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New insights into lightning processes gained from triggered-lightning experiments in Florida and Alabama

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Abstract. Analyses of electric and magnetic fields measured at distances from tens to hundreds of meters from the ground strike point of triggered lightning at Camp Blanding, Florida, and at 10 and 20 m at Fort McClellan, Alabama, in conjunction with currents measured at the lightning channel base and with optical observations, allow us to make new inferences on several aspects of the lightning discharge and additionally to verify the recently published "two-wave" mechanism of the lightning *M* component. At very close ranges (a few tens of meters or less) the time rate of change of the final portion of the dart leader electric field can be comparable to that of the return stroke. The variation of the close dart leader electric field change with distance is somewhat slower than the inverse proportionality predicted by the uniformly charged leader model, perhaps because of a decrease of leader charge density with decreasing height associated with an incomplete development of the corona sheath at the bottom of the channel. There is a positive linear correlation between the leader electric field change at close range and the succeeding return stroke current peak at the channel base. The formation of each step of a dart-stepped leader is associated with a charge of a few millicoulombs and a current of a few kiloamperes. In an altitude-triggered lightning the downward negative leader of the bidirectional leader system and the resulting return stroke serve to provide a relatively low-impedance connection between the upward moving positive leader tip and the ground, the processes that follow likely being similar to those in classical triggered lightning. Lightning appears to be able to reduce, via breakdown processes in the soil and on the ground surface, the grounding impedance which it initially encounters at the strike point, so at the time of channel-base current peak the reduced grounding impedance is always much lower than the equivalent impedance of the channel. At close ranges the measured *M*-component magnetic fields have waveshapes that are similar to those of the channel-base currents, whereas the measured *M*-component electric fields have waveforms that appear to be the time derivatives of the channel-base current waveforms, in further confirmation of the "two-wave" *M*-component mechanism.

1. Introduction

Many aspects of the physics of the lightning discharge and of the interaction of lightning with objects and systems can only be properly understood by way of measurements made on very close lightning. The probability for a natural lightning to strike at or close to a given point of interest on the Earth's surface is very low, even in areas of relatively high lightning activity. The study of the properties and the effects of close lightning has been made practical via the use of artificially initiated (triggered) lightning, i.e., lightning stimulated to occur between an overhead thundercloud and a designated point on the ground.

1.1. Lightning Triggering Techniques

The most common technique for triggering lightning involves the launching upward of a small rocket trailing a grounded copper wire in the presence of a sufficiently charged cloud overhead. This triggering method is sometimes called "classical" triggering and is illustrated in Figure 1. The cloud charge is remotely sensed by measuring the electric field at ground level, with values of -4 to -10 kV/m usually being good indicators of favorable conditions for lightning initiation (based on the Kennedy Space Center experiments where the probability of triggering at these fields was 60% or higher (W. Jafferis, as reported by *Willett et al.* [1992]). When the rocket, ascending at about 200 m/s, is typically 200 to 300 m high [*Hubert et al.*, 1984; *Uman*, 1987], the electric field enhancement near the upper end of the wire is sufficient to trigger a positively charged

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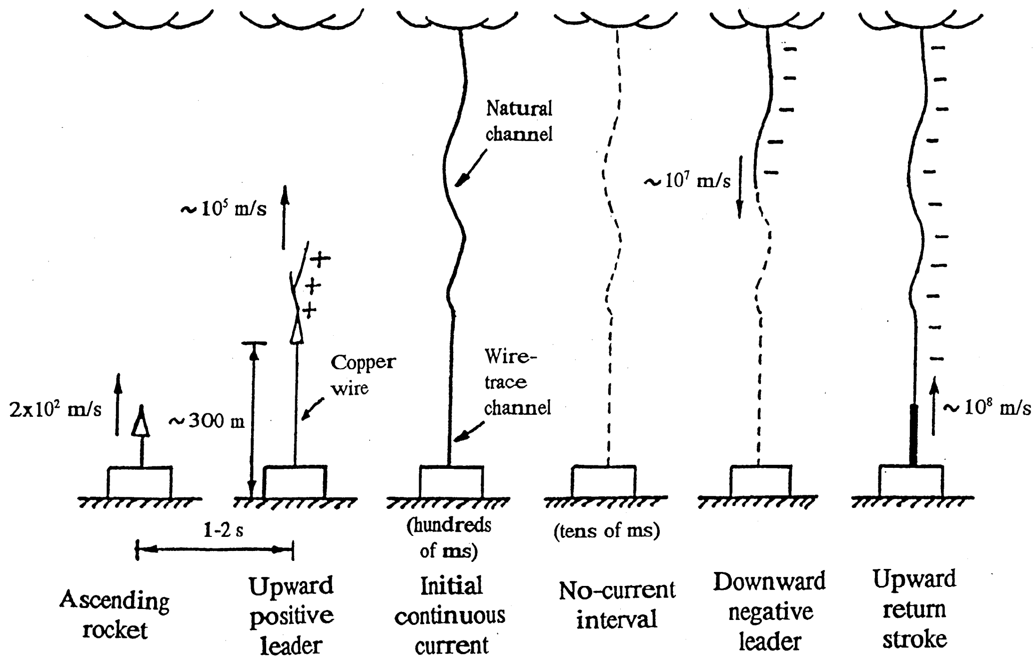

Figure 1. Sequence of events involved in the formation of the first stroke in classical triggered lightning.

(in the most common case of predominantly negative charge at the bottom of the cloud) leader extending toward the cloud. The upward leader melts and vaporizes the trailing wire and establishes a so-called "initial continuous current" [e.g., *Fisher et al.*, 1993] of the order of some hundred amperes along the wire trace, which effectively serves to transport negative charge from the cloud charge source to the ground via the instrumented triggering facility. Additional information on the initial phase of a classical triggered lightning is given by *Lalande et al.* [this issue]. After the cessation of the initial continuous current, several downward leader/upward return stroke sequences often traverse the same path to the triggering facility. The return strokes in triggered lightning are similar [e.g., *Le Vine et al.*, 1989] to subsequent return strokes in natural lightning, although the initial processes in natural and classical triggered lightning are distinctly different: in natural lightning, a negative downward stepped leader and ground attachment followed by a first return stroke versus, in triggered lightning, an upward positive leader followed by an initial continuous current.

It is possible to provide a close simulation to the stepped leader and ground attachment processes in natural lightning by triggering a lightning discharge via a wire not attached to the ground, with the bottom end of the wire being typically some hundreds of meters aboveground (see Figure 2) . This technique, however, produces a ground strike point that is generally only predictable within a few hundred meters rather than precisely, as is usually the case in classical triggering. In order to increase the probability of lightning attachment to the launcher where the current can be directly measured, an additional "intercepting" wire (typically 50 m long) connected to the rocket launcher (see Fig. 2) can be used. The ungrounded-triggering-wire technique is called "altitude" triggering and involves, as seen in Fig. 2, a bidirectional (positive charge up and negative charge down) leader process from the elevated wire, the negative downward stepped leader initiating the first return stroke from ground. Not shown in Fig. 2 is the process of the lightning ground attachment that immediately precedes the first return stroke and involves a positive upward-going connecting discharge from the intercepting 50-m wire attached to the rocket launcher. Additional information on the initial processes in an altitude-triggered flash is given by *Lalande et al.* [this issue].

1.2. Instrumentation

Lightning-triggering facilities and measuring systems at Camp Blanding are described by *Uman et al.* [1994a, 1997] and *Rakov et al.* [1995a, b], and facilities and systems at Fort McClellan by *Fisher et al.* [1994]. A brief summary of the instrumentation used for this study is given below, with more complete information being found in the references listed above.

1.2.1 Camp Blanding. The current at the bottom of a lightning channel was sensed by a 1-mΩ coaxial current viewing resistor (shunt) manufactured by the Laboratoire d'Applications Spéciales de la Physique, Centre d'Etudes Nucléaires de Grenoble, France. The signal from the shunt was transmitted via a fiber-optic system to a LeCroy 9314 digitizing oscilloscope operating at a 50-MHz sampling rate and with 8-bit amplitude resolution. The overall 3-dB frequency bandwidth of the current-measuring system was from 150 Hz (set by the fiber-optic system) to 20 MHz (set by the shunt). Electric fields were measured using (1) E31 Thomson-CSF spherical sensors in conjunction with fiber-optic links and 8-bit, 50-MHz LeCroy 9314 digitizers and (2) flat-plate antennas placed flush with ground and connected via passive integrators and fiber-optic links to either 12-bit, 10-MHz or 8-bit, 20-MHz Nicolet Pro 90 digitizers or to a 12-bit, 2-MHz ADTEK digitizer. The Thomson-CSF system had an overall 3-dB bandwidth from 1 kHz (set by the sensor) to 30 MHz (set by the digitizer). The upper frequency bandwidth of the flat-plate system was set by the fiber-optic link at about 12 MHz, and its lower-frequency bandwidth was determined by the integrator's RC decay time constant which was from some milliseconds to some tens of milliseconds. Magnetic fields were measured by using (1) H31 Thomson-CSF sensors, fiber-optic links, and 8-bit, 50-MHz

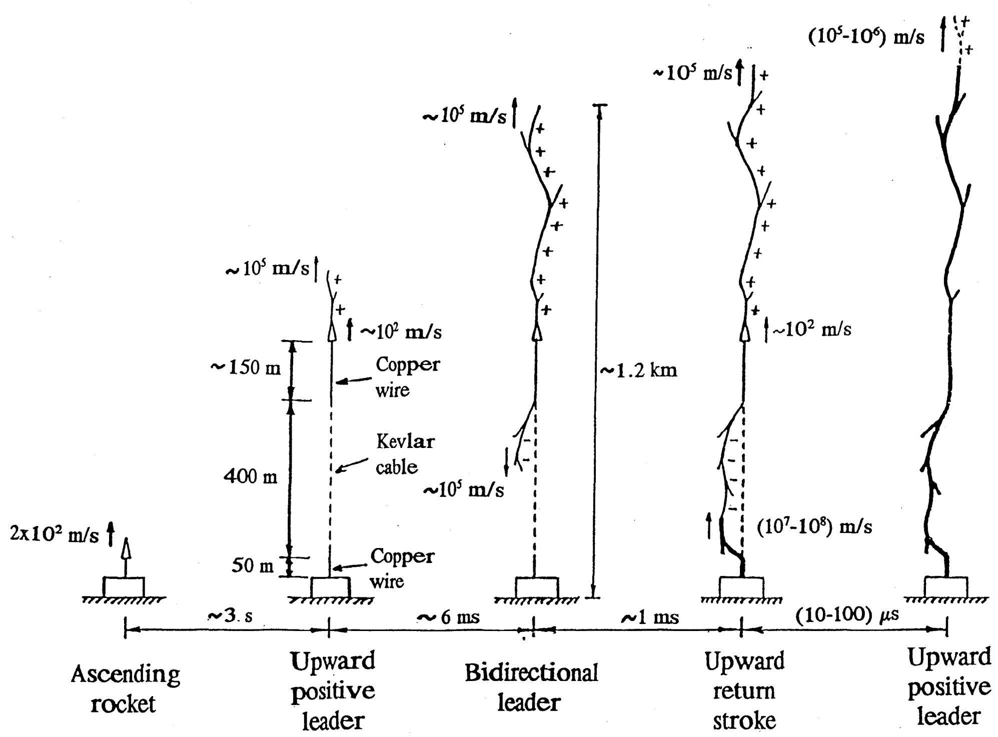

Figure 2. Sequence of events involved in the formation of the first stroke in altitude triggered lightning (based on *Laroche et al.* [1991]).

LeCroy 9314 digitizers with an overall 3-dB frequency bandwidth from 2 kHz (set by the sensor) to 30 MHz (set by the digitizer) and (2) an ~ 1 x 1 m^2 square loop antenna connected via an active integrator and coaxial cables to a 12-bit, 2-MHz ADTEK digitizer (the system's risetime was determined to be better than 1 μs and decay time a few milliseconds).

1.2.2. Fort McClellan. The lightning current was sensed by a K-5000-10 T&M Research 1-mΩ coaxial shunt. The return stroke signals from the shunt were transmitted to an 8-bit 25-MHz LeCroy 9400A digitizer via a fiber-optic system. The overall 3-dB frequency bandwidth of the return stroke current-measuring channel was from about 10 Hz (set by the fiber-optic link) to about 6 MHz (set by the shunt). Electric fields were measured using flat-plate antennas with active integrators, and magnetic fields were measured using MGL-4 EG&G B-dot sensors followed by 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 and magnetic-field-measuring systems was 10 MHz. Optical images of lightning channels, including the surface arcing discussed in section 2.3, were obtained by using several video cameras, photographic cameras, and a 16-mm framing camera having 3- to 5-ms time resolution.

In this paper, from triggered-lightning experiments at Camp Blanding, Florida, in 1993, 1994, and 1995, and at Fort McClellan, Alabama, in 1993 and 1995 we present new results concerning (1) dart and dart-stepped leaders, (2) the bidirectional leader and its associated return stroke, (3) the lightning channel termination on ground, and (4) the lightning *M* component. Earlier triggered-lightning experiments in Florida (near Melbourne in 1983 and at the NASA Kennedy Space Center from 1984 to 1991) have been reviewed by *Willett* [1992]. The most recent findings on parameters of the triggered-lightning discharge derived from channel-base currents measured in Florida and in Alabama have been published by *Fisher et al.* [1993] and by *Thottappillil et al.* [1995].

2. Results and Discussion

2.1. Dart and Dart-Stepped Leaders

2.1.1. Electric field waveshapes. Leader/return stroke vertical electric field waveforms appear as asymmetrical V-shaped pulses, the bottom of the V being associated with the transition from the leader (the leading edge of the pulse) to the return stroke (the trailing edge of the pulse), as described, from earlier Kennedy Space Center (KSC) measurements, by *Rubinstein et al.* [1995]. Examples of leader/return stroke electric fields simultaneously measured at 30, 50, and 110 m from the 1993 Camp Blanding experiment are shown in Figures 3 and 4. From the 1993 experiment the geometric mean width of the V at half of peak value 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. This waveshape characteristic can be viewed as a measure of the closeness of the leader electric field rate of change to that of the following return stroke. As seen in Figure 3, at 30 m the rate of change of leader electric field near the bottom of the V can be comparable to that of the return stroke field, while at 110 m the two rates differ considerably, with the leader rate of change being appreciably less. This observation, in conjunction with the fact that within some hundreds of meters the leader and return stroke electric field changes are about the same in magnitude [*Uman et al.*, 1994a] (see also Figures 3 and 4), suggests that induced voltages and currents on power and other systems from very close (a few tens of meters or less) lightning subsequent strokes can be due as much to the leader as to the return stroke, whereas to date, most coupling calculations have considered

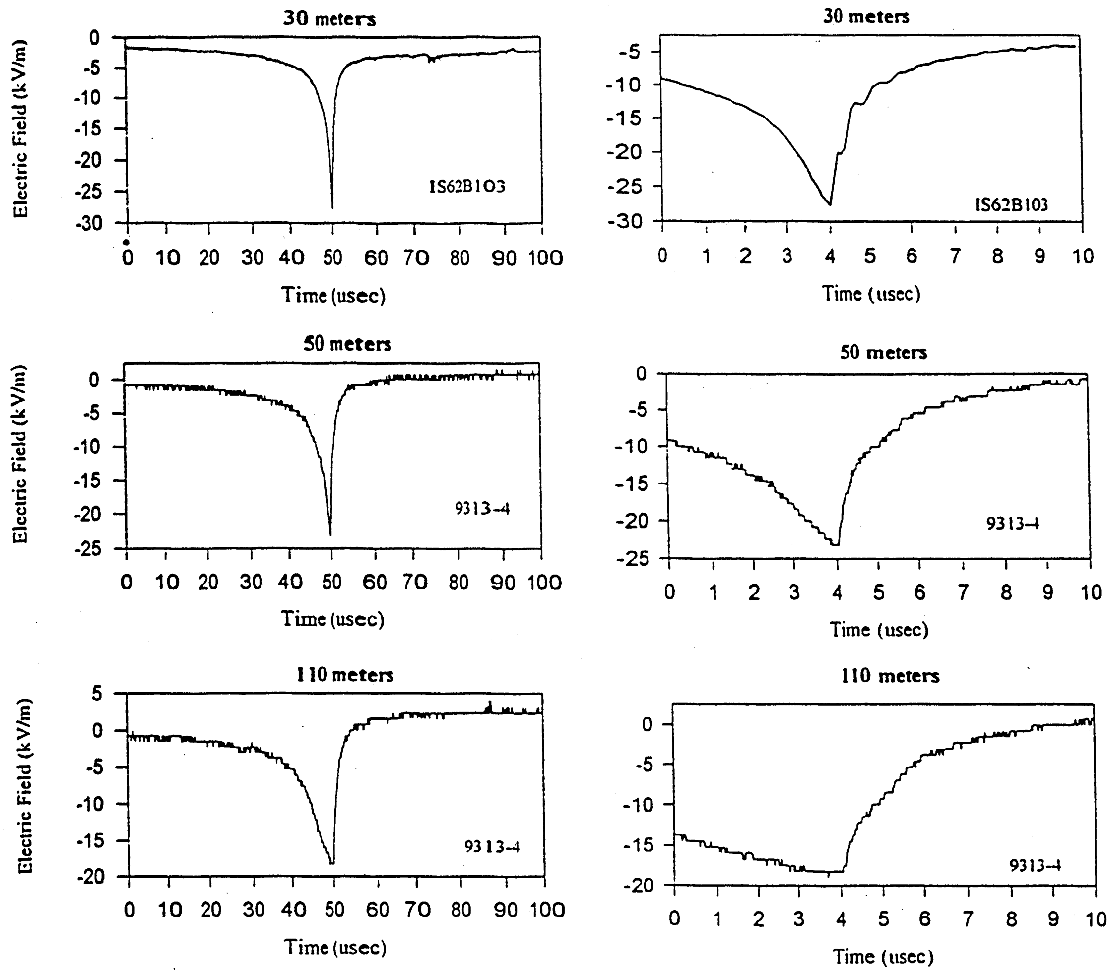

Figure 3. Electric field waveforms of the fourth leader/return stroke sequence of five-stroke flash 9313 as recorded at three different distances at Camp Blanding, shown on 100-μs and 10-μs time scales. Records at 30 m were obtained by using a flat-plate measuring system and records at 50 and 110 m using E31 Thomson-CSF systems.

only the return stroke component of the driving field [e.g., *Rachidi et al.*, 1996], neglecting the leader contribution as relatively insignificant.

2.1.2. Leader electric field versus distance. From measurements at 30, 50, and 110 m at Camp Blanding [*Uman et al.*, 1994a] the variation of the leader electric field change with distance was observed to be somewhat slower than the inverse proportionality theoretically predicted by using a uniformly-charged leader model by *Rubinstein et al.* [1995]. The uniformly charged leader model, although clearly a crude approximation, is supported by experimental data, as we explain now. *Thottappillil et al.* [1997] showed that the modified transmission line return stroke model with linear current decay with height (MTLL), developed using the assumption that there exists a uniform distribution of leader charge along the channel, predicts a ratio (R) of leader to return stroke electric field between +0.81 and +0.97 at distances between 20 and 50 km, assuming a total channel length of 7.5 km (see their Table 2). These values of R are consistent with the mean value of R = +0.8 determined experimentally (97 measurements) for this distance range by *Beasley et al.* [1982, Figure 23d]. On the other hand, the return stroke model that is derived assuming that there exists a distribution of leader charge exponentially decreasing with height (MTLE) predicts values of R between +2.6 and +3.0 [see *Thottappillil et al.*, 1997, Table 2], while the lightning model that is derived assuming that there exists a vertically symmetrical bidirectional leader process (positively charged part propagating upward and negatively charged downward) predicts values of R approximately between +0.2 and +0.3 [see *Mazur and Ruhnke*, 1993, Figure 25], in both cases inconsistent with the experimental data of *Beasley et al.* [1982]. From the 1993 Camp Blanding experiment, individual leader electric field changes for six strokes, simultaneously recorded at the three distances, are given in Table 1. Arithmetic mean values of the leader electric field changes for the six events in Table 1 are 25, 21, and 16 kV/m at 30, 50, and 110 m, respectively. Using the 50-m value, 21 kV/m, as a reference and assuming an inverse distance dependence, we estimate values of 35 (versus 25) and 10 (versus 16) kV/m at 30 and 110 m, respectively. A relative insensitivity of the leader electric field change to distance was also observed from measurements at 10 and 20 m at Fort McClellan [*Fisher et al.*, 1994]. An electric field versus distance dependence that is slower than an inverse proportionality, observed within 110 m of the channel, is consistent with a decrease of line charge density with decreasing height near the bottom of the channel. Such a leader charge distribution near ground might be due to the incomplete development there of the radially formed corona sheath that

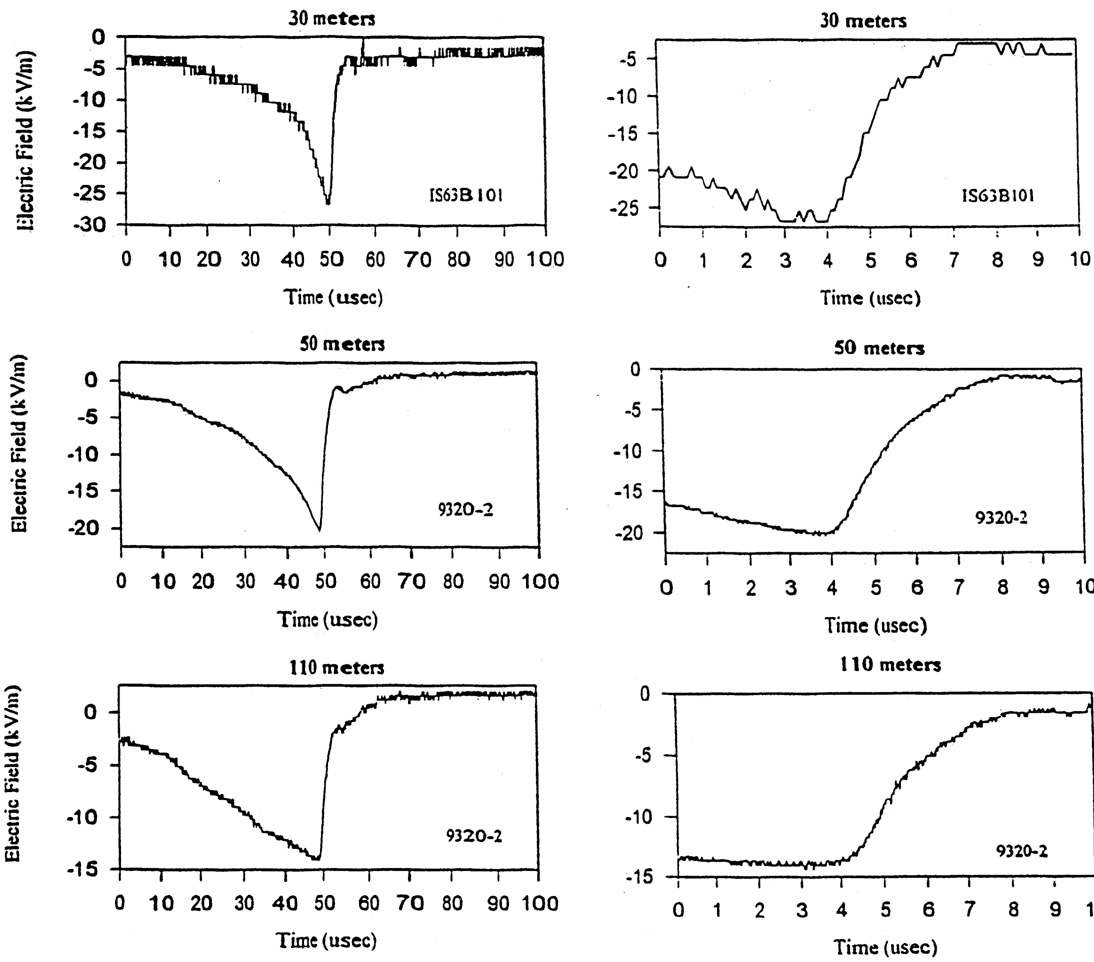

Figure 4. Same as Figure 3 but for the second leader/return stroke sequence of seven-stroke flash 9320.

surrounds the channel core and presumably contains most of the leader charge. Some support for this speculation comes from the observation that the propagation speeds of radial corona streamers from conductors subjected to negative high voltage in the laboratory are about 10^5 m/s (0.1 m/μs) [*Cooray*, 1993], so some microseconds are required for the development of a corona sheath with a radius of the order of meters. Since for dart leaders the downward propagation speeds (10^7 m/s) are about 2 orders of magnitude higher than the radial-streamer speeds, the delay in corona-sheath formation may be appreciable. On the other hand, *Depasse* [1994] observed, from triggered-lightning experiments in France, that seven simultaneously measured vertical electric fields due to return strokes at 50 and 77 m, expected to be approximately equal in magnitude to the fields due to the corresponding leaders [*Uman et al.*, 1994a] (see also Figures 3 and 4), exhibited an inverse distance dependence, consistent with a uniform distribution of charge density along the channel. Since the variation of the electric field with distance can be influenced by channel geometry and since the sample sizes of our data and those of *Depasse* [1994] are rather small, additional multiple-station data are needed to confirm or refute the above conjecture regarding a decreasing leader charge density with decreasing height. It is worth noting that, as shown by *Rubinstein et al.* [1995] based on a uniformly charged leader model, the presence of a triggering structure of about 5 m has a very small effect on the leader field at distances of 30 m and greater. They computed an error of about 1% at 30 m, with fields at greater distances being even less sensitive to the presence of the triggering structure.

Table 1. Values of the Vertical Electric Field Change, kV/m, Due to Six Leaders in Two 1993 Camp Blanding Flashes Simultaneously Recorded at 30, 50, and 110 m

Distance, m		
30	50	110
23	20	16
25	21	17
27*	23*	18*
23	21	17
30	24	16
24†	20†	14†

* Waveforms are shown in Figure 3.
† Waveforms are shown in Figure 4.

2.1.3. Leader electric field versus return-stroke peak current. There is a positive linear correlation between the leader

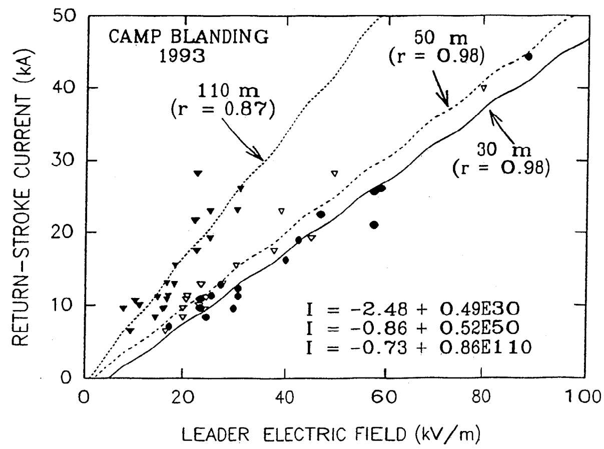

Figure 5. Return-stroke peak current I versus leader electric field change at 30 m (E30), 50 m (E50), and 110 m (E110) from the 1993 experiment at Camp Blanding. Data for 30 m are represented by solid circles, for 50 m by open triangles, and for 110 m by solid triangles. Also given are the correlation coefficients (r) and regression equations.

electric field change and the succeeding return stroke current peak. From the 1993 Camp Blanding experiment, correlation coefficients are 0.98, 0.98, and 0.87 at 30, 50, and 110 m, respectively, and from the 1993 Fort McClellan experiment, 0.70 and 0.95 at 10 (9.3) and 20 (19.3) m, respectively. A similar strong correlation between the leader field change and return stroke current peak (correlation coefficient 0.8) was also found by *Rubinstein et al.* [1995] at 500 m at KSC. Scatterplots at 30, 50, and 110 m from the 1993 Camp Blanding experiment are given in Figure 5 and at 10 (9.3) and 20 (19.3) m from the 1993 Fort McClellan experiment in Figure 6. The intercepts in the current/field regression equations for measurements at Camp Blanding (see Figure 5) are all negative, while those for measurements at Fort McClellan (see Figure 6) are all positive. If we neglect the intercept and express the vertical electric field E as due to an essentially uniformly charged line (the latter assumption being inconsistent with the inference in the previous paragraph) extending vertically upward from a perfectly conducting ground plane, $E = \rho/2\pi\varepsilon_0 r$ [*Rubinstein et al.*, 1995], where r is the distance and ρ is the line charge density, we find from each current/field regression equation (see Figures 5 and 6) a proportionality coefficient v between ρ and peak current I, the corresponding relation being $I = v\rho$. This proportionality coefficient has the dimension of speed, and its value is of the order of the typically measured speed for return strokes.

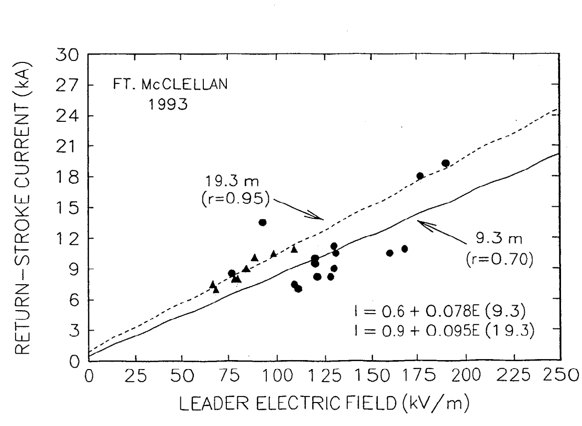

Figure 6. Return-stroke peak current I versus leader electric field change E at 10 (9.3) m and 20 (19.3) m from the 1993 experiment at Fort McClellan. Data for 10 (9.3) m are represented by circles and for 20 (19.3) m by triangles. Also given are the correlation coefficients (r) and regression equations.

2.1.4. Electric and magnetic fields due to leader steps. Individual leader steps occurring during the stepped portion of dart-stepped leaders can produce appreciable ramp-like electric field changes and corresponding magnetic field pulses. Some of the individual electric field steps at 30 and 50 m were observed to account for as much as 10% of the total leader field change. Electric fields produced at 50 and 110 m by a dart-stepped leader (and by the following return stroke) from the 1993 Camp Blanding experiment are shown in Figure 7. Figure 8 presents corresponding magnetic fields at 50 and 110 m showing pulses due to the last two steps prior to the return stroke. Leader steps in electric field records were also observed at 10 and 20 m at Fort McClellan, but no corresponding pulses were detectable in magnetic field records (see Figure 9). On the basis of the two-station field measurements from Camp Blanding we estimate, using electrostatic and magnetostatic approximations [e.g., *Uman*, 1987], that the formation of each step is associated with a charge of a few millicoulombs and a current of a few kiloamperes.

2.2. Bidirectional Leader and Its Associated Return Stroke in Altitude-Triggered Lightning

We first show, with reference to Figures 10 and 11, that the return stroke initiated by the downward extending, negatively charged part of the bidirectional leader in altitude-triggered lightning is distinctly different from a "normal" return stroke. In Figure 10 we compare the magnetic fields produced by the first return strokes in Camp Blanding altitude-triggered flashes 9514 and 9516 (Figures 10a and 10b), respectively, with the magnetic fields due to the second strokes in the same flashes

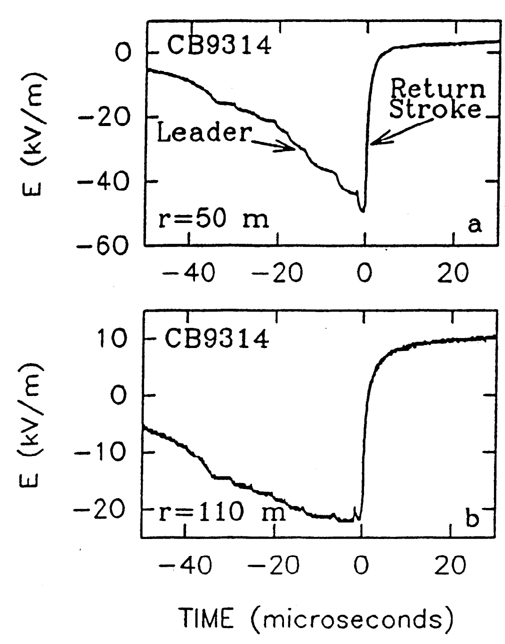

Figure 7. Electric fields produced at (a) 50 m and (b) 110 m by a dart-stepped leader and the ensuing return stroke (Camp Blanding, 1993).

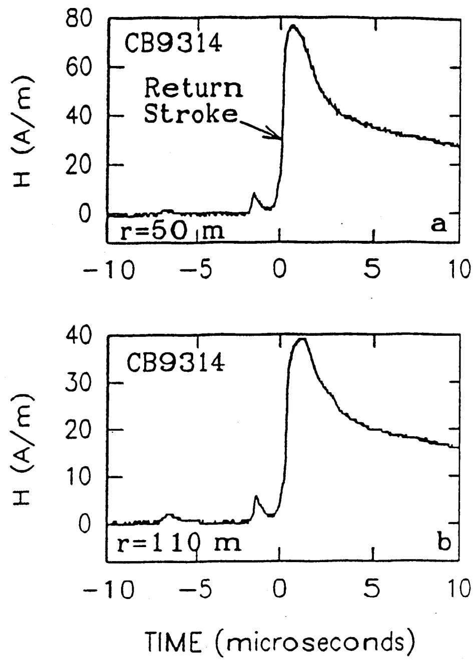

Figure 8. Magnetic fields produced at (a) 50 m and (b) 110 m by the same dart-stepped leader/return stroke sequence as shown in Figure 7. Records were obtained by using H31 Thomson-CSF measuring systems.

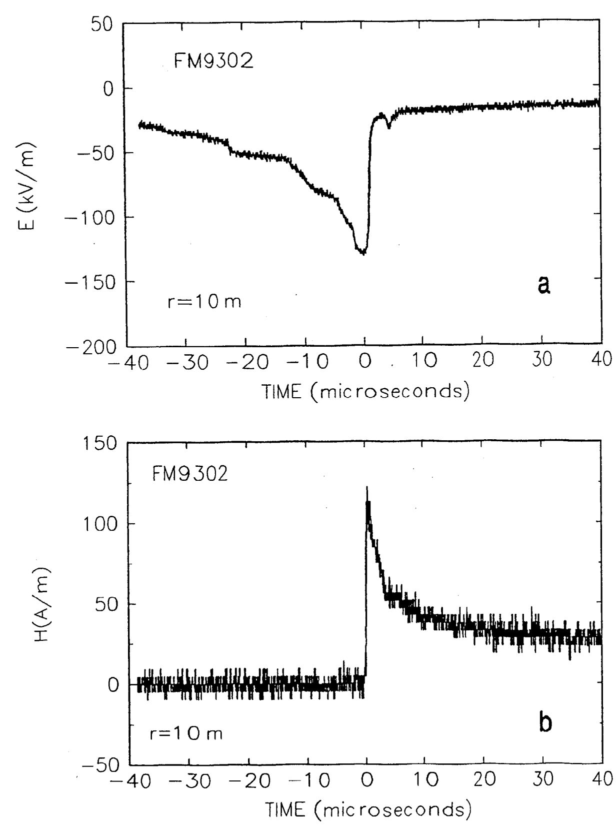

Figure 9. (a) Electric and (b) magnetic fields produced at 10 m by a dart-stepped leader and the ensuing return stroke (Fort McClellan, 1993). No leader pulses are evident in the magnetic field record.

(Figures 10c and 10d), respectively. These second strokes are initiated by dart leaders, as opposed to bidirectional leaders in the case of the first strokes, and presumably have magnetic field waveforms like natural subsequent strokes. Note that the first-stroke magnetic field pulses in Figures 10a and 10b are

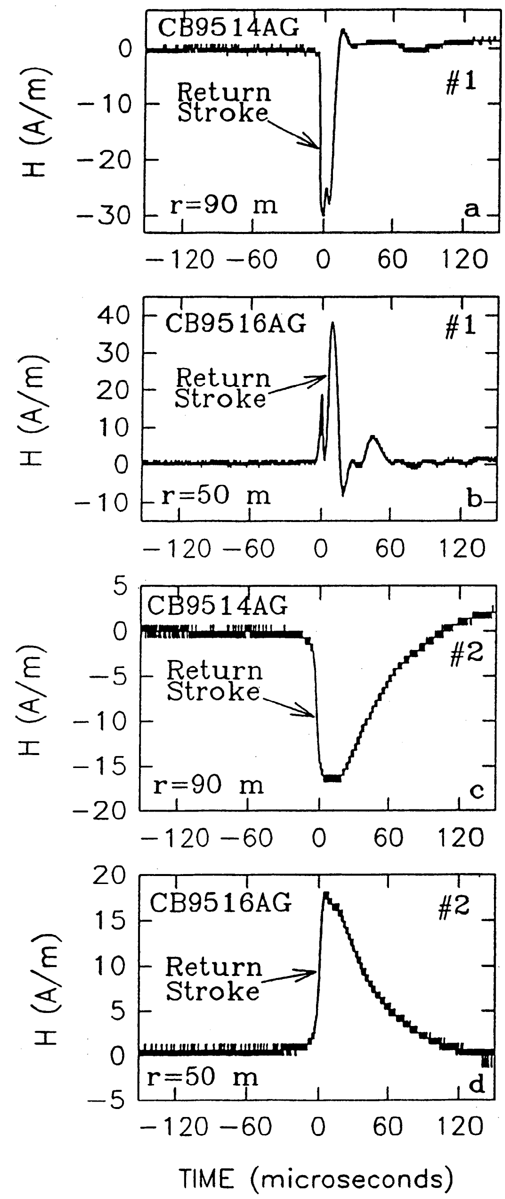

Figure 10. Magnetic fields produced by the first two strokes of the Camp Blanding altitude triggered lightning flashes 9514 (a, first stroke; c, second stroke; four strokes total) and 9516 (b, first stroke; d, second stroke; four strokes total). In each case, the waveshapes of all the higher-order strokes are similar to the second-stroke waveshape. The measuring system's (H31 Thomson-CSF) decay time constant is about 120 μs. The difference in polarity of the waveforms is due to different positions of the lightning channel with respect to the magnetic field antenna, all strokes lowering negative charge to ground. Note that the first-stroke magnetic field pulses in Figures 10a and 10b are appreciably shorter than the corresponding second-stroke magnetic field pulses in Figures 10c and 10d, respectively.

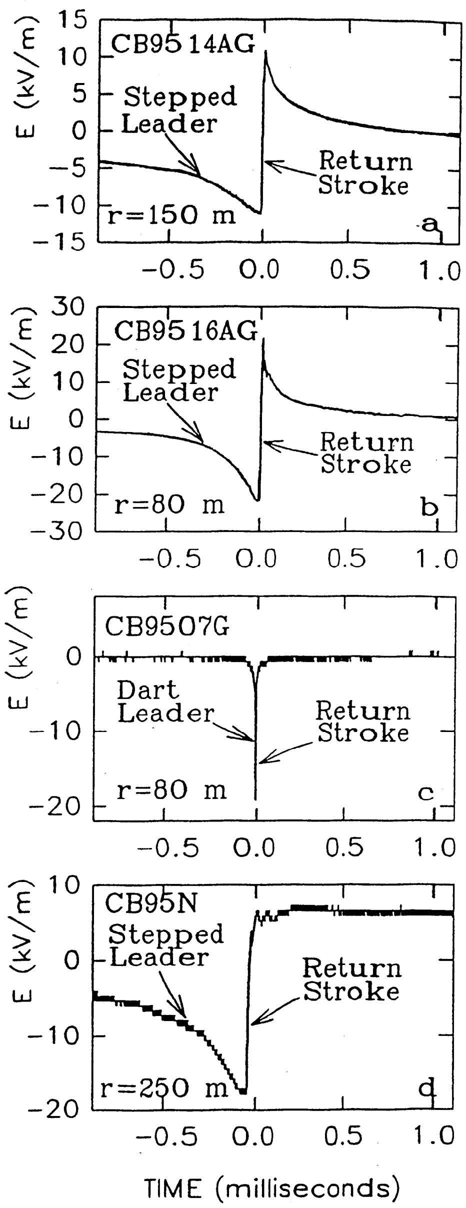

Figure 11. Electric fields produced by the first leader/return stroke sequence in four different Camp Blanding flashes, all recorded with the same flat-plate measuring system having a decay time constant of 10 ms: (a and b) altitude-triggered lightning flashes 9514 and 9516, respectively (bi-directional leader); (c) classical triggered-lightning 9507 (downward dart leader); (d) natural lightning (downward stepped leader). The initial downward field deflection in Figures 11a and 11b is predominantly due to the downward negative stepped leader of the bidirectional leader system. Note the decrease of field after the return stroke in Figures 11a and 11b but not in Figures 11c and 11d.

appreciably shorter than the corresponding second-stroke magnetic field pulses in Figures 10c and 10d. Further, in Figure 11 we compare the electric fields produced by the first (bidirectional) leader/return stroke sequences in altitude triggered flashes 1914 and 9516 (Figures 11a and 11b), respectively, with (1) the electric field due to a dart leader/return stroke sequence in a classical triggered lightning (Figure 11c), the latter field being presumably similar to those produced by natural lightning subsequent strokes, and (2) the electric field due to a stepped leader/return stroke sequence in natural lightning (Figure 11d). The initial downward field deflection in Figures 11a and 11b is predominantly due to the downward negative stepped leader of the bidirectional leader system (see Figure 2). The difference in the apparent duration of the stepped leader in Figure 11b and the dart leader in Figure 11c, recorded at the same distance of 80 m, is due to the dart leader's propagating downward considerably faster than the stepped leader. Note that the electric field immediately following the rapid return stroke field deflection in Figures 11a and 11b exhibits an appreciable decay, whereas at about the same time in Figures 11c and 11d (strokes in classical triggered and natural lightning, respectively) the electric field shows essentially no change. As discussed below, one likely explanation for the difference between the first return stroke in altitude-triggered lightning and the other return strokes is the relatively short length (of the order of 1 km; see Figure 2) of the channel available for the upward propagation of the return stroke wave in altitude-triggered lightning. As a result, the return stroke process can only propagate for 10 μs or so after which it must transform itself into an upward moving positive leader that is apparently more intense than the upward positive leader of the bidirectional leader system and similar to the upward propagating positive leader of classical triggered lightning after the triggering wire has melted. A streak photograph from the 1989 KSC experiment, obtained by using a near-ultraviolet lens, apparently showing this transformation at a height less than 650 m, has been published by *Idone* [1992]. The processes that follow are probably similar to those in classical triggered lightning. Thus it appears that the downward moving negative leader of the bidirectional leader system and the resulting return stroke serve to provide a relatively low-impedance connection between the upward moving positive leader tip and the ground. We postulate that when the upward moving return stroke front catches up with the upward moving leader tip (after 10 μs or so), an opposite-polarity downward going reflected current wave is produced that is responsible for the chopped shape of the channel-base current and magnetic field waveforms, the latter being shown in Figures 10a, and 10b. Alternatively, an explosion of the upper wire section at 450-600 m (see Figure 2) might serve to cut off the return stroke current, although this hypothesis is apparently inconsistent with the observation of *Idone* [1992] for the 1989 KSC flash (8911) that the return stroke wave propagated beyond the upper end of the wire channel section and caught up with the upward moving leader tip. Further, as inferred by *Laroche et al.* [1991] from current and high-speed photographic records for another altitude-triggered flash (8925) from the 1989 KSC experiment, the upper (triggering) section of the wire melts at about the same time as the lower (intercepting) section, several microseconds before the main current peak. The near-zero field occurring after the first small peak in the magnetic field waveform in Figure 10b, shown on an expanded timescale in Figure 12b, and the corresponding features in the current waveform (see Figure 12a) and in the electric field waveform (see Figure 12c, which is a time expansion of Figure 11b) are apparently associated with the explosion of the lower 50-m section of wire (see Figure 2). This wire explosion serves to interrupt the current flow that is reestablished several microseconds later. The magnetic field waveform shown in Figure 10a does not exhibit an initial small peak followed by a near-zero field because in this case the downward developing lightning channel attached to ground as opposed to attaching to the 50-m section of wire at the rocket

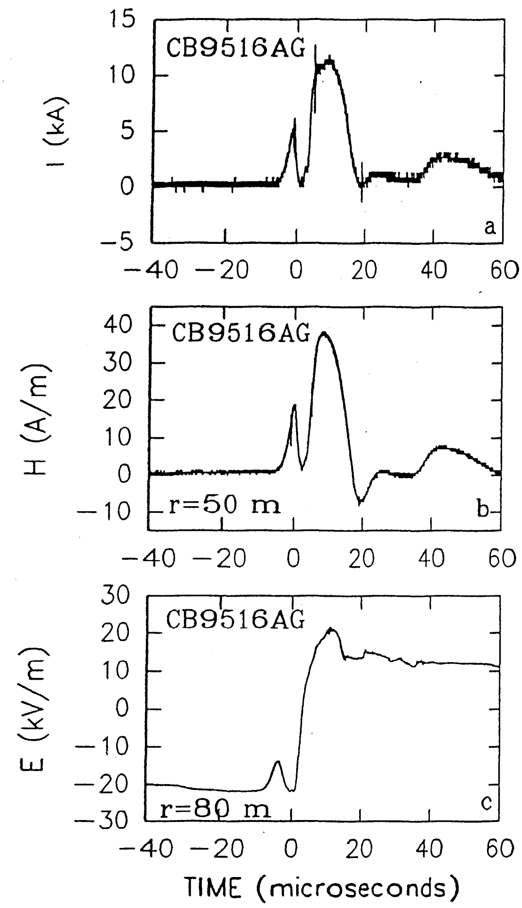

Figure 12. (a) Current, (b) magnetic field at 50 m (a time expansion of Figure 10b), and (c) electric field at 80 m (a time expansion of Figure 11b) from the lightning channel for the first stroke in altitude-triggered lightning flash 9516. Note the small peak separated by several microseconds from the main peak in all three waveforms, a feature apparently associated with the explosion of the lower 50-m section of wire (see Figure 2).

launcher, so there was no exploding wire near ground to interrupt the current flow, while the elevated wire probably behaved in a way similar to that in the event presented in Figure 10b. It appears therefore that the melting of the upper wire does not influence significantly the salient features of the return stroke current and field waveforms. In the case of classical triggered lightning, the melting of the grounded copper triggering wire of a few hundreds of meters in length occurs during the upward positive leader stage (see Figure 1), when the relatively slow varying current in the wire is some tens of amperes, and usually does not lead to a current zero at ground [e.g., *Fisher et al.*, 1993].

2.3. Channel Termination on Ground

In examining the lightning current flowing from the bottom of the channel into the ground, it is convenient to approximate lightning by a Norton equivalent circuit [*Carlson*, 1996], i.e., by a current source equal to the lightning current that would be injected into the ground if that ground were perfectly conducting (the short-circuit current) in parallel with a lightning-channel equivalent impedance Z_{ch} assumed to be constant. The lightning grounding impedance Z_{gr} is a load connected in parallel with the lightning Norton equivalent. Thus the "short-circuit" lightning current I_{sc} effectively splits between Z_{gr} and Z_{ch} so the current measured at the lightning-channel base is found as $I_{meas} = I_{sc}Z_{ch}/(Z_{ch} + Z_{gr})$. Both source characteristics, I_{sc} and Z_{ch}, vary from stroke to stroke, and Z_{ch} is a function of channel current, the latter nonlinearity being in violation of the linearity requirement necessary for obtaining the Norton equivalent circuit. Nevertheless, if we are concerned only with the peak value of current and assume that for a large number of strokes the average peak value of I_{sc} and the average value of Z_{ch} at current peak are more or less constant, the Norton equivalent becomes a useful tool for studying the relation between lightning current peak and the corresponding values of Z_{ch} and Z_{gr}. For instance, if the measured channel-base current peak statistics are similar under a variety of grounding conditions, then Z_{gr} must always be much lower than Z_{ch} at the time of the current peak.

Camp Blanding measurements of lightning currents that entered sandy soil with a relatively poor conductivity of 2.5 x 10^{-4} S/m without any grounding electrode resulted in a value of the geometric mean return-stroke peak current, 13 kA, that is similar to the geometric mean value, 14 kA, from measurements at KSC made by using a launcher of the same geometry which was much better grounded into salt water with a conductivity of 3-6 S/m via underwater braided metallic cables. Additionally, a fairly similar geometric mean value, about 10 kA, of return stroke current peak was found from KSC measurements using a well-grounded ground-based launcher of significantly greater height, and fairly similar geometric mean values were found from the Fort McClellan measurements using a relatively small-height, poorly grounded launcher (10 kA) and the same launcher well grounded (11 kA). Additionally, *Ben Rhouma et al.* [1995] give arithmetic mean values of return stroke current peaks in the range from 15 to 16 kA for the triggered-lightning experiments at Camp Blanding in 1993 and at KSC in 1987, 1989, and 1991. The geometric mean values of peak current indicated above along with other pertinent information on the measurements are summarized in Table 2. The values of grounding resistance (probably the dominant component of Z_{gr}) given in Table 2 should be understood as the initial values encountered by lightning before the onset of any breakdown processes in the soil or along the ground surface. Note from Table 2 that the grounding resistance varies from 0.1 Ω to 64 kΩ, while Z_{ch} was estimated from the analysis of the current waves traveling along the 540-m high tower to be in the range from hundreds of ohms to several kiloohms [*Gorin et al.*, 1977; *Gorin and Shkilev*, 1984]. The observation that the average return stroke current is not much influenced by the level of man-made grounding, ranging from excellent to none, implies that lightning is capable of lowering its grounding impedance to a value that is always much lower than the equivalent impedance of the main channel. On the basis of the evidence of the formation of plasma channels (fulgurites) in the sandy soil at Camp Blanding [*Uman et al.*, 1994b, 1997] and on optical records showing arcing along the ground at both Camp Blanding and Fort McClellan (see an excellent example given by *Fisher et al.* [1994, Figure 15]), we infer that surface and underground plasma channels are the principal means of lowering the lightning grounding impedance, at least for the types of soil at the lightning triggering sites in Florida and Alabama. Injection of laboratory currents up to 20 kA into loamy sand in the presence of water sprays imitating rain resulted in surface arcing that significantly reduced the grounding resistance at the current peak (M. Darveniza, personal communication, 1995). The fulgurites found at Camp Blanding usually show that the in-soil plasma channels develop

Table 2. Geometric Mean Peak Current From Different Triggered-Lightning Experiments

Experiment	Reference	Trigger Threshold, kA	Sample Size	GM Peak Current, kA	Soil	Artificial Grounding	Grounding Resistance, Ω
KSC, Florida, 1985	*Hamelin et al.* [1986], *Eybert-Berard et al.* [1986], *Leteinturier et al.* [1990]	2.5 (the lowest value in data presented by *Hamelin et al.* [1986])	85 (negative return strokes only)	9.9	sand (~10^{-2} S/m); water table at 1-2 m below ground surface	15x15x4.5 m Faraday cage with 6-m long vertical grounding rods in each corner, interconnected 0.6 m below ground level by horizontal wires	0.12
KSC, Florida, 1987	*Eybert-Berard et al.* [1988], *Leteinturier et al.* [1991], as reported by *Fisher et al.* [1993]	5	36	14	0.5-m deep salt water (3-6 S/m)	1.2x1.2 m square metal plane connected through three 0.5 m long wires at the four corners to salt water	0.1
KSC, Florida, 1990	*Fisher et al.* [1993]	1	8	15	same as in 1985	same as in 1985	same as in 1985

Table 2. (continued)

Experiment	Reference	Trigger Threshold, kA	Sample Size	GM Peak Current, kA	Soil	Artificial Grounding	Grounding Resistance, Ω
Fort McClellan, Alabama, 1991	*Fisher et al.* [1993]	2 (two strokes below 2 kA from continuous tape record included)	37	11	clay ($3x10^{-3}$ S/m)	rebar framework of the munition storage bunker interconnected with lightning protection system including air terminals, down conductors and buried counterpoise	presumably low
Camp Blanding, Florida, 1993	*Uman et al.* [1994a, 1997]	3.3 and 4.2	37	13	sand ($2.5x10^{-4}$ S/m)	none launcher was based on two parallel 15-m long, 2 m apart concrete slabs above three unenergized power cables buried 1 m deep and 5 m apart	$64x10^3$ (assuming that the contact surface between the channel and ground was a hemisphere with 1-cm radius)
Fort MCClellan, Alabama, 1993	*Fisher et al.* [1994]	~4	31	10	heavy red clay ($1.8x10^{-3}$ S/m)	single 0.3-m or 1.3 m long vertical grounding rod	260

KSC, Kennedy Space Center. The values of grounding resistance are determined by the geometry of the grounding electrode (or the geometry of the contact surface between the channel and the ground in the absence of grounding electrode) and soil conductivity. They are measured under low-frequency, low-current conditions, for instance, using a megger, and should be understood as the initial values of resistance encountered by lightning before the onset of any breakdown processes in the soil or along the ground surface.

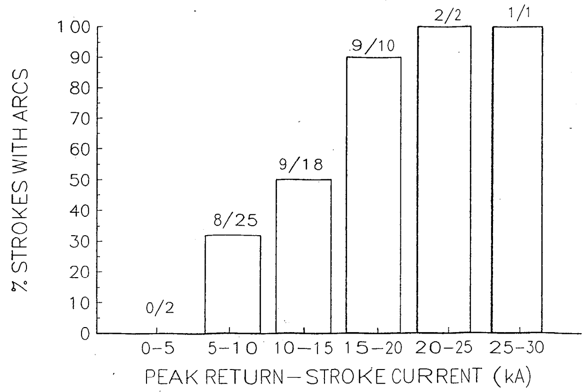

Figure 13. Percentages of return strokes producing optically detectable surface arcing as a function of return stroke peak current (Fort McClellan, 1993 and 1995). Numbers above each histogram column indicate the number of strokes producing optically detectable arcing (numerator) and the total number of strokes in that return stroke current range (denominator).

toward the better conducting layers of soil or toward buried metallic objects that, when contacted, serve to further lower the grounding resistance. The percentages of return strokes producing optically detectable surface arcing versus return stroke peak current, from the 1993 and 1995 Fort McClellan experiments, are shown in Figure 13. The surface arcing appears to be random in direction and often leaves little if any evidence on the ground. Even within the same flash, individual strokes can produce arcs developing in different directions. In one case it was possible to estimate the current carried by one arc branch which contacted the instrumentation: approximately 1 kA or 5% of the total current peak in that stroke. The observed horizontal extent of surface arcs was up to 20 m, which was the limit of photographic coverage during the 1993 Fort McClellan experiment. No fulgurites were found in the soil (red clay) at Fort McClellan, only concentrated current exit points at several spots along the 0.3- or 1.3-m steel earthing rod (see Table 2). It is likely that uniform ionization of soil, usually postulated in studies of the behavior of grounding electrodes subjected to lightning surges, is not a valid assumption, at least in the southeastern United States, where distinct plasma channels in the soil and on the ground surface appear to be the principal means of lowering the grounding resistance.

2.4. *M* component

Rakov et al. [1995a] have proposed a "two-wave" mechanism of the lightning M component based on the results of the 1993 triggered-lightning experiment in Florida. According to this mechanism, an *M* component involves a downward progressing incident wave (the analog of a leader) and an upward progressing reflected wave (the analog of a return stroke). Ground is sensed by the incident *M* wave as a short circuit, so the reflection coefficient for current at ground is close to +1, and the reflection coefficient for the associated charge density is close to -1. At each channel section, the two waves are shifted in time, the time shift being small near ground and increasing toward the cloud. The time-shifted current components of the two waves add at each point on the channel, while the time-shifted charge density components subtract. As a result, at close ranges the *M* component magnetic fields have waveshapes similar to those of the channel-base currents, whereas the *M*-component electric fields have waveforms that appear to be the time derivatives of the channel-base current waveforms. Additionally, the proposed mechanism predicts that (1) *M* component magnetic field magnitudes vary as the inverse distance from the lightning channel, and (2) *M* component electric field magnitudes are relatively insensitive to distance from the lightning channel. Electric and magnetic fields at distances from 30 to 370 m from the lightning channel, including simultaneous measurements at two different distances from the 1995 Florida experiment, are in support of the "two-wave" *M* component mechanism. As an example, the channel-base current and electric and magnetic fields at 280 m from the channel of one relatively large *M* component that followed stroke 2 in flash 9518 (Camp Blanding, 1995) are presented in Figure 14, the first report of the simultaneous measurement of

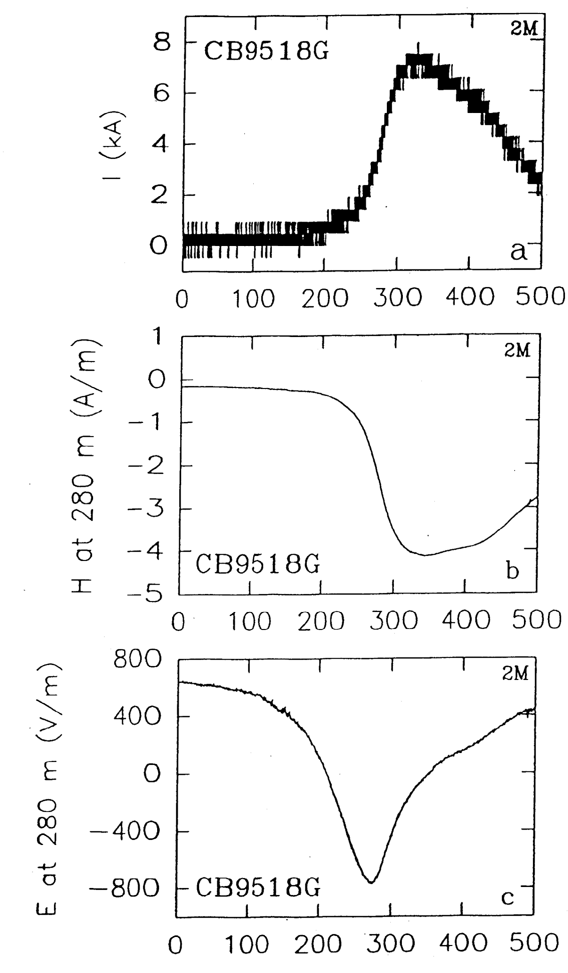

Figure 14. (a) Current and (b and c) magnetic and electric fields, respectively, at 280 m from the lightning channel for a large *M* component that followed the second stroke in seven-stroke Camp Blanding flash 9518. The electric and magnetic fields were obtained using a flat plate antenna and a loop antenna, respectively, in two channels of the same ADTEK digitizing system. The current was recorded independently and aligned with the fields using the magnetic field as a guide. Note that the electric field peak occurs appreciably earlier than the current and magnetic field peaks, as if the electric field were proportional to the time derivative of the current.

the three quantities for an M component. This figure illustrates the similarity of the current and close magnetic field waveforms and the fact that the close electric field waveform has its peak when the current rate of rise is approximately maximum, as if the electric field waveform were the time derivative of the current. The measured current peak (see Figure 14a) and the current peak inferred, using Ampere's law, from the measured magnetic field (see Figure 14b) are both equal to 7 kA, an order of magnitude greater than for a typical M component [*Thottappillil et al.*, 1995].

3. Summary

1. At very close ranges (a few tens of meters or less) the time rate of change of the final portion of the dart leader electric field can be comparable to that of the return stroke. This observation, coupled with the fact that within some hundreds of meters the leader and return stroke electric fields are about equal in magnitude, suggests that very close dart leaders can make as significant a contribution as return strokes in inducing voltages and currents on power and other systems.

2. The variation of the close dart leader electric field change with distance is somewhat slower than the inverse proportionality predicted by the uniformly charged leader model, perhaps due to a decrease of leader charge density with decreasing height associated with an incomplete development of the corona sheath at the bottom of the channel. More data are needed to confirm or refute this inference. The uniformly charged leader model, although a crude approximation, is more consistent with experimental data of *Beasley et al.* [1982] than the vertically symmetrical bidirectional leader model of *Mazur and Ruhnke* [1993] or a leader model assuming an exponential charge decay with height (e.g., *Nucci et al.* [1990]).

3. There is a positive linear correlation between the leader field change at close range and the succeeding return stroke current peak at the channel base. Correlation coefficients are 0.70, 0.95, 0.98, 0.98, and 0.87 at 10, 20, 30, 50, and 110 m, respectively.

4. The formation of each step of a dart-stepped leader is associated with a charge of a few millicoulombs and a current of a few kiloamperes.

5. In an altitude triggered lightning, the downward negative leader of the bidirectional leader system and the resulting return stroke serve to provide a relatively low-impedance connection between the upward moving positive leader tip and ground, the processes that follow likely being similar to those in classical triggered lightning. Current of the first return stroke in altitude-triggered lightning is of shorter duration than for normal return strokes, probably due to the shorter channel length available.

6. Judging from the similar average current peak values in dissimilar grounding situations, lightning appears to be able to reduce the grounding impedance which it initially encounters at the strike point so that at the time of channel-base current peak the reduced grounding impedance is always (regardless of the initial grounding impedance) much lower than the equivalent impedance of the channel (hundreds of ohms to several kiloohms). Breakdown processes forming distinct plasma channels in the soil and on the ground surface are probably the principal means of lowering the grounding impedance, at least in the case of poorly conducting (of the order of 10^{-3} - 10^{-4} S/m) sandy and clay soils.

7. At close ranges the measured M-component magnetic fields have waveshapes that are similar to those of the channel-base currents, whereas the measured M-component electric fields have waveforms that appear to be the time derivatives of the channel-base current waveforms, in further confirmation of the "two-wave" M component mechanism suggested by *Rakov et al.* [1995a].

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