JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 104, NO. D4, PAGES 4213–4222, FEBRUARY 27, 1999

Characterization of the initial stage of negative rocket-triggered lightning

D. Wang,[1,2] V.A. Rakov,[1] M.A. Uman,[1] M.I. Fernandez,[1] K.J. Rambo,[1]
G.H. Schnetzer,[3] and R.J. Fisher[3]

Abstract. We performed a statistical study on the initial stage (IS) of negative rocket-triggered lightning using 37 channel-base current recordings obtained during the summer of 1994 at Fort McClellan, Alabama, and during the summers of 1996 and 1997 at Camp Blanding, Florida. The IS can be viewed as composed of an upward positive leader (UPL) followed by an initial continuous current (ICC). The IS has a geometric mean (GM) duration of 279 ms and lowers a GM charge of 27 C to the ground. The average IS current in an individual lightning discharge varies from a minimum of 27 A to a maximum of 316 A with a GM value of 96 A for the entire sample of 37 discharges. We examined the current variation at the beginning of the IS in 24 flashes. In 22 out of 24 cases this initial current variation (ICV) includes a current drop, probably associated with the disintegration of the copper triggering wire and the subsequent current reestablishment. The GM time interval between the onset of the initial stage and the abrupt decrease in current is 8.6 ms, and the GM current level just prior to the current decrease is 312 A, a value about 3 times the GM value of average current for the whole IS, 96 A. Before this abrupt current decrease, a GM charge of 0.8 C has been lowered to ground with a corresponding GM action integral of 110 A^2 s. The abrupt current decrease takes typically several hundred microseconds and is followed, immediately or after a time interval up to several hundred microseconds, by a pulse with a typical peak of about 1 kA and a typical risetime of less than 100 μs. The ICC usually includes impulsive processes that resemble the *M* processes observed during the continuing currents that follow return strokes in both natural and triggered lightning. We present statistics for the following parameters of current pulses superimposed on the ICC: magnitude, risetime, half-peak width, duration, charge transferred, preceding continuous current level, interpulse interval, and time interval between the onset of the IS and the first ICC pulse. The observed characteristics of ICC pulses varied significantly among the three data sets. For all data combined, the characteristics of the ICC pulses are similar to those of the *M*-component current pulses studied by *Thottappillil et al.* [1995]. This latter finding suggests that ICC impulsive processes are of the same nature as *M* processes.

1. Introduction

The rocket-triggered lightning technique has been widely used to study both the physics of the lightning discharge and the effects of lightning on various systems [e.g., *Fieux et al.*, 1978; *Horii*, 1982; *Morris et al.*, 1994; *Uman et al.*, 1997; *Rakov et al.*, 1998]. A typical negative rocket-triggered lightning, which is similar to a natural upward initiated lightning from a tall structure [*Uman*, 1987], involves an initial stage (IS) that can be viewed as composed of an upward positive leader (UPL) followed by an initial continuous current (ICC). We have not been able to identify the transition from the UPL to the ICC from an examination of channel-base current records. If we assume that the average UPL speed is 2 x 10^5 m/s and that the primary negative charge involved in the ICC is located at a height of 6 to 8 km, then the first 30-40 ms (~10%) of the IS is due to the UPL, and the rest of the IS is due to the ICC. The ICC is often followed by dart leader/return stroke sequences, similar to those constituting subsequent strokes in natural downward initiated lightning. When there are no return strokes involved [e.g., *Fieux et al.*, 1978; *Laroche et al.*, 1985], the triggered lightning event consists of the IS only and is sometimes termed a "wire burn." Return strokes and *M* components in negative rocket-triggered lightning have been characterized by *Hubert et al.* [1984], *Fisher et al.* [1993], and *Thottappillil et al.* [1995]. Although there have been several previous studies of the IS [e.g., *Laroche et al.*, 1985; *Nakamura et al.*, 1987; *Rakov et al.*, 1996], no detailed statistical characteristics of this stage are available in the literature. In this paper, we provide such characteristics using experimental data acquired in Alabama and Florida. Further, it has been known from the early days of rocket-triggered lightning experiments that the ICC involves impulsive processes [*Fieux et al.*, 1978]. Since similar pulses, referred to as *M*-component current pulses,

[1]Department of Electrical and Computer Engineering, University of Florida, USA
[2]Consultants to the University of Florida
[3]Department of Electrical and Electronic Engineering, Gifu University, Japan

Paper number 1998JD200087.
0148-0227/99/1998JD200087$09.00

also occur during the continuing current that follows return strokes, it seems reasonable to hypothesize that both ICC pulses and *M*-component current pulses are produced by similar processes. To test this hypothesis, we compare the statistical characteristics of these two types of current pulses. We show that they are similar. Both the *M*-component current pulses and the ICC pulses are associated in optical records with brightening of the already luminous lightning channel [*Fisher et al.*, 1993]. According to the "two-wave" mechanism of the lightning *M* component proposed by *Rakov et al.* [1995], 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 two waves are expected to be optically indistinguishable below the cloud base, but the presence of the two waves manifests itself in the observed features of the *M*-component electric and magnetic fields at ranges from tens to hundreds of meters. More detailed information on various aspects of lightning *M* components, including a review of the previous literature, is found in the work of *Rakov et al.* [1995], *Jordan et al.* [1995], and *Thottappillil et al.* [1995].

2. Data

The data used for this study include 37 channel-base current recordings of classical rocket-triggered lightning, 9 of which are from the 1994 summer experiment at McClellan, Alabama, and the remaining 28 from the 1996 (12) and 1997 (16) summer experiments at Camp Blanding, Florida [*Uman et al.*, 1997, *Rakov et al.*, 1998]. All flashes effectively lowered negative charge to ground. Two slightly different triggering facilities were used in acquiring the data. For convenience we will call one of them the SNL (Sandia National Laboratories) system and the other one the UF (University of Florida) system. The SNL system has been described in detail by *Fisher et al.* [1993]. The SNL currents used in this study were measured with a 1-mΩ current viewing resistor, the output of which was relayed via a fiber optic link and tape recorded with a bandwidth from DC to 400 kHz, a noise level of approximately 20 A, and an upper amplitude limit of about 2 kA. The tape-recorded data were later digitized with a sampling interval of 40 μs. The SNL system was used in all three experiments (one in Alabama and two in Florida), and 34 of 37 records used in this study were obtained with this system. The remaining three records were obtained using the UF system in the 1996 Florida experiment. There is no significant difference between the SNL system and the UF system except that the UF launcher was mounted atop an 11-m-high wooden tower with a metallic wire connecting the launcher's metallic frame to the grounding rod at the base of the tower, while the SNL launcher was on the ground. The current in the UF system was measured at the launch unit with a 1-mΩ current viewing resistor whose output was relayed via a fiber-optic link to be digitized and recorded by a Nicolet Pro 90 oscilloscope. The UF system recorded the triggered-lightning current for a duration up to 1 s with a sampling interval of 2 μs and an amplitude range of ± 5 kA.

3. Results and Discussion

3.1. Overall Characteristics of the Initial Stage

Waveforms of the overall channel-base current of negative classical rocket-triggered lightning have been published, for example, by *Hubert et al.* [1984, Figure 3] and by *Fisher et al.* [1993, Figure 2]. These are basically similar to the currents of the upward lightning initiated from tall structures, as documented by *McEachron* [1939] and by *Berger* [1967] some decades ago [*Uman*, 1987]. All the current records analyzed in this paper (an example is shown in Figure 1) have more or less similar overall waveshapes during the initial stage (IS) except that the pronounced current variation seen in Figure 1 at the beginning of IS could be identified by the authors in only 24 out

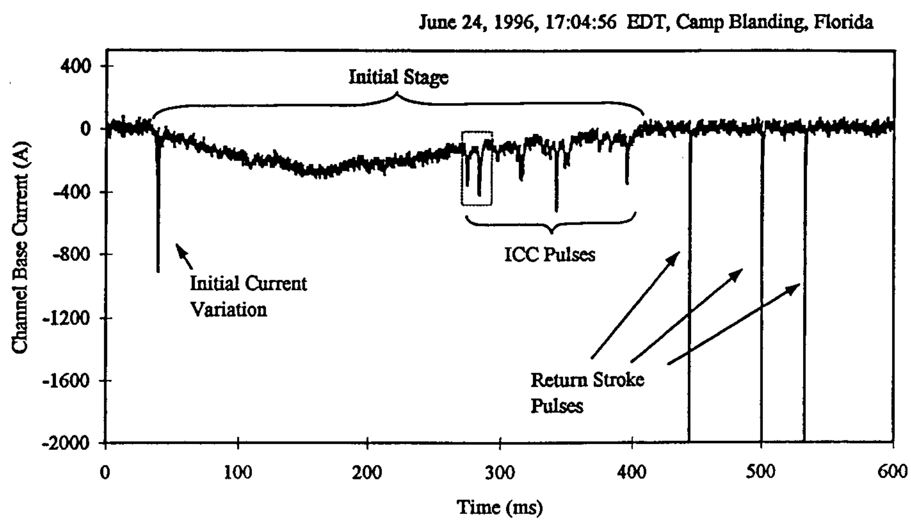
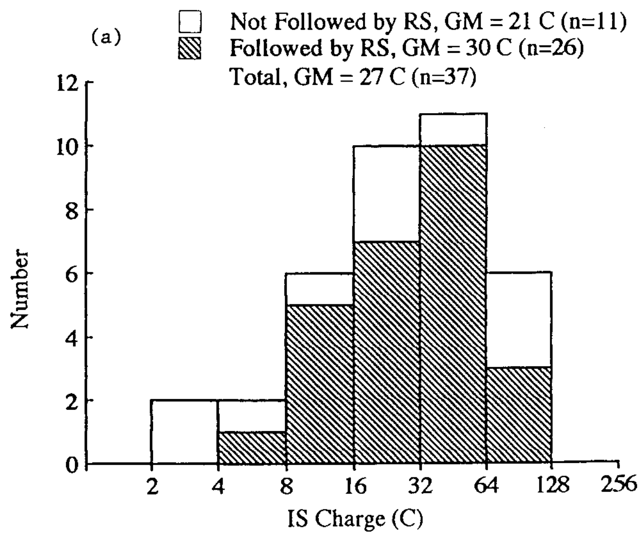


Figure 1. Example of overall current record of a triggered lightning at Camp Blanding, Florida, containing an initial stage (IS) and three subsequent return strokes. The initial tens of milliseconds of IS are due to the upward positive leader (UPL), while the rest of IS is due to the initial continuous current (ICC). The record is intentionally clipped at about 2 kA.

of 37 records. This variation usually (22 out of 24 cases) includes a rapid current drop (unresolved in Figure 1 but readily seen in Figures 4 and 5), probably associated with the wire-melting process, followed by a large current pulse. In the following we will call the pronounced current variation at the beginning of IS the initial current variation (ICV). The overall duration of this variation does not exceed 10 ms. Besides the ICV (if any), the IS typically includes pronounced pulses superimposed on the ICC, labeled ICC pulses in Figure 1. The initial stage in Figure 1 is followed, after a zero-current interval, by three return strokes. Of the 37 triggered flashes analyzed, 26 contain return strokes, and the remaining 11 flashes contain only the initial stage without any following return strokes. To characterize the initial stage as a whole, statistics have been compiled for the following three parameters: (1) IS charge, the numerical time integral of the entire IS waveform, including impulsive components, if any; (2) IS duration measured from the onset of the initial stage current until this current decays to zero; and (3) average IS current found as the IS charge divided by the IS duration. Figure 2 presents the distributions of those parameters. The shaded and unshaded histogram areas represent the data for the events followed by return strokes and not followed by return strokes, respectively. From Figure 2, some differences are evident in terms of IS charge and average IS current for those two types of flashes: geometric mean (GM) values of 30 C and 110 A for the flashes containing return strokes and GM values of 21 C and 69 A for those not containing return strokes, while no appreciable difference is evident in terms of IS duration. Since there are large variations within each category, and the sample size for those without return strokes is rather small, we cannot attach much significance to the differences in the GM values of either IS charge or average IS current. The GM of charge effectively lowered to the ground during the IS is 27 C with a range from 3 C to 112 C. This GM value is an order of magnitude larger than the charge, 2.5 C, lowered by individual return strokes in triggered lightning reported by *Fisher et al.* [1993] and more than 2 times larger than the charge, 12 C, lowered by long (defined as having duration longer than 40 ms) continuing current in natural negative cloud-to-ground flashes inferred from electric field change measurements by *Brook et al.* [1962]. Apparently, the IS stage is a very effective mode of lowering cloud charge to ground. The GM IS duration is 279 ms, which is appreciably larger than the average duration, 150 ms, reported by *Brook et al.* [1962] for long continuing current in natural cloud-to-ground flashes. The average IS current for an individual lightning discharge varies over a range from a minimum of 27 A to a maximum of 316 A with a GM value of 96 A for the entire sample of 37 discharges, slightly larger than the average value, 79 A, for the long continuing current in natural cloud-to-ground flashes found by *Brook et al.* [1962] from electric field measurement. *Williams and Brook* [1963], from magnetic field measurements, reported average values of 184 A, 31 C, and 174 ms for continuing current magnitude, charge, and duration, respectively.

Figure 3 presents scatterplots illustrating correlations among the above three parameters. From Figures 3a and 3b, IS charge is moderately correlated with both IS duration and IS current (correlation coefficients are 0.7 and 0.8, respectively). Essentially, no correlation exists (correlation coefficient is 0.2) between IS current and IS duration.



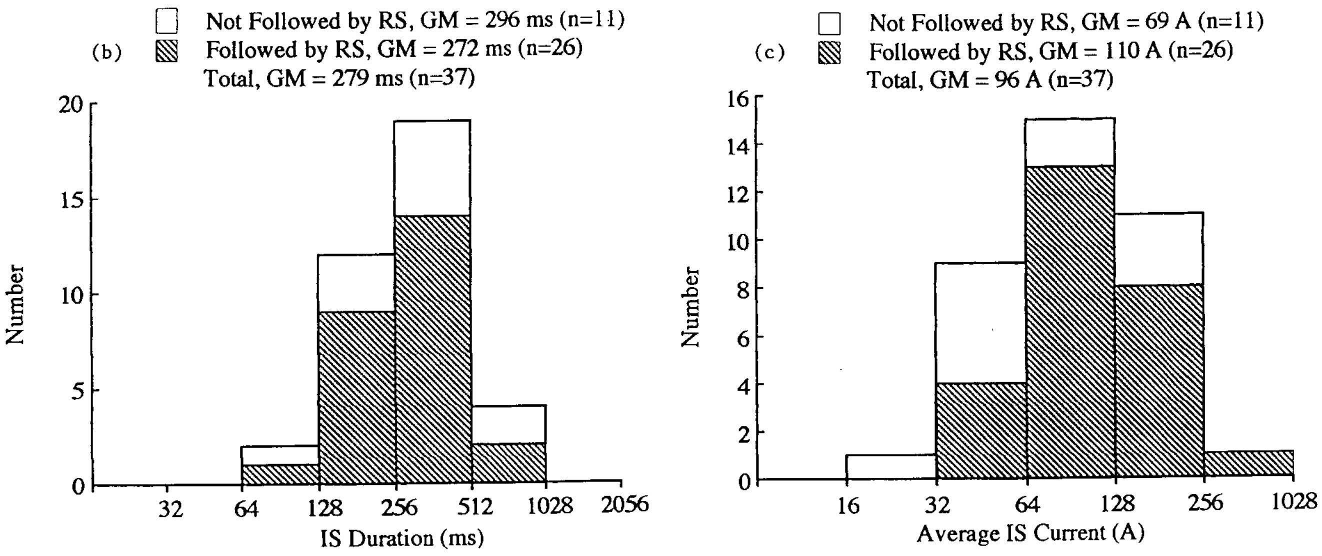


Figure 2. Overall characteristics of the initial stage (IS): (a) charge, (b) duration, and (c) average current.

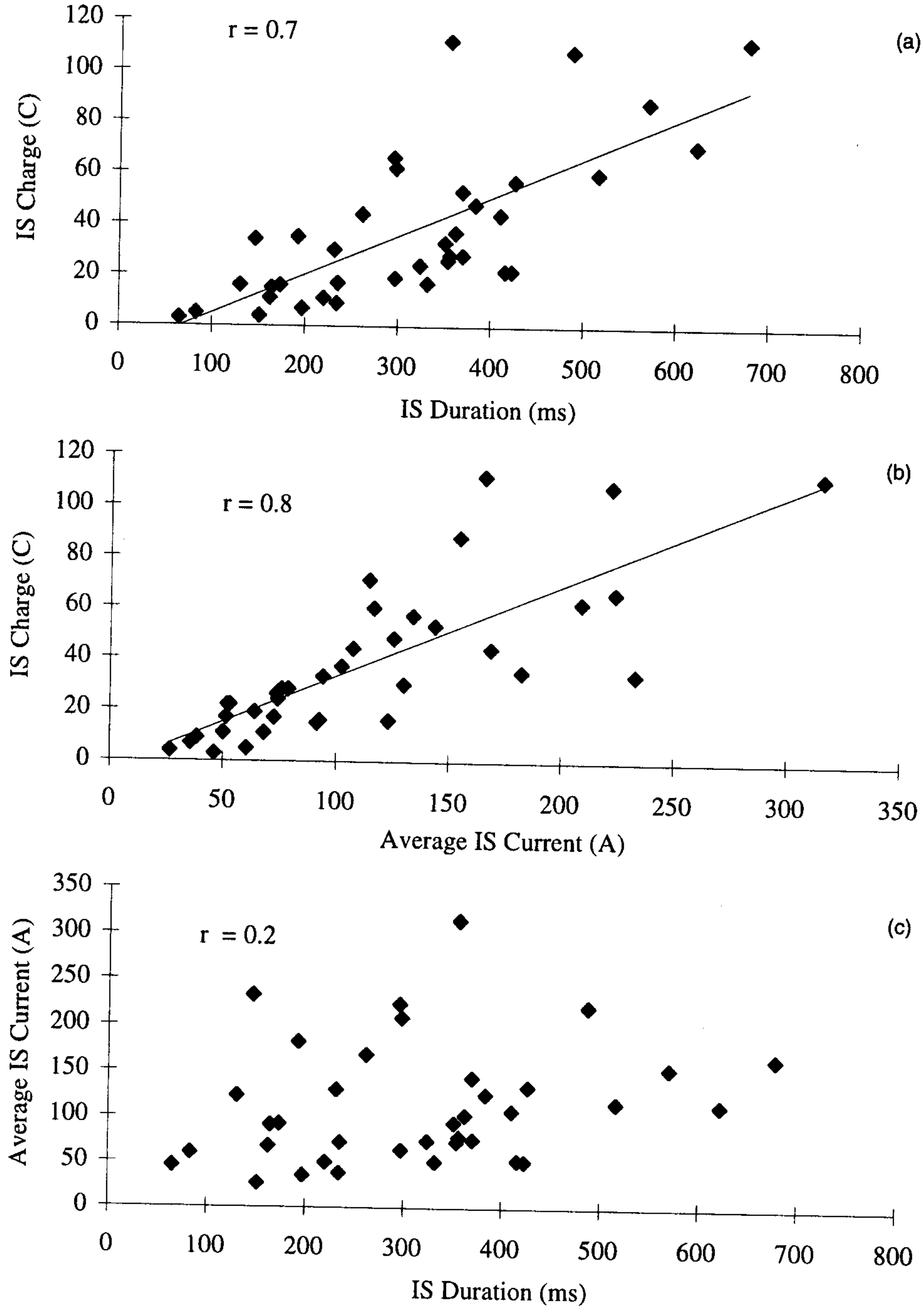


Figure 3. Correlation between initial stage (IS) characteristics: (a) charge versus duration, (b) charge versus average current, and (c) average current versus duration.

3.2. Initial Current Variation

As noted in the previous section 3.1., the initial current variation (ICV) was identified in 24 out of 37 current records. In 22 out of 24 cases the ICV includes a pronounced current drop as illustrated in Figures 4 and 5, and in two cases, there is no pronounced current drop (these two cases are not illustrated here). For most of the ICVs analyzed, the charge transferred by the entire ICV above the background current level is less than 1 C. A "typical" ICV is illustrated in Figure 4 which shows an inverted expansion of the early part of the IS shown in Figure 1. In 5 out of the 24 cases, 3 containing a pronounced current drop (an example being shown in Figure 5) and the 2 not containing it, the ICV transferred to ground a considerably larger charge of several coulombs. These 5 are discussed in the last paragraph of this section. As seen in Figure 4 illustrating the "typical" case, once the channel-base current increases to some level A, it drops to a relatively low value B, and then increases to a value C, greater than A. We hypothesize that the rapid current drop is a result of the explosion of the 0.2-mm-diameter copper triggering wire when the wire-extending rocket is at a height of typically 200-300 m. It is possible that mechanical breakage of the wire is also involved.

For the 22 cases in which the ICV exhibited a pronounced drop we measured the elapsed time of the abrupt current drop from the onset of the IS, the corresponding charge lowered to the ground, and the action integral until the current drop begins, along with the current level at the beginning of the current drop.

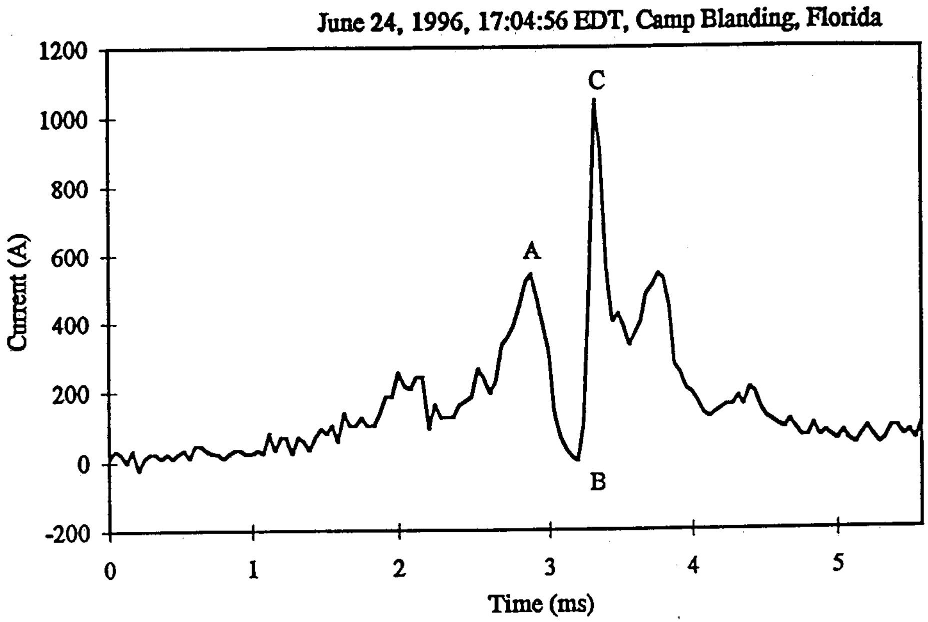


Figure 4. Initial current variation (ICV) shown in Figure 1 but on an expanded timescale and inverted. This figure illustrates a "typical" ICV waveform.

The statistical results are given in Figure 6. The current begins to drop rapidly at a GM current level of 312 A attained during a GM time interval of 8.6 ms from the onset of the IS. Prior to this rapid current decrease, a GM charge of 0.8 C has been lowered through the wire and a GM action integral (energy per unit resistance) of 110 A^2 s has been expended. In 16 cases the current drops to zero, while in the remaining six cases, the current decreases to a value around 100 A. After the drop, the current rises again immediately in 15 cases and after a zero-current or lower-level-current interval lasting for up to several hundred microseconds in seven cases. Interestingly, in the early days of rocket-triggered lightning, steel-triggering wires were used which reportedly melted at a current value of several tens of amperes [*Fieux et al.* 1978], as opposed to the hundreds of amperes (GM of 312 A) we inferred for our copper wires.

We also measured the duration of the current drop, which is the time interval from the beginning of current decrease within the ICV to the lowest value of current before it rises again (from point A to point B in Figure 4), as well as the peak and risetime of the following large pulse. The current drop occurs typically within several hundred microseconds. The large pulse following the current drop usually has a peak magnitude of about 1 kA and a risetime of less than 100 μs.

As noted above, the charge transferred by the entire ICV, such as that shown in Figure 4, above the background current level is less than 1 C for most of the ICVs analyzed. However,

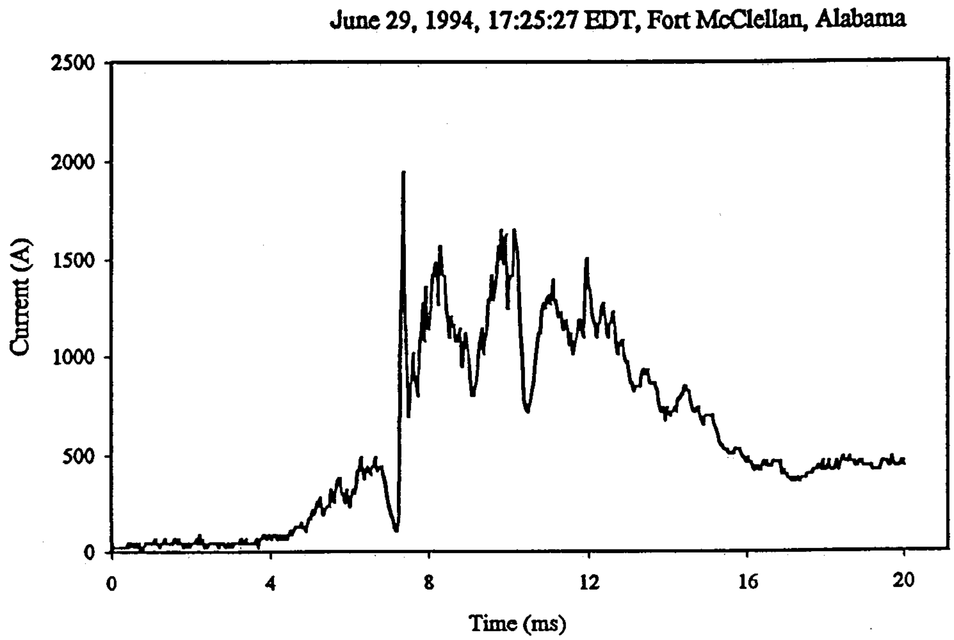


Figure 5. Example of the initial current variation (ICV) transferring a relatively large charge of several coulombs (above the background current level) over a period of about 10 ms and showing a relatively complicated structure.

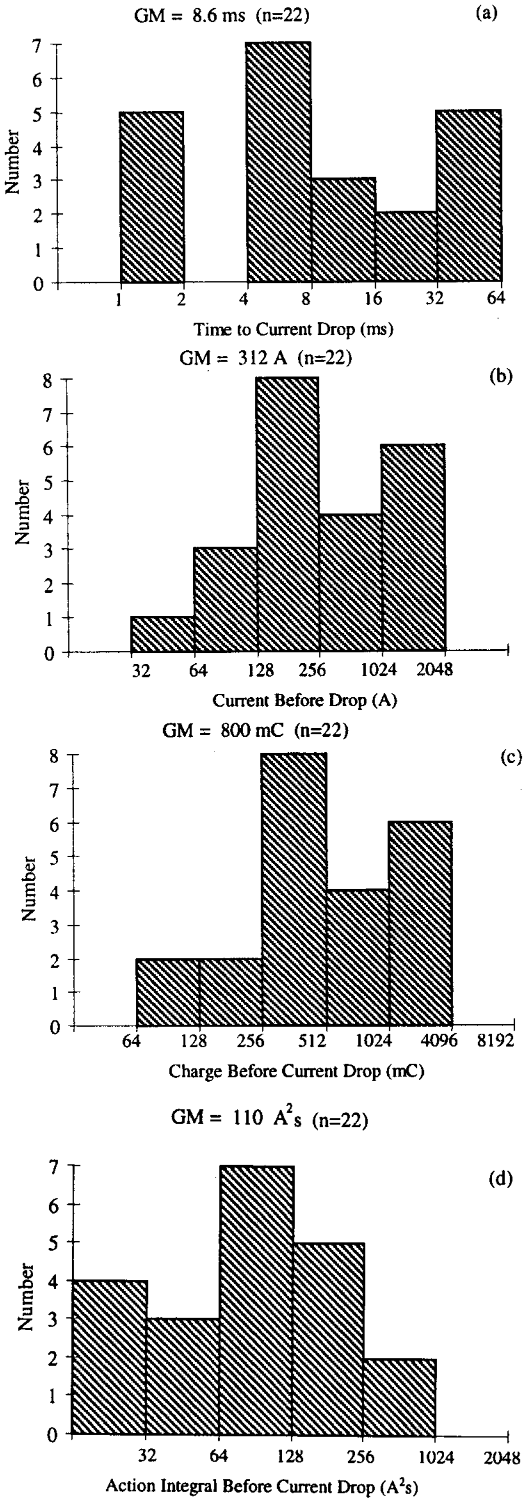


Figure 6. Distributions of initial current variation (ICV) parameters associated with the abrupt current drop: (a) time to current drop, (b) current level at which current begins to drop (current before drop), (c) charge transferred to ground before current begins to drop (charge before current drop), (d) action integral expended before current begins to drop (action integral before current drop).

5 out of 24 ICVs (three containing the characteristic current drop and the two not containing it) transferred to ground a charge as large as several coulombs. This charge is comparable to the charge transferred to ground by first strokes in natural lightning. The larger-charge ICVs usually exhibit a more complicated structure (involving several overlapping current pulses), have a duration of several milliseconds, and have an overall peak value from 1 to 2 kA, as shown in the example in Figure 5. Since the ICV in Figure 5 attains its peak within 10 ms of the onset of the IS (the GM value of this time interval is 8.6 ms), we infer, assuming an average UPL speed of 2 x 10^5 m/s, that the process producing the ICV takes place when the channel has extended to a height of 2 km or less, i.e., before it has reached the primary negative cloud charge, typically located at a height of 6 to 8 km in Florida. It is possible, particularly in the case of the larger ICV charge transfers, that the upward positive leader encounters a region of negative charge near the visible cloud base (1 to 2 km in Florida) or even a negatively charged downward moving leader, the latter process being analogous to that inferred by *Berger* [1967] for flashes that appeared to be initiated by upward negative leaders from his tower. It is not clear in the hypothetical scenario involving the downward leader if such a leader would be initiated in response to the upward leader or independently.

3.3. Characteristics of the ICC Pulses

In this section we will examine the ICC pulses illustrated in Figure 1. Figure 7 shows inverted waveforms of the two ICC pulses enclosed in the rectangle in Figure 1. The waveforms are moving-averaged using a four-data-point window. Sixteen out of 26 IS current records followed by return strokes exhibit such well-defined pulses, some of the records having more than 20 pulses, and others having only a few pulses. The remaining 10 IS records followed by return-stroke current pulses do not contain pronounced ICC pulses, only small and noisy pulses or pulses having complicated waveshapes which are not suitable for unambiguous measurement of pulse parameters. The initial stages which are not followed by return strokes tend to be noisy and only 2 out of a total of 11 such events contain a few well-defined pulses. In the following, we consider only pulses from the 16 IS records which are followed by return strokes and contain well-defined pulses (4 are from the 1994 Alabama data set, 7 are from the 1996 Florida data set, and 5 are from the 1997 Florida data set). For each pulse, we measured the following parameters: magnitude, risetime, half-peak width, duration, transferred charge, interpulse interval, preceding continuous current level, and time interval between the onset of IS and the first ICC pulse. Figure 7 illustrates how the various measured parameters are defined: ICC pulse magnitude (I_M) is the difference between the peak of the ICC pulse and the preceding continuous current level. ICC pulse risetime (R_T) is the time interval on the wavefront between the 10% and the 90% values of the magnitude. ICC pulse half-peak width (T_H) is the time interval between the 50% values of the magnitude on the wave front and on the falling portion of the ICC pulse. ICC pulse duration (T_D) is the time interval measured from the beginning of the wave front, identified as the initial deflection from the preceding continuous current level, to a point at which the trailing edge of the ICC pulse becomes indistinguishable from the overall continuous current waveform. The estimated beginning and ending points of the waveform are to some extent subjective. ICC pulse charge is the time integral of the ICC pulse above the background continuous current level. ICC interpulse interval (T_I) is the time interval between peak values of successive ICC pulses. Preceding continuous current level (I_{CC}) is the value of the continuous current immediately prior to the ICC pulse. All these definitions are exactly the same as those used for the analysis of M-component current pulses that

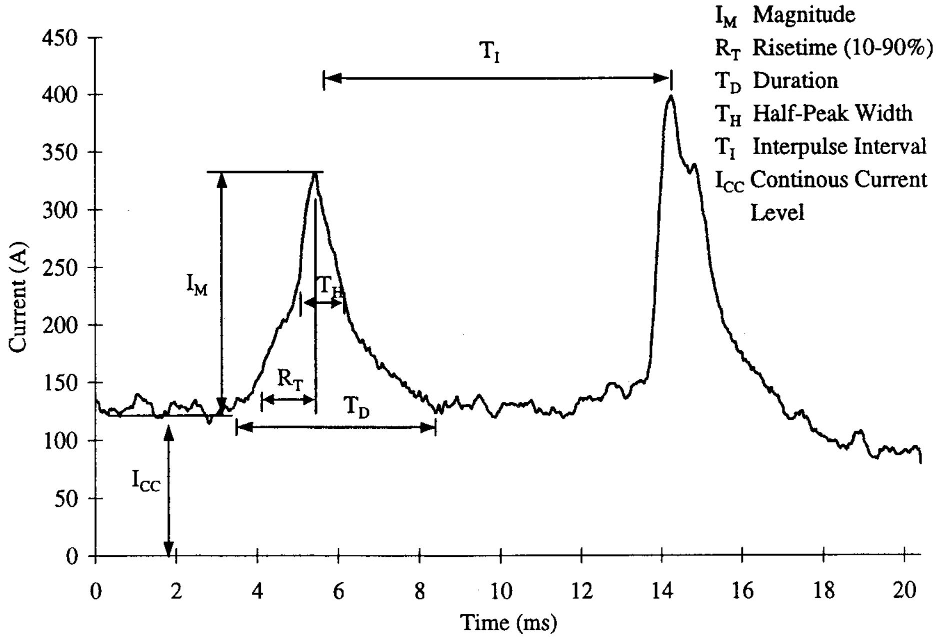


Figure 7. First two initial continuous current (ICC) pulses of Figure 1 on an expanded timescale and inverted, showing the method of measurement of the ICC pulse magnitude I_M, 10-90% risetime R_T, duration T_D, half-peak width T_H, preceding continuous current level I_{CC}, and interpulse interval T_I. The waveforms of the two pulses are moving-averaged using a four-data-point window.

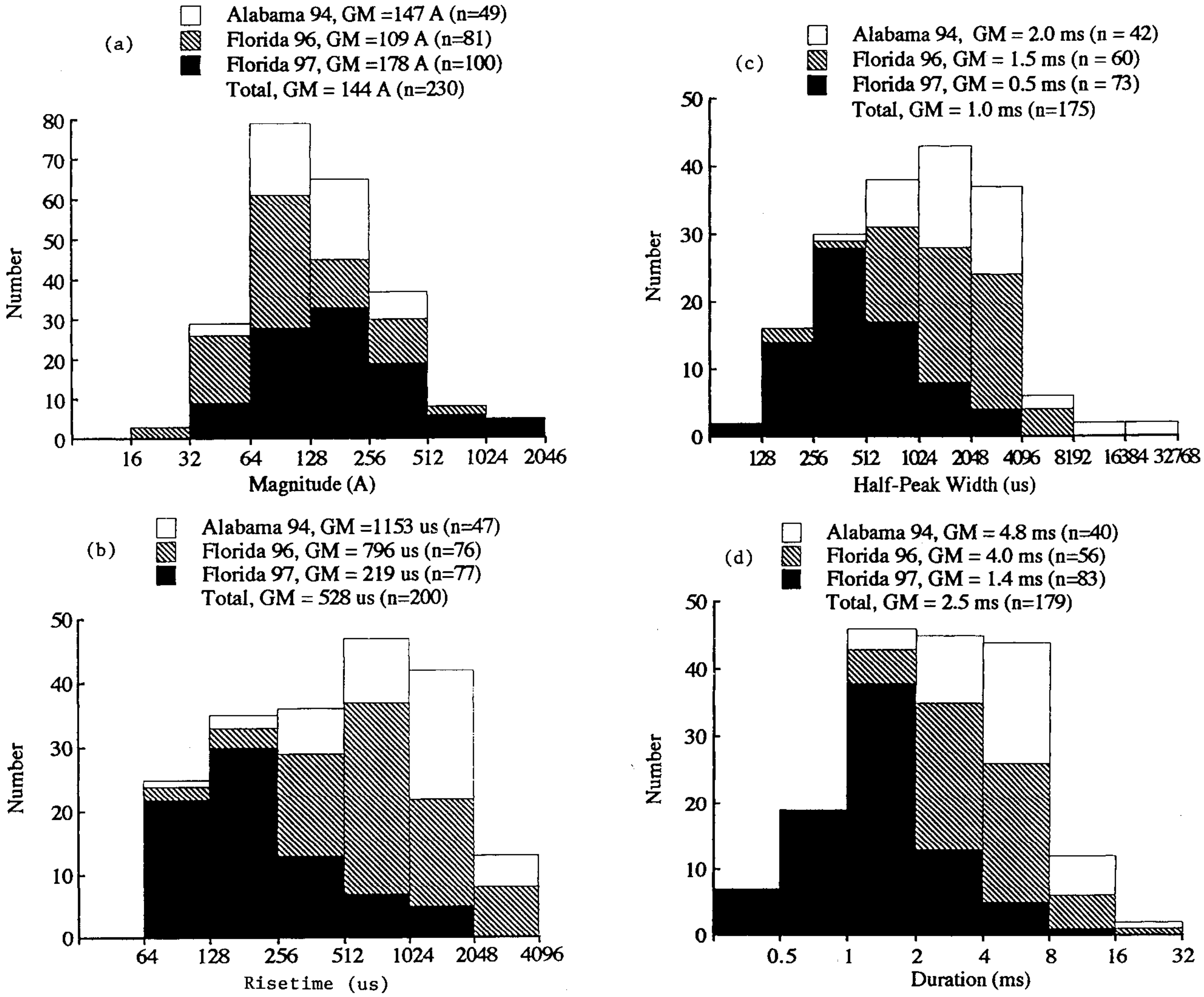


Figure 8. Distribution of initial continuous current (ICC) pulse parameters: (a) magnitude, (b) 10-90% risetime, (c) half-peak width, (d) duration, and (e) charge transferred to ground.

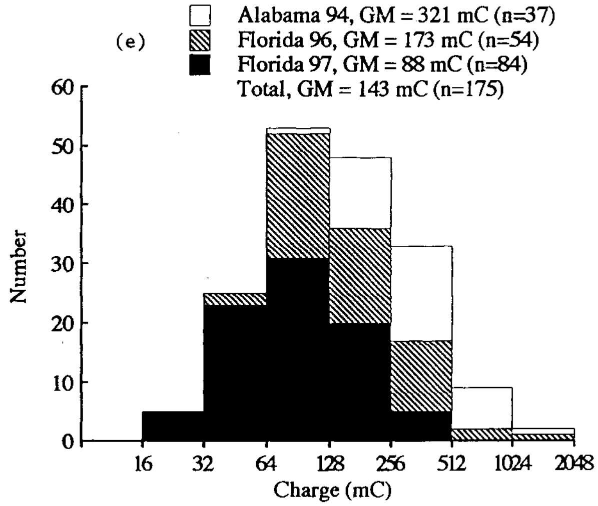


Figure 8. (continued)

are superimposed on the continuing current following return strokes [*Thottappillil et al.*, 1995]. For the pulses overlapping each other, some of parameters such as risetime, half-peak width, duration, and charge could not be adequately measured and therefore were not included in the statistics. Similarly, we did not include the pulse parameters that were limited by the amplitude measurement range (clipped pulses) or by the sampling interval (pulses having less than four data points in their initial rising portion). As a result, our statistics for ICC pulses are somewhat biased toward lower magnitudes and longer risetimes, the statistics for other parameters being less sensitive to the exclusion of unmeasurable or unresolved events. Since the pulses with inadequately resolved initial rising portions (all from the 1997 data set) constitute less than 30% of the 1997 data set (32 out of 109 pulses) and less than 15% of the overall data set (32 out of 232 pulses), the bias introduced is probably not too large.

Figures 8a-8e show, respectively, the distributions of ICC pulse magnitude, risetime, half-peak width, duration, and charge with different shading for different data sets. The distributions of ICC pulse parameters for the 1994 Alabama and 1996 Florida data set, on the one hand, and the 1997 Florida data set, on the other hand, differ significantly. As seen in Figure 8a, pulses in the 1997 Florida data set tend to have larger magnitudes. However, in terms of risetime (Figure 8b), half-peak width (Figure 8c), duration (Figure 8d), and charge (Figure 8e), pulses in the 1997 Florida data set exhibit appreciably lower values than in the 1994 Alabama and the 1996 Florida data. Figures 9a and 9b show, respectively, the distributions of ICC pulse interval and the continuing current level (CC level) at which ICC pulses occur.

The statistical distributions of various parameters of ICC pulses shown in Figures 8 and 9 for all data combined have been compared with the corresponding distributions for *M*-component current pulses given by *Thottappillil et al.* [1995, Figures 3 and 4] and found to be similar. Comparison of the GM values of all the parameters for ICC pulses with their counterparts for *M*-component current pulses is found in Table 1. As seen in Table 1, ICC pulses and *M*-component current pulses have quite similar GM values for all measured parameters. Further, similar to the analysis of *M*-component current pulses [*Thottappillil et al.*, 1995], the various parameters of ICC pulses were also analyzed for correlation between each other. No appreciable difference between ICC pulses and the *M*-component current pulses has been found in this regard. A histogram of the elapsed time to the first ICC pulse from the onset of the IS is given in Figure 10. The GM elapsed time of 94 ms is about 2 orders of magnitude greater than the GM time interval, 1.2 ms, between the first *M*-component current pulse and the preceding return-stroke current pulse, perhaps reflecting the difference between the propagation times from ground to the primary cloud charge source of the upward positive leader and of the return stroke.

4. Concluding Remarks

The initial stage (IS) in negative rocket-triggered lightning is characterized by a channel-base current with a duration of some hundreds of milliseconds, an average magnitude of the order of 100 A, and a charge transferred of some tens of coulombs.

A pronounced initial current variation (ICV), occurs at the beginning of the IS in most of the current records analyzed. The ICV usually involves an abrupt decrease in current followed by a pulse, the current drop being likely associated with the interruption (or attempted interruption) of current due to the

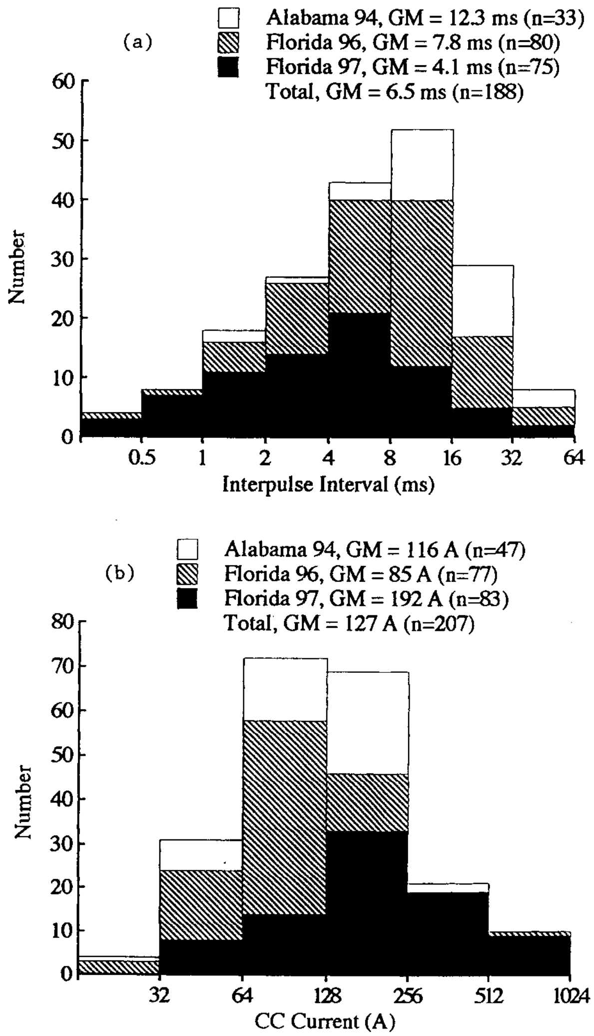


Figure 9. Distributions of (a) ICC interpulse interval and (b) continuous current level just prior to ICC pulses.

Table 1. Comparison of ICC Pulses Studied Here (All Data Combined) and *M*-Component Current Pulses Analyzed by *Thottappillil et al.* [1995]

Type of Pulse	Parameter (GM Value)						
	Magnitude, A	10-90% Risetime, μs	Half-Peak Width, ms	Duration, ms	Charge, mC	CC Level, A	Interpulse Interval, ms
ICC pulse	144	528	1.0	2.5	143	127	6.5
M pulse	117	422	0.8	2.1	129	177	4.9

explosion of the wire used in lightning triggering. At the time of the abrupt decrease in current, the copper wire carries a typical current of about 300 A (sample size = 22), about 3 times the GM average current of the whole IS (sample size = 37), carried primarily by the air plasma channel. It is worth noting, however, that the instantaneous, as opposed to average, current of the IS after the destruction of the triggering wire can be much larger than 300 A. Additionally, we note that a few ICVs had a duration of several milliseconds and transferred to ground a charge of several coulombs, comparable to the charge transferred by individual first strokes in natural lightning.

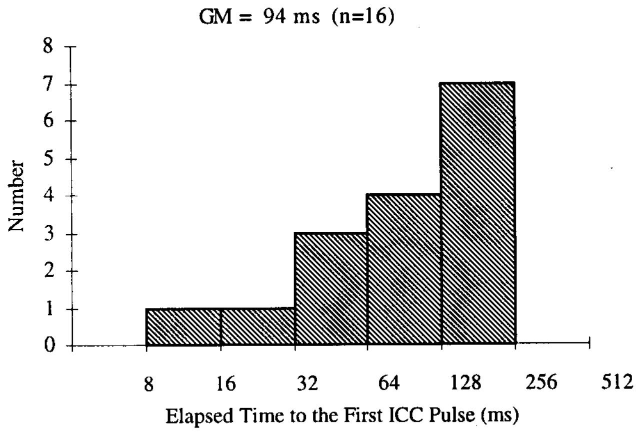


Figure 10. Distribution of elapsed time to the first ICC pulse from the onset of the initial stage.

Eighteen of 37 IS records studied contain pronounced pulses superimposed on the ICC. The characteristics of these pulses (measured from the 16 IS records that are followed by return strokes) appear to vary between data sets. In particular, in the 1997 Florida data, ICC pulses tend to have larger magnitude, shorter risetime, shorter duration, and smaller charge transferred than in the 1996 Florida and 1994 Alabama data. For all data combined, we found that the ICC pulses and *M*-component current pulses have similar characteristics, and hence ICC pulses are likely to be of the same nature as M-component current pulses.

Acknowledgments. This research was supported in part by NSF grants ATM-9415507 (Program Director R.C. Taylor) and ATM-9726100 (Program Director S.P. Nelson) and by the Ministry of Education of Japan. The authors would like to thank H. Shmizu, T.Watanabe, N. Takagi, and M. Chen for their various support, which allowed the first author to perform this study at the University of Florida while on leave from Gifu University, Japan.

References

Berger, K., Novel observations on lightning discharges, results and research on Mount San Salvatore, *J. Franklin Inst.*, *283*, 478-525, 1967.

Brook, M., N. Kitagawa, and E. J. Workman, Quantitative study of strokes and continuing currents in lightning discharges to ground, *J. Geophys. Res.*, *67*, 649-659, 1962.

Fieux, R.P., C.H. Gary, B.P.Hutzler, A.Eybert-Berard, P.L.Hubert, A.C.Meesters, P.H.Perroud, J.H.Hamelin, and J.M. Person, Research on artificially triggered lightning in France, *IEEE Trans. Power Appar. Syst.*, *PAS-97*, 725-733, 1978.

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*, 22,887-22,902, 1993.

Horii, K., Experiment of artificial lightning triggered with rocket, *Mem. Fac. Eng.*, Nagoya Univ., Japan, *34*, 77-112, 1982.

Hubert, P., P. Laroche, A. Eybert-Berard, and L. Barret, Triggered lightning in New Mexico, *J. Geophys. Res.*, *89*, 2511-2521, 1984.

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.

Laroche, P., A. Eybert-Berard, and L.Barret, Triggered lightning flash characterization, paper presented at the 10th International Aerospace and Ground Conference on Lightning and Static Electricity, organized by AAAF, Paris, June 1985.

Morris, E.M., R.J. Fisher, G.H. Schnetzer, K.O. Merewether, and R.E. Jorgenson, Rocket-triggered lightning studies for the protection of critical assets, *IEEE Trans. Ind. Appl. 30*, 791-804, 1994.

Nakamura, K., H. Sakurano, S.Aiba, and K. Horii, Predischarge current and its effect on the electric field in the lightning triggered by a rocket, *Trans. IEE Japan*, *107B*, 8, 381-388, 1987.

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, K.J. Rambo, M.I. Fernandez, A. Eybert-Berard, J.P. Berlandis, P.P. Barker, R.J. Fisher, and G.H. Schnetzer, Initial processes in triggered lightning, *Eos Trans., AGU*, *77*, Fall Meet. Suppl., F86, 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.

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., *The Lightning Discharge*, Academic, San Diego, Calif., 1987.

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, *Trans. IEE Japan*, *117B*, 446-452, 1997.

Williams, D.P. and M. Brook, Magnetic measurement of thunderstorm currents, 1, Continuing currents in lightning, *J. Geophys. Res.*, *68*, 3243-3247, 1963.

M.I. Fernandez, V.A. Rakov, K.J. Rambo, M.A. Uman, and D. Wang, Department of Electrical and Computer Engineering, University of Florida, 553 Eng. Bldg., P.O. Box 116130, Gainesville, FL 32611. (e-mail: rakov@ece.ufl.edu)

R.J. Fisher and G.H. Schnetzer, Consultants to the University of Florida, Gainesville, FL 32611.

(Received June 4, 1998; revised September 3, 1998; accepted November 6, 1998.)