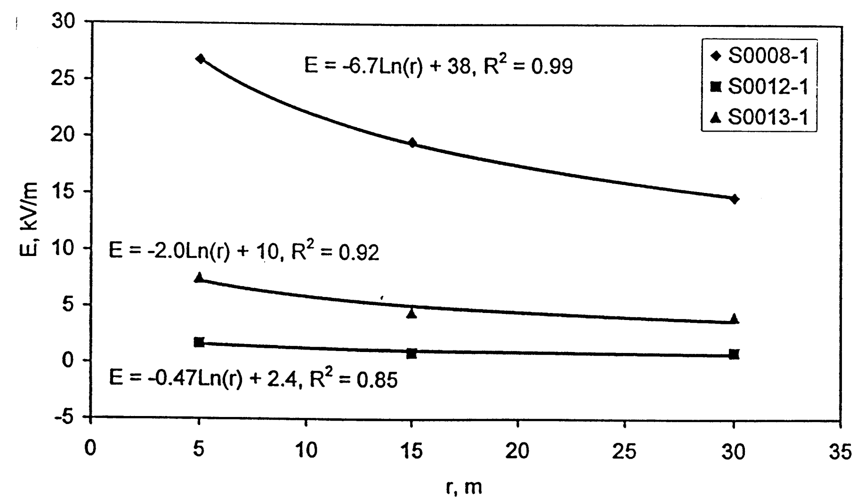

Figure 11. *M*-component electric field peak as a function of distance (5 to 30 m) from the lightning channel for data obtained at the ICLRT in 2000. Note that the distance dependence is close to logarithmic. See also Table 3.

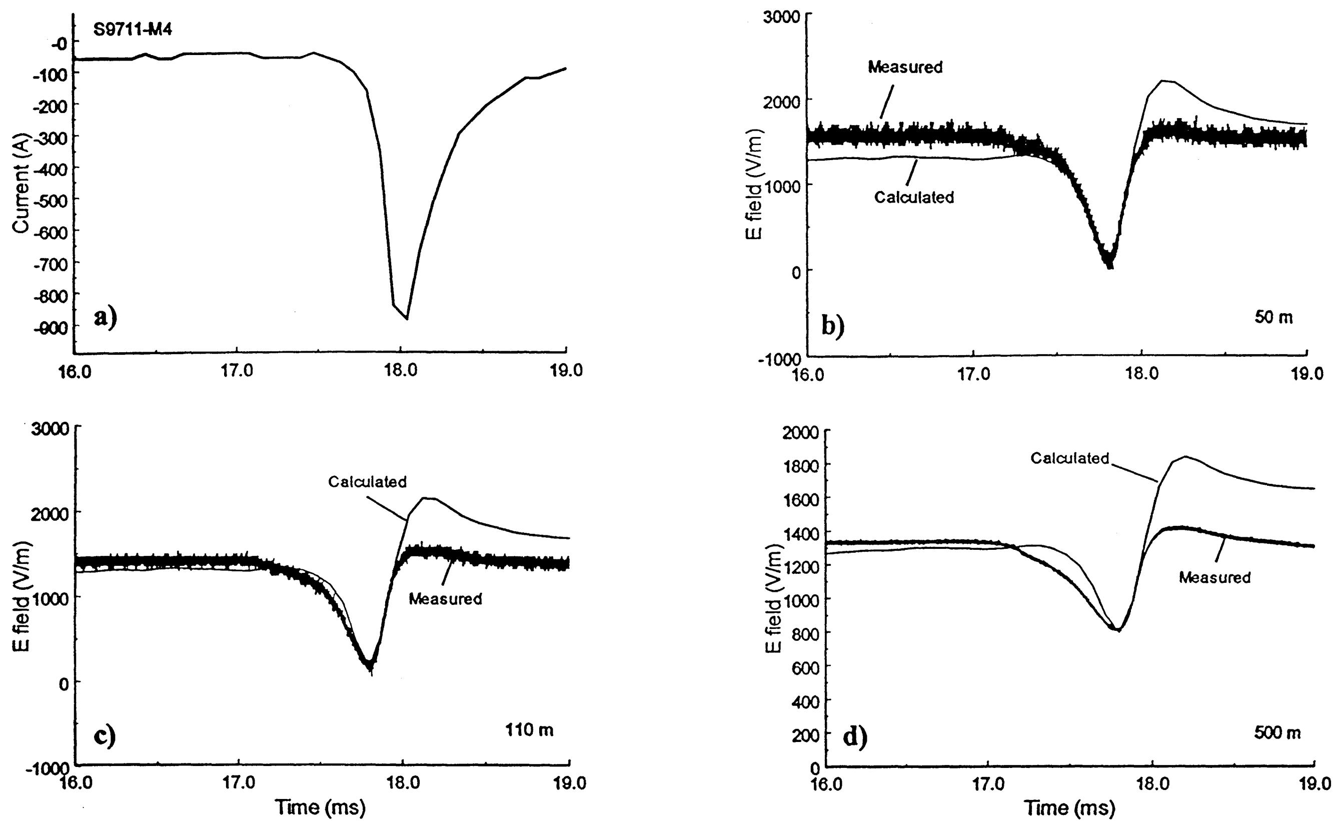

Figure 12. Comparison of model-predicted and measured electric fields for S9711-M4: (a) current at the channel base used for modeling; (b–d) measured and calculated electric fields at 50, 110, and 500 m, respectively.

contact results in the launching of the initial, downward moving *M* wave, which subsequently reflects off ground. Similar pulses were reported by *Rakov et al.* [1992, 1996] from measurements of electric fields due to natural lightning at distances ranging from about 2.5 to 27 km. The pulses were typically observed at the beginning of hook-shaped electric field waveforms characteristic of *M* components in the distance range studied by *Rakov et al.* [1992, 1996]. The amplitude of one such pulse was larger than that of one of the smaller return-stroke pulses in the same flash. This unusually large pulse was immediately preceded by a regular pulse burst that is thought to be produced by an in-cloud process similar to a dart-stepped leader [*Krider et al.*, 1975; *Rakov et al.*, 1996]. *Shao et al.* [1995], from their analysis of electric field measurements in conjunction with VHF images of lightning channels, found that the microsecond-scale pulses similar to those studied by *Rakov et al.* [1992, 1996] were associated with the initiation of *M*-component charge transfer at the top of the channel to ground.

4. Remarks on the Significance of M Components

M-components are more numerous than leader/return stroke sequences [*Thottappillil et al.*, 1995] and are a threat to various objects and systems. When *Uman et al.* [1997] studied the responses of a test power distribution system to lightning strikes, they found that, in the transformer secondary, the current pulses due to return strokes and those due to *M*-components had peaks of the same order of magnitude, while the corresponding currents at the channel base differed by 1 to 2 orders of magnitude. The transformer primary was connected to an underground cable that was connected to an overhead line subjected to direct lightning

Table 4. Comparison of Model-Predicted and Measured Field Peaks for S0013-M1

Field Peak	Calculated	Measured
B15m, $\mu Wb/m^2$	36	44
B30m, $\mu Wb/m^2$	18	22
B15m/B30m	2.0	2.0
E5m, *kV/m*	6.3	7.5
E15m, *kV/m*	4.7	4.5
E30m, *kV/m*	3.8	4.1
E = f(*r*)	E = -1.4 ln(*r*) + 8.5	E = -2.0 ln(*r*) +10

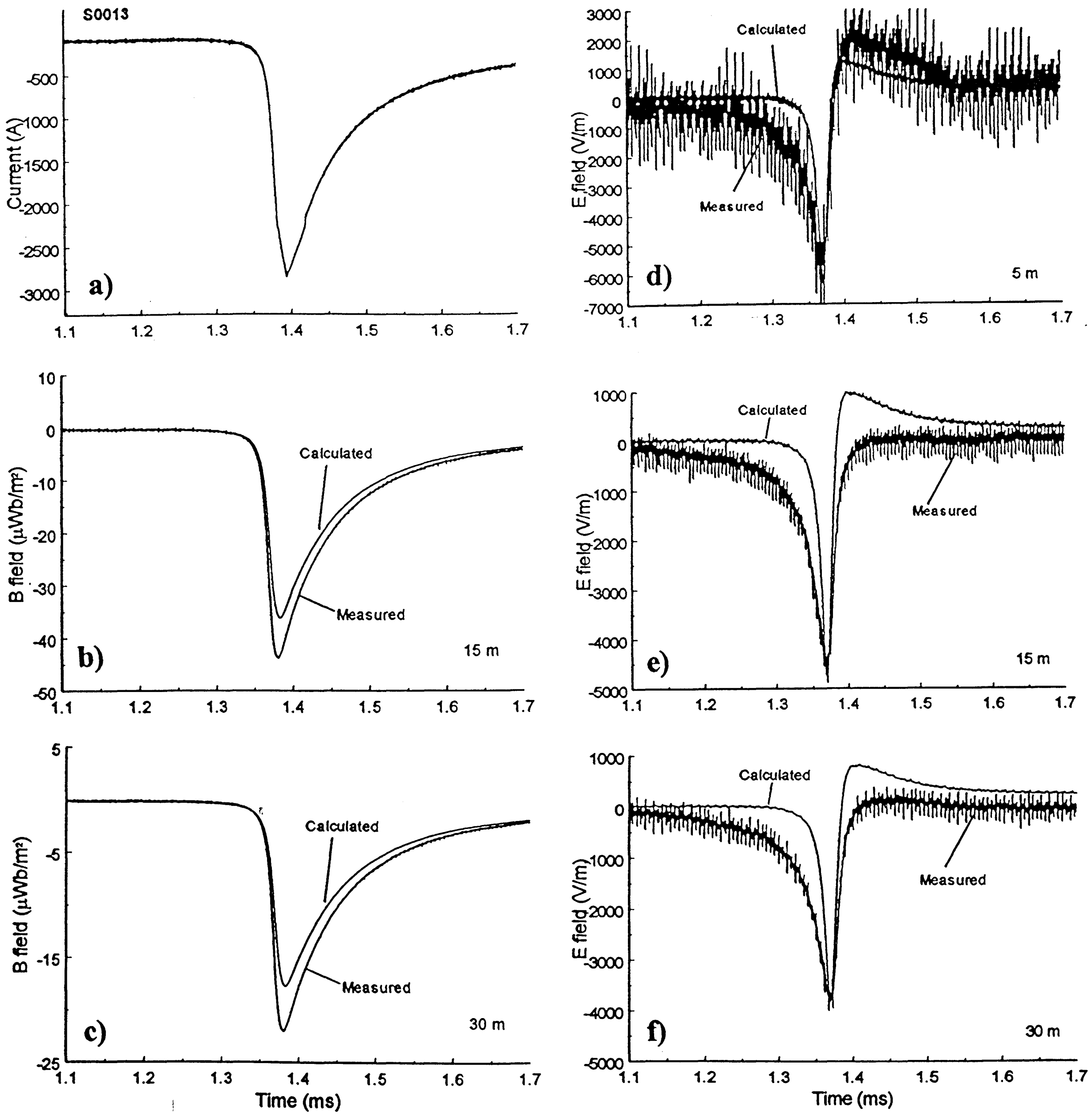

Figure 13. Comparison of model-predicted and measured fields for S0013-M1: (a) current at the channel base; (b, c) measured and calculated magnetic fields at 15 and 30 m, respectively; (d-f) measured and calculated electric fields at 5, 15, and 30 m, respectively.

strikes. Further, *M*-components may impart electrodynamic stresses on metallic structural elements that are already weakened by the thermal effects of the background continuing current. Additionally, we speculate that *M*-component type processes in positive lightning [*Rakov*, 2000] may play a role in the initiation of so-called delayed sprites that occur many tens of milliseconds after the return stroke [e.g., *Reising et al.*, 1999].

5. Summary

Multiple-station electric and magnetic field measurements obtained at Camp Blanding, Florida, and associated modeling are generally consistent with the guided-wave concept of lightning *M*-components. Specifically, the *M*-component electric field peak exhibits logarithmic distance dependence, which is indicative of a line charge density that is zero at ground and increases with height. Such a distribution of charge is distinctly different from the more or less uniform charge density that is characteristic of the dart leaders in triggered lightning, as inferred from close electric field measurements. The M-component magnetic field peak decreases as the inverse distance, which is generally consistent with a uniform current within the lowest kilometer or so of channel. The M-component electric field at 45 km appeared as a bipolar, microsecond-scale pulse that started prior to the onset of the *M*-component current at the channel base. *M*-component-type processes can produce acoustic signals with peak pressure values of the same order of magnitude as those from the leader/return stroke sequences in triggered lightning.

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References

Bazelyan, E. M. Waves of ionization in lightning discharge, *Plasma Phys. Rep.*, *21*, 470-478, 1995.

Berger, K., and E. Vogelsanger, Messungen und Resultate der Blitzforschung der Jahre 1955-1963 auf dem Monte San Salvatore, *Bull. Schweiz. Elektrotech. Ver.*, *56*, 2-22, 1965.

Berger, K., R.B. Anderson, and H. Kroninger, Parameters of lightning flashes, *Electra, 80*, 223-237, 1975.

Crawford, D. E., Multiple-station measurements of triggered lightning electric and magnetic fields, M.S. Thesis, Univ. of Florida, Gainesville, Fla., 1998.

Crawford, D. E., V. A. Rakov, M. A. Uman, G. H. Schnetzer, K. J. Rambo, M. V. Stapleton, and R. J. Fisher, The close lightning electromagnetic environment: Dart-leader electric field change versus distance, *J. Geophys. Res.*, *106*, 14,909-14,917, 2001.

Fisher, R. J., G. H. Schnetzer, R. Thottappillil, V. A. Rakov, M. A. Uman, and J.D. Goldberg, Parameters of triggered-lightning flashes in Florida and Alabama, *J. Geophys. Res.*, *98*, 887-902, 1993.

Fisher, R. J., G. H. Schnetzer, and M. E. Morris, Measured fields and Earth potentials at 10 and 20 meters from the base of triggered-lightning channels, paper presented at the 22nd International Conference on Lightning Protection, Tech. Univ. of Budapest, Budapest, Hungary, 1994.

Idone, V.P., and R.E. Orville, Lightning return stroke velocities in the Thunderstorm Research International Program (TRIP), *J. Geophys. Res.*, *87*, 4903-4915, 1982.

Idone, V.P., and R.E. Orville, Correlated peak relative light intensity and peak current in triggered lightning subsequent return strokes, *J. Geophys. Res.*, *90*, 6159-6164, 1985.

Jordan, D. M., V. P. Idone, R.E. Orville, V. A. Rakov, and M. A. Uman, Luminosity characteristics of lightning M components, *J. Geophys. Res.*, *100*, 25,695-25,700, 1995.

Krider, E.P., G.J. Radda, and R.C. Noggle, Regular radiation field pulses produced by intracloud lightning discharges, *J. Geophys. Res.*, *80*, 3801-3804, 1975.

Latham, D.J., A channel model for long arcs in air, *Phys. Fluids*, *23*(8), 1710-1715, 1980.

Malan, D. J., and H. Cöllens, Progressive lightning III – The fine structure of return lightning strokes, Proc. *R. Soc. London, ser. A*, *162*, 175-203, 1937.

Orville, R.E., and V.P. Idone, Lightning leader characteristics in the Thunderstorm Research International Program (TRIP), *J. Geophys. Res.*, *87*, 11,177-11,192, 1982.

Plooster, M.N., Numerical model of the return stroke of the lightning discharge, *Phys. Fluids, 14*, 2124-2133, 1971.

Rakov, V. A., Some inferences on the propagation mechanisms of dart leaders and return strokes, *J. Geophys. Res.*, *103*, 1879-1887, 1998.

Rakov, V. A., Positive and bipolar lightning discharges: A review. paper presented at the 25th International Conference on Lightning Protection, Univ. of Patras, Rhodes, Greece, 2000.

Rakov, V.A., and M.A. Uman, Long continuing current in negative lightning ground flashes, *J. Geophys. Res.*, *95*, 5455-5470, 1990.

Rakov, V.A., R. Thottappillil, and M.A. Uman, Electric field pulses in K and M changes of lightning ground flashes, *J. Geophys. Res.*, *97*, 9935-9950, 1992.

Rakov, V. A., R. Thottappillil, M.A. Uman, and P. P. Barker, Mechanism of the lightning M-component, *J. Geophys. Res.*, *100*, 25,701-25,710, 1995.

Rakov, V.A., M.A. Uman, G.R. Hoffman, M.W. Masters, and M. Brook, Bursts of pulses in lightning electromagnetic radiation: Observations and implications for lightning test standards, *IEEE Trans. Electromagn. Compat.*, *38*, 156-164, 1996.

Rakov, V.A, et al., New insights into lightning processes gained from triggered-lightning experiments in Florida and Alabama, *J. Geophys. Res.*, *103*, 14,117-14,130, 1998.

Rakov, V. A., M. A. Uman, D. Wang, K. J. Rambo, D. E. Crawford, and G. H. Schnetzer, Lightning properties from triggered-lightning experiments at Camp Blanding, Florida (1997-1999), paper presented at the 25th International Conference on Lightning Protection., Univ. of Patras, Rhodes, Greece, 2000.

Reising, S.C., U.S. Inan, and T.F. Bell, ELF steric energy as a proxy indicator for sprite occurrence, *Geophys. Res. Lett.*, *26*, 987-990, 1999.

Rubinstein, M., F. Rachidi, M. A. Uman, R. Thottappillil, V. A. Rakov and C.A. Nucci, Characterization of vertical electric fields 500 m and 30 m from triggered lightning, *J. Geophys. Res.*, *100*, 8863-8872, 1995.

Schnetzer, G. H., and R. J. Fisher, 1991 Rocket-triggered lightning test of the DoD Security Operations Test Site (SOTS) munitions storage bunker, Ft. McClellan, Alabama, *SANDIA Rep. SAND91-2343*, 46 pp. with 4 appendices, Sandia Natl. Lab., Albuquerque, N.M., 1992.

Shao, X.M., P.R. Krehbiel, R.J. Thomas, and W. Rison, Radio interferometric observations of cloud-to-ground lightning phenomena in Florida, *J. Geophys. Res.*, *100*, 2749-2783, 1995.

Shindo, T., and M.A. Uman, Continuing current in negative cloud-to-ground lightning, *J. Geophys. Res.*, *94*, 5189-5198, 1989.

Thottappillil, R., J. D. Goldberg, V. A. Rakov, and M. A. Uman, Properties of *M*-components from currents measured at triggered lightning channel base, *J. Geophys. Res.*, *100*, 25,711-25,720, 1995.

Uman, M. A., V. A. Rakov, K. J. Rambo, T.W. Vaught, M. I. Fernandez, D. J. Cordier, R. M. Chandler, R. Bernstein, and C. Golden, Triggered-lightning experiments at Camp Blanding, Florida (1993-1995), *Trans. IEE Jpn, 117(B)*, 446-452, 1997.

Uman, M.A., V.A. Rakov, G.H. Schnetzer, K.J. Rambo, D.E. Crawford, and R.J. Fisher, Time derivative of the electric field 10, 14, and 30 m from triggered lightning strokes, *J. Geophys. Res.*, *105*, 15,577-15,595, 2000.

Wang, D., V.A. Rakov, M. A. Uman, M. I. Fernandez, K.J. Rambo, G.H. Schnetzer, and R.J. Fisher, Characterization of the initial stage of negative rocket triggered-lightning, *J. Geophys. Res.*, *104*, 4213-4222, 1999b.

Yos, J.M., Transport properties of nitrogen, hydrogen, oxygen, and air to 30,000°K, *Tech. Mem. RAD-TM-63-71*, Avco Corp., Wilmington, Del., 1963.

D.E. Crawford, V.A. Rakov, K.J. Rambo, G.H. Schnetzer, and M.A. Uman, Department of Electrical and Computer Engineering, University of Florida, 553 Engineering Bldg., 33, Gainesville, FL 32611-6130, USA. (rakov@ece.ufl.edu)

R. Thottappillil, Institute of High Voltage Research, Uppsala University, Box 539, S71 21 Uppsala, Sweden.

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