JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 100, NO. D12, PAGES 25,711–25,720, DECEMBER 20, 1995

Properties of M components from currents measured at triggered lightning channel base

Rajeev Thottappillil,[1] Jon D. Goldberg, Vladimir A. Rakov,[2] and Martin A. Uman
Department of Electrical and Computer Engineering, University of Florida, Gainesville

Richard J. Fisher and George H. Schnetzer
Sandia National Laboratories, Albuquerque, New Mexico

Abstract. Channel base currents from triggered lightning were measured at the NASA Kennedy Space Center, Florida, during summer 1990 and at Fort McClellan, Alabama, during summer 1991. An analysis of the return stroke data and overall continuing current data has been published by *Fisher et al.* [1993]. Here an analysis is given of the impulsive processes, called M components, that occur during the continuing current following return strokes. The 14 flashes analyzed contain 37 leader-return stroke sequences and 158 M components, both processes lowering negative charge from cloud to ground. Statistics are presented for the following M current pulse parameters: magnitude, rise time, duration, half-peak width, preceding continuing current level, M interval, elapsed time since the return stroke, and charge transferred by the M current pulse. A typical M component in triggered lightning is characterized by a more or less symmetrical current pulse having an amplitude of 100-200 A (2 orders of magnitude lower than that for a typical return stroke [*Fisher et al.*, 1993]), a 10-90% rise time of 300-500 μs (3 orders of magnitude larger than that for a typical return stroke [*Fisher et al.*, 1993]), and a charge transfer to ground of the order of 0.1 to 0.2 C (1 order of magnitude smaller than that for a typical subsequent return stroke pulse [*Berger et al.*, 1975]). About one third of M components transferred charge greater than the minimum charge reported by *Berger et al.* [1975] for subsequent leader-return stroke sequences. No correlation was found between either the M charge or the magnitude of the M component current (the two are moderately correlated) and any other parameter considered. M current pulses occurring soon after the return stroke tend to have shorter rise times, shorter durations, and shorter M intervals than those which occur later. M current pulses were observed to be superimposed on continuing currents greater than 30 A or so, with one exception out of 140 cases, wherein the continuing current level was measured to be about 20 A. The first M component virtually always (one exception out of 34 cases) occurred within 4 ms of the return stroke. This relatively short separation time between return stroke and the first M component, coupled with the observation of *Fisher et al.* [1993] that continuing currents lasting longer than 10 ms never occur without M current pulses, implies that the M component is a necessary feature of the continuing current mode of charge transfer to ground.

Introduction

This study is an extension of the work done by *Fisher et al.* [1993], who reported on parameters of triggered lightning return strokes in Florida and Alabama. In that paper they established that optical M components [e.g., *Malan and Collens*, 1937] are associated with channel base current pulses that are superimposed on continuing current of some tens to some hundreds of amperes. These M current pulses have amplitudes of typically some hundreds of amperes and rise times of some hundreds of microseconds; that is, they are distinctly different from return stroke current pulses, which occur only after the cessation of any preceding current through the channel base and which typically exhibit submicrosecond rise times [*Fisher et al.*, 1993]. In this paper we present detailed statistical analyses of various parameters of M components as derived from records of the channel base current of triggered lightning in Florida and Alabama. Only M components that follow return strokes, as in natural lightning, are considered here, although M components

[1]Now at Institute of High Voltage Research, Uppsala University, Uppsala, Sweden.

[2]Also at High Voltage Research Institute, Tomsk Polytechnical University, Tomsk, Russia.

Paper number 95JD02734.
0148-0227/95/95JD-02734$05.00

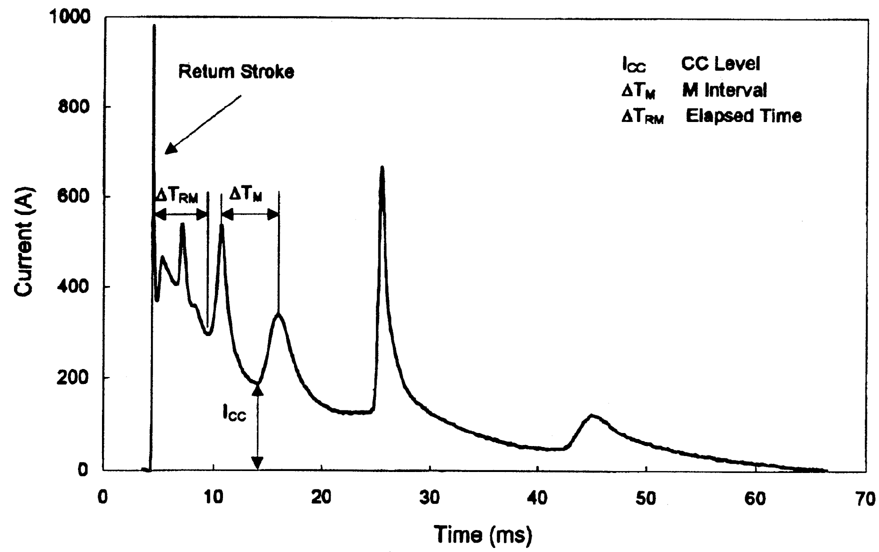


Figure 1. Current record showing one return stroke (saturated at about 1000-A level) followed by several M components in flash 90-02 triggered at KSC in 1990. Shown are the measurements of the continuing current level I_{cc}, M interval ΔT_M, and elapsed time ΔT_{RM}. This record is also reproduced in Figure 8a of *Fisher et al.* [1993].

were also found [*Fisher et al.*, 1993] to occur during the initial continuous current following vaporization of the triggering wire, that is before the first leader-return stroke sequence of triggered lightning.

Data

The triggering facilities and instrumentation used in the 1990 and 1991 triggered lightning experiments in Florida and Alabama, respectively, have been described by *Fisher et al.* [1993]. In Florida the bandwidth, from dc to 1 MHz, of the system used for measuring low-level currents was determined by the characteristic of a fiber-optic link. Currents used in the Florida study were digitized at a 40-μs sampling interval on two channels, one having a 1-kA upper limit and a noise floor of about 4 A and the other with a 75-A upper limit and a noise floor of less than 2 A. The currents in the Florida experiment were additionally tape recorded on two channels with a bandwidth from dc to 400 kHz and upper amplitude limits of about 1 kA and 75 A. In Alabama, currents used in this study were tape-recorded with a system 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 from both Florida and Alabama were later digitized with a sampling interval of 0.2 μs.

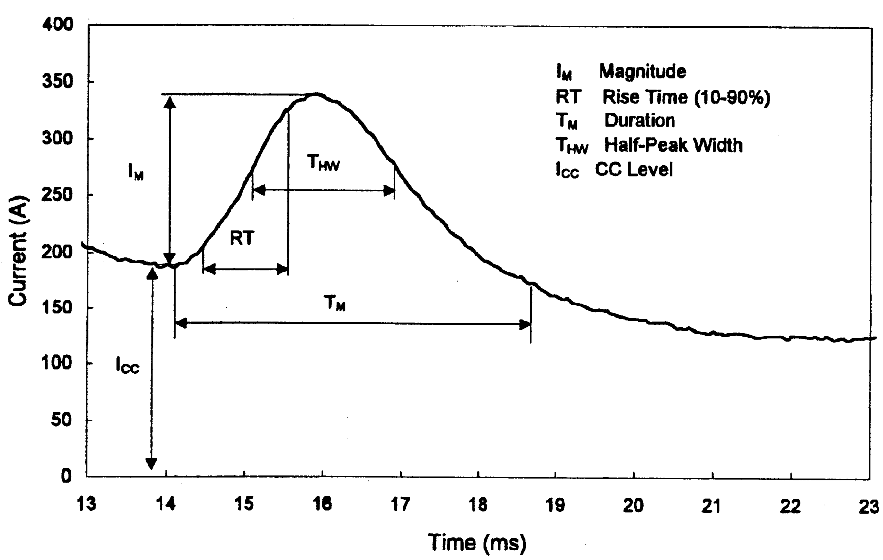


Figure 2. An expanded portion of the current record of Figure 1 showing the measurements of the M current magnitude I_M, 10-90% rise time RT, duration T_M, and half-peak width T_{HW}.

Figure 1 shows a typical current record for one return stroke followed by several M components. Figure 2 shows an expanded portion of the record of Figure 1. Figures 1 and 2 illustrate how the various measured parameters are defined: M current magnitude is the difference between the peak of the M component current pulse and the preceding continuing current level. M current rise time (10-90%) is the time interval on the wavefront between the 10% and 90% values of the magnitude. M current duration is the time interval measured from the beginning of the wave front (identified as the initial deflection from the preceding continuing current level) to the somewhat subjectively selected point at which the trailing edge of the M current pulse becomes indistinguishable from the overall continuing current waveform. M current half-peak width is the time interval between the 50% values of the magnitude on the wave front and on the falling portion of the M pulse. M charge is the time integral of the M current above the continuing current. Continuing current (CC) level is the value of the continuing current immediately preceding the M current pulse. M interval is the time interval between the peak values of successive M current pulses. Elapsed time is the time interval between the beginning of the wave front of the return stroke and the beginning of the wave front of the M component.

There were a total of 158 M current pulses identified in the channel base current records. Sixteen had peak values which exceeded the upper limit of the recorder.

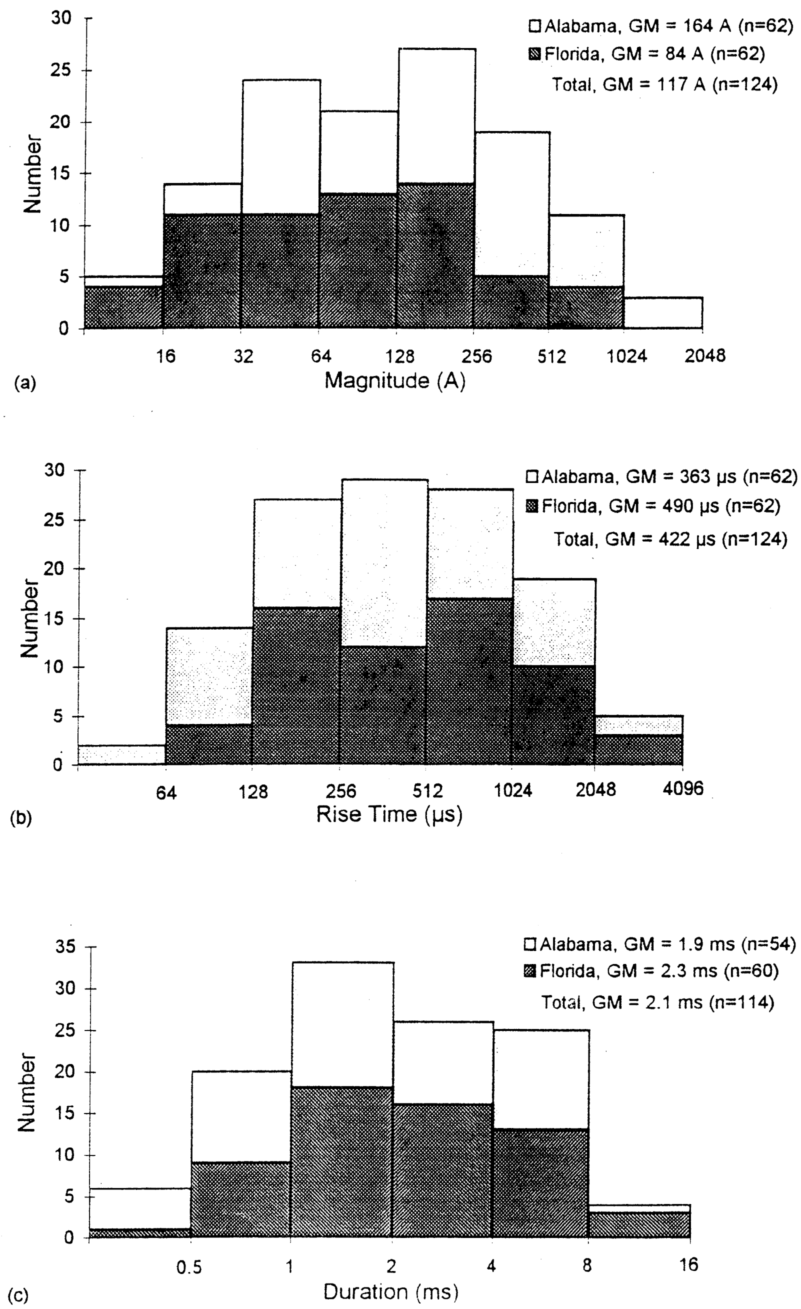
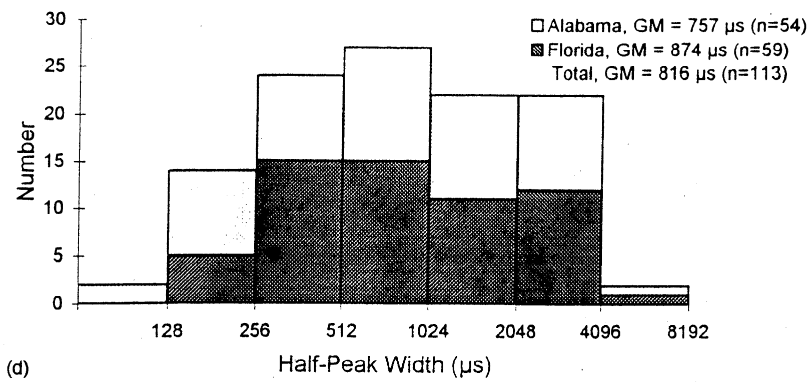
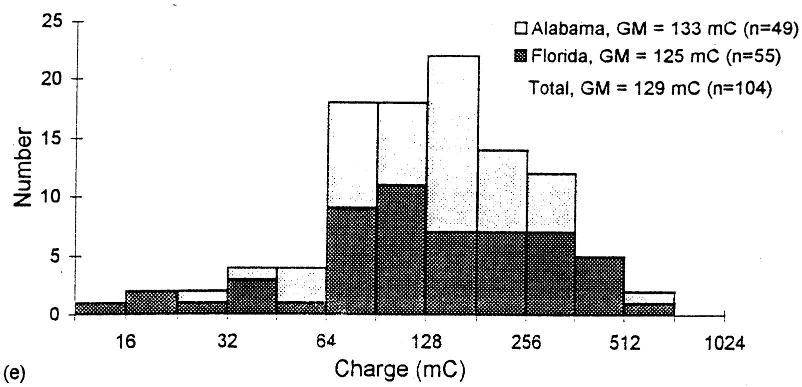


Figure 3. Distributions of individual M current pulse parameters: (a) magnitude, (b) 10-90% rise time, (c) duration, (d) half-peak width, and (e) charge transferred to ground. See text and Figure 2 for definitions of the parameters.

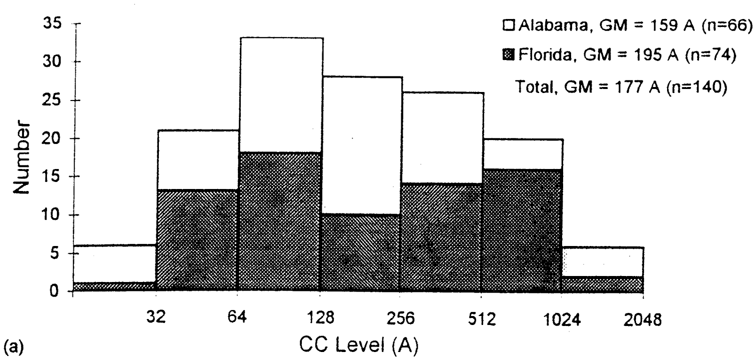


(d)

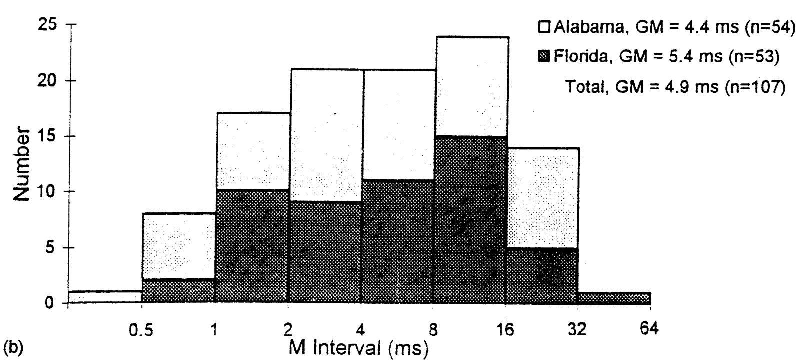


(e)

Figure 3. (continued)

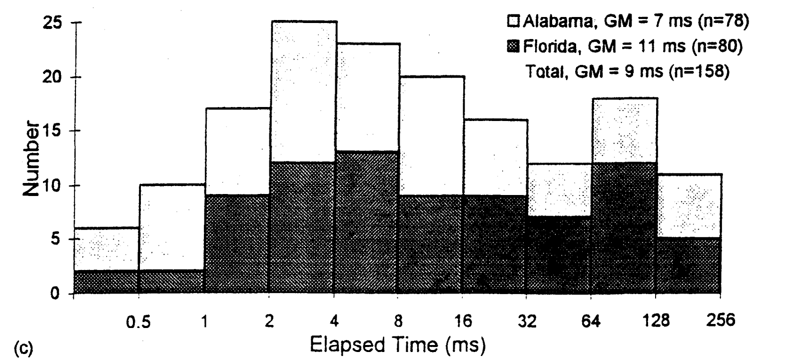


(a)



(b)

Figure 4. Distributions of (a) continuing current level just prior to M current pulse, (b) M interval, (c) elapsed time since the return stroke, and (d) elapsed time for the first M component. See text and Figure 1 for definitions of the parameters.



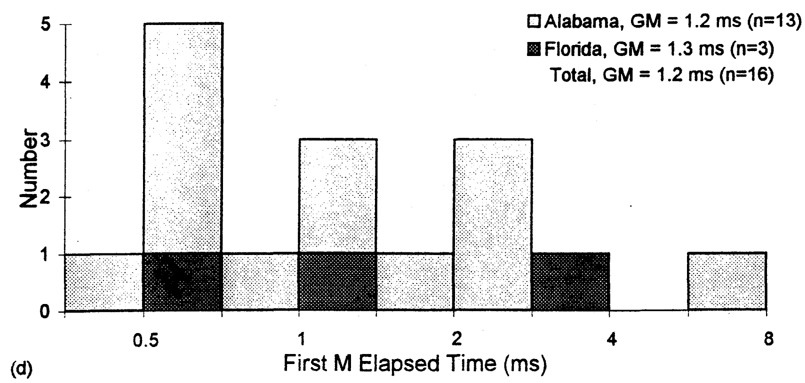


Figure 4. (continued)

Parameters of these saturated M current pulses, with the exception of elapsed time, were not included in the analysis. Of the remaining 142, some were overlapping with each other and hence did not allow an unambiguous measurement of such parameters as rise-time, duration, half-peak width and charge. As a result, some of the parameters of such M components were not measured. These overlapping M components (typically coming in pairs) tend to occur during the first 5 ms following the return stroke.

Analysis and Discussion

Figures 3a through 3e show the distributions of individual M current pulse parameters: magnitude, rise time,

Table 1. Summary of Statistics on M Component Parameters From Florida and Alabama Combined

Parameter	Sample Size	GM	Cases Exceeding Tabulated Value			
			SD $\log_{10}(x)$	95%	50%	5%
Magnitude, A	124	117	0.50	20	121	757
Rise time, μs	124	422	0.42	102	415	1785
Duration, ms	114	2.1	0.37	0.6	2.0	7.6
Half-peak width, μs	113	816	0.41	192	800	3580
Charge, mC	104	129	0.32	33	131	377
CC level, A	140	177	0.45	34	183	991
M interval, ms	107	4.9	0.47	0.8	4.9	23
Elapsed time, ms	158	9.1	0.73	0.7	7.7	156

GM and SD are the geometric mean value and standard deviation, respectively.

duration, half-peak width, and charge. The distributions of M current magnitude for the two data sets differ significantly. The geometric mean values are 164 and 84 A for Alabama and Florida, respectively. The fraction of larger-magnitude M current pulses is greater in Alabama than in Florida. The difference in the geometric means could be exaggerated because of the exclusion of saturated M current pulses from the statistics. In the Alabama data, five of the M components exceeded the saturation level of 2000 A, compared to 11 in the Florida data that reached the saturation level of 1000 A. In the Alabama data, if we exclude all events (11 total) that exceed the 1000-A level, that is, if we simulate the Florida saturation level, the geometric mean current magnitude is 121 A, closer to the value for Florida. The geometric mean rise times are more or less similar, 363 and 490 μs for Alabama and Florida, respectively, and are about 3 orders of magnitude larger than those for the return stroke current pulses [*Fisher et al.*, 1993]. The geometric mean values for M current duration are 1.9 and 2.3 ms for Alabama and Florida, respectively, 2-3 times larger than the geometric mean duration of the hook-shaped M component electric fields in natural lightning estimated by *Thottappillil et al.* [1990] from their measurements in Florida. The distributions for half-peak width are characterized by geometric mean values of 757 and 874 μs for Alabama and Florida, respectively.

The geometric mean values for M component charge are similar for both locations, 133 and 125 mC for Alabama and Florida, respectively. From the distributions it can be seen that most of the M components transfer charge in excess of 64 mC to ground, although values as low as 10-20 mC were observed. Note that the minimum charge transferred to ground by a subsequent leader-return stroke sequence in natural lightning was estimated by *Brook et al.* [1962], from single-station electric field measurements in New Mexico, to be 0.22 C, similar to the minimum value of the so-called impulse charge reported for negative subsequent strokes by *Berger et al.* [1975, Figure 4]. The order of magnitude difference in minimum charge for M components and for leader-return stroke sequences might be related to the status of the channel, a smaller minimum charge being required at the top of the channel to drive an M wave [*Rakov et al.*, this issue] all the way to ground along the better conditioned current-carrying channel than for a leader wave which traverses a decaying channel effectively disconnected from ground. The minimum charge required for a stepped leader to forge its way to ground has been inferred to be about 3 C [*Brook et al.*, 1962; *Proctor et al.*, 1988], although the minimum value observed by *Berger et al.* [1975, Figure 4] was about 0.4-0.5 C.

Figures 4a through 4c show the distributions of continuing current level, M interval, and elapsed time. The geometric mean values of continuing current level for both locations are more or less similar, 159 and 195 A for Alabama and Florida, respectively. It follows from these distributions that roughly 95% of the M components occur when the continuing current level is above 32 A. Further, there was only one case in 140 when the continuing current was less than 30 A or so, the continuing current in that case being about 20 A. *Krehbiel et al.* [1979] reported values of continuing current, averaged typically over 10- to 20-ms time intervals, from 50 to 580 A. The apparent existence of a minimum continuing current level that allows the development of an M component might be related to the dependence between the longitudinal electric field strength E in the arc channel and arc current I [*King*, 1962]. The derivative of E with respect to I is the differential resistance of the arc per unit length. This resistance is negative for currents below 50 A or so and about zero for higher currents. When a relatively high (say, hundreds of amperes) continuing current, which is in fact a quasi-stationary arc, starts to decay, the resistance $R = E/I$ per unit channel length increases, the rate of increase being relatively small for currents above 50 A or so and significantly larger for lower currents. Therefore we hypothesize that channels that carry less than 30 A or so are very unlikely to be able to support an M component. *Heckman* [1992] predicted that the "minimum stable current" for a lightning channel increases with the channel length and is 100 A for a 3 km long channel. Since the negative charge in Florida thunderclouds is typically located at about 7.5 km [e.g., *Krehbiel*, 1981], it appears that the latter assertion is not supported by our data. The distributions for M interval show fairly similar geometric mean values for both locations, 4.4 and 5.4 ms for Alabama and Florida, respectively. The geometric mean values for elapsed time of all M components are 7 and 11 ms for Alabama and Florida, respectively. The geometric mean values of elapsed time between the return stroke and the first M component, 1.2 and 1.3 ms, for Alabama (13 values) and Florida (3 values), respectively, are about 4 times shorter than the geometric mean values of M interval. Since M components may occur within as short a time as a few hundred microseconds of the return stroke [e.g., *Jordan et al.*, this issue], 21 cases in which the saturated portion of the return stroke current pulse lasted longer than 200 μs were not included in the statistics on the elapsed time between the return stroke and the first M component. It follows that these statistics may be biased toward smaller strokes. The distribution of the elapsed time for the first M component is shown in Figure 4d. The first M component virtually always occurs within 4 ms of the return stroke (one exception in 34 cases which include those 21 in which the saturated portion of the return stroke current pulse lasted longer than 200 μs but the first detected M pulse occurred within 4 ms), perhaps marking the transition from the return stroke to a continuing current mode of charge transfer to ground, as suggested by *Rakov et al.* [1990] and *Fisher et al.* [1993]. Further, *Thottappillil et al.* [1990] reported that 84% of the 38 first M components in Florida natural lightning occurred within 3 ms of the return stroke. Finally, *Fisher et al.* [1993] never observed continuing currents lasting longer than 10 ms occurring without the presence of an M component. Thus we speculate that the M components serve to provide channel conditions suitable for the continuing current mode of charge transfer to ground.

Table 1 summarizes statistics on the parameters measured, with the data from Florida and Alabama combined. For most of the parameters the geometric mean and 50% values are very similar, suggesting that these parameters are lognormally distributed. The 50% value of M current magnitude, 121 A, is 2 orders of

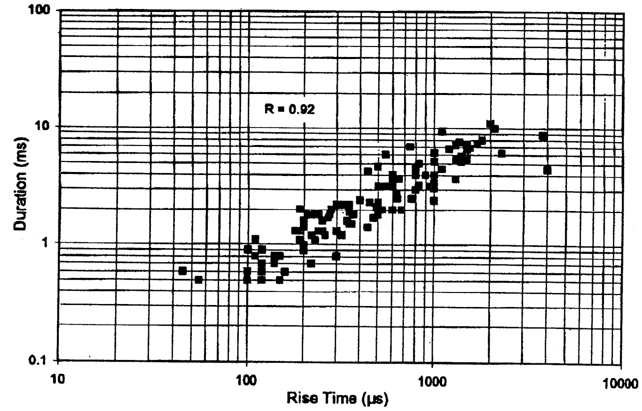


Figure 5. Duration versus 10-90% rise time.

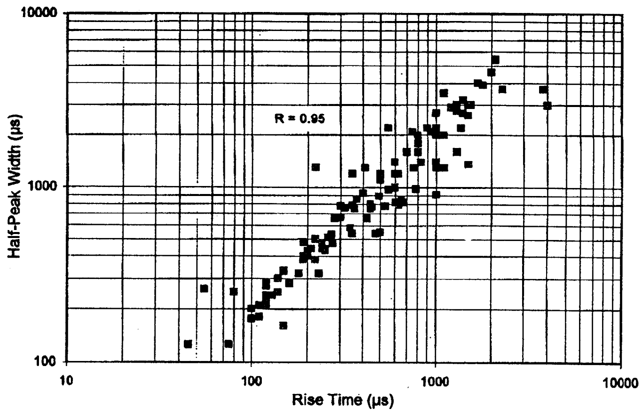


Figure 6. Half-peak width versus 10-90% rise time.

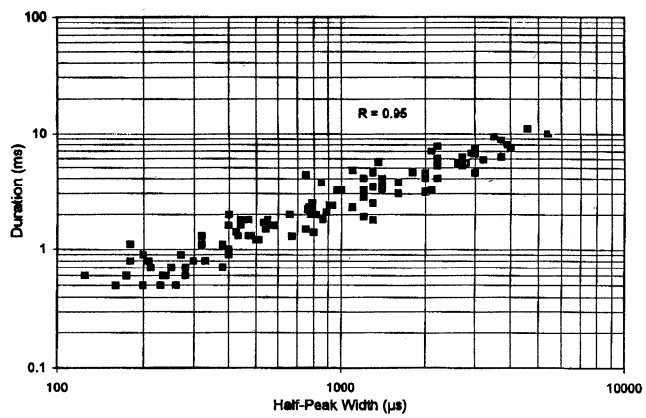


Figure 7. Duration versus half-peak width.

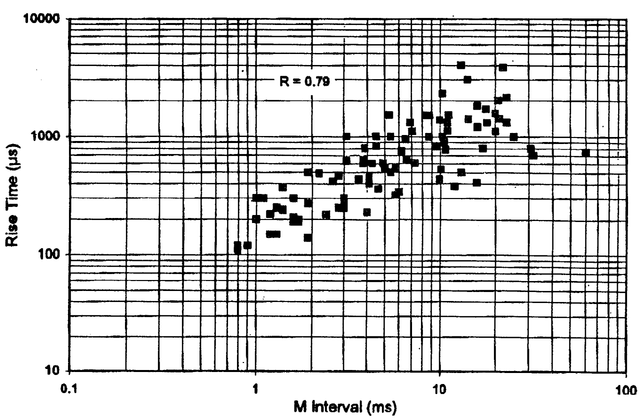


Figure 8. The 10-90% rise time versus M interval.

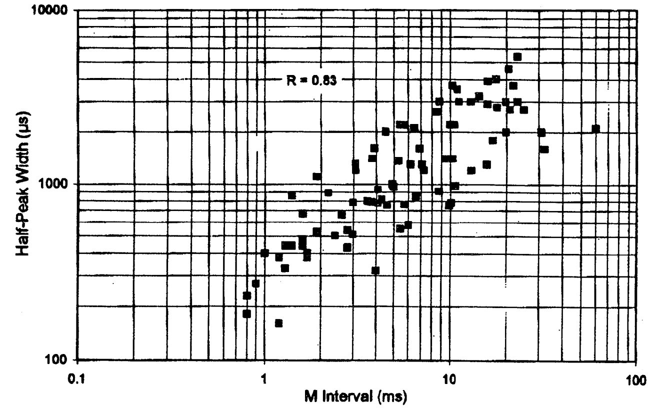


Figure 9. Half-peak width versus M interval.

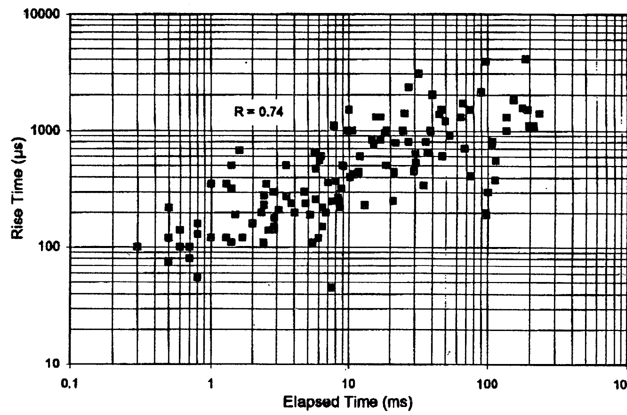


Figure 10. The 10-90% rise time versus elapsed time since the return stroke.

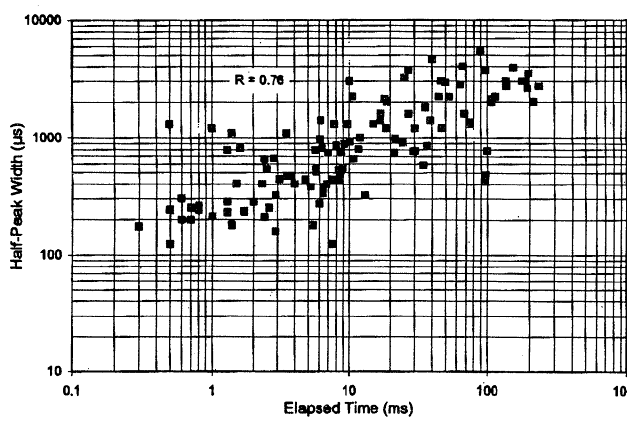


Figure 11. Half-peak width versus elapsed time since the return stroke.

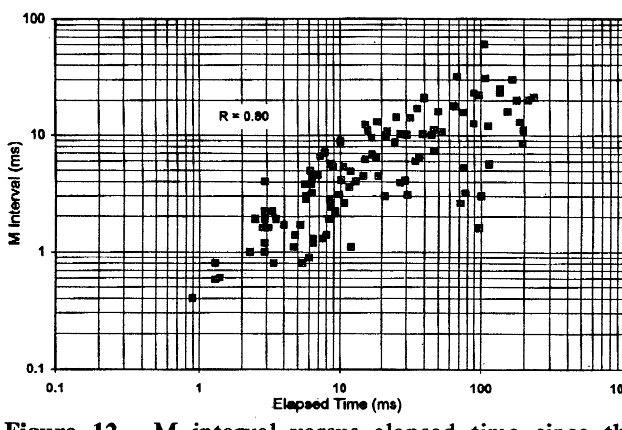


Figure 12. M interval versus elapsed time since the return stroke.

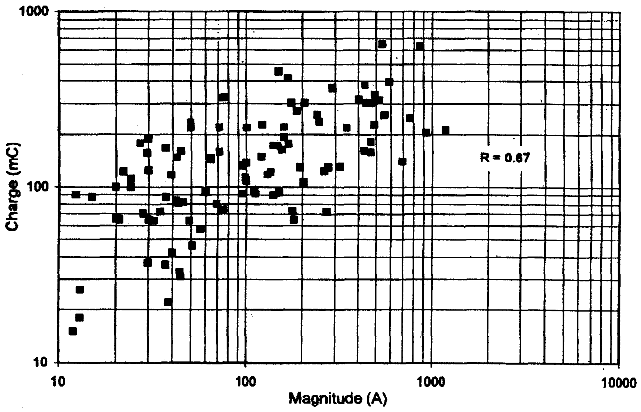


Figure 13. Charge versus current magnitude.

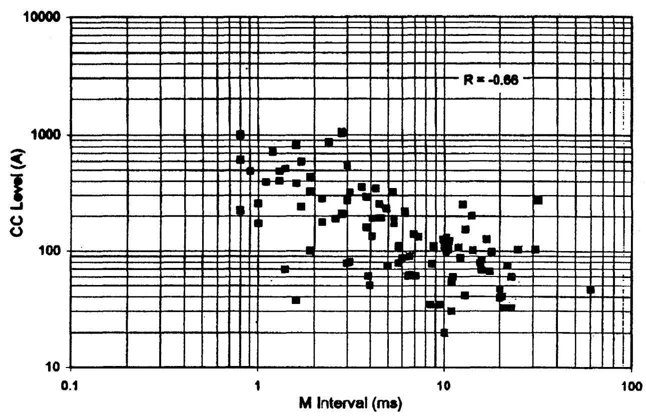


Figure 14. Continuing current level versus M interval.

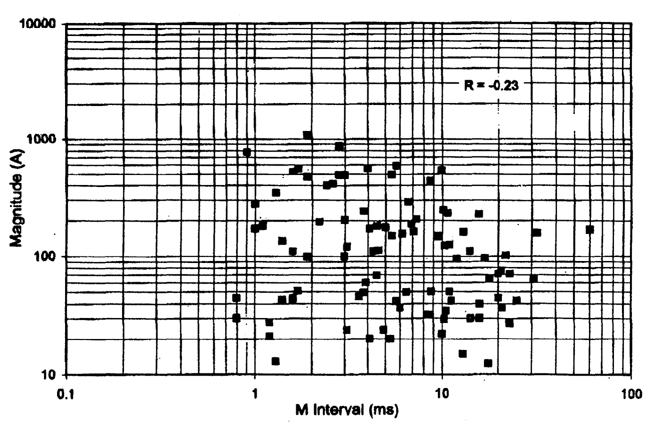


Figure 15. M current magnitude versus M interval.

magnitude smaller than the 50% value of current associated with subsequent strokes of either natural [*Berger et al.*, 1975] or triggered [*Fisher et al.*, 1993] lightning. However, since the 50% value of M current rise time is 3 orders of magnitude longer than that for the return stroke current, one should expect a relatively small difference in charge associated with return strokes and M components. Indeed, the 50% value of M charge is only 1 order of magnitude lower than that observed for natural lightning negative subsequent strokes (the so-called "impulse charge") by *Berger et al.* [1975]. About one third of M components transferred charge greater than the minimum charge (about 0.2 C) reported by *Berger et al.* [1975, Figure 4] for subsequent leader-return stroke sequences. Further, since M components are more numerous than return strokes (the proportion being 4 to 1 in our data), the total charges transferred by the two lightning processes within a flash are probably of the same order of magnitude. The 50% time interval between M current pulses, 4.9 ms, is about an order of magnitude shorter than the 50% interval between return stroke pulses, 48 ms, reported by *Fisher et al.* [1993].

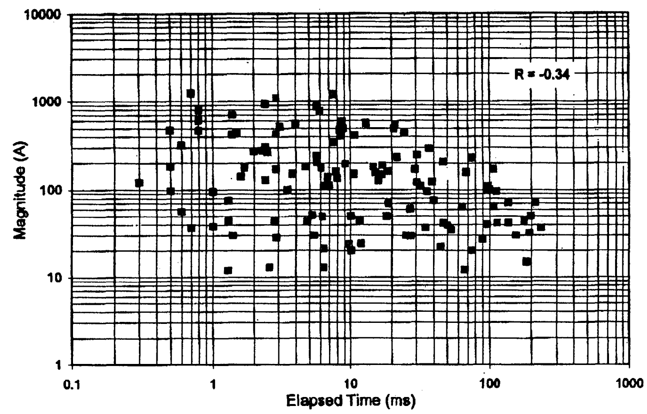


Figure 16. M current magnitude versus elapsed time since the return stroke.

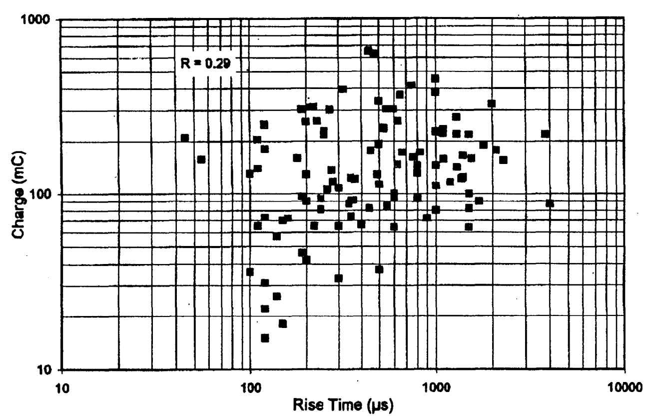


Figure 17. Charge versus 10-90% rise time.

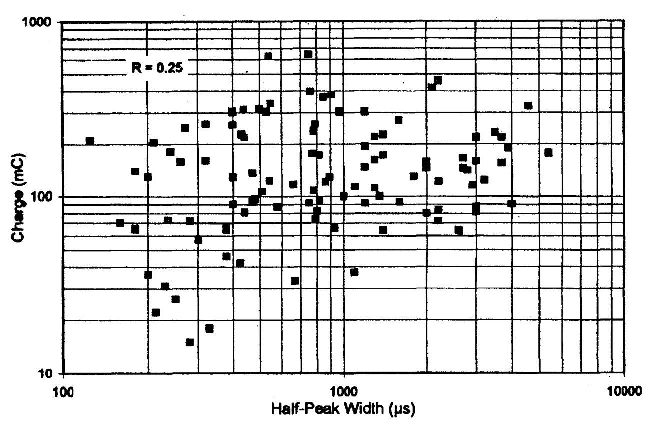


Figure 18. Charge versus half-peak width.

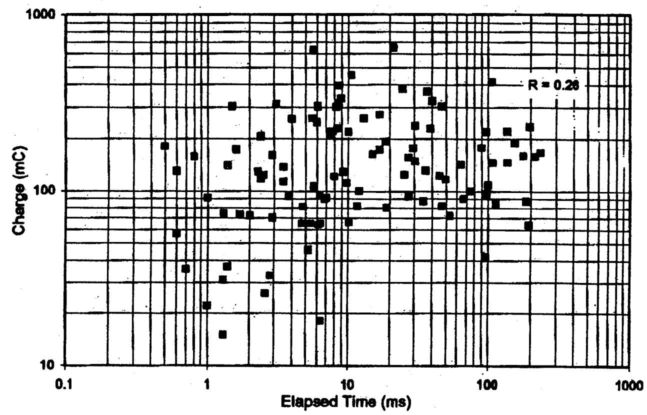


Figure 19. Charge versus elapsed time since the return stroke.

The various parameters measured were analyzed for correlation between each other. The scatterplots are shown in Figures 5 through 19 for the logarithms of the selected parameters. Table 2 gives the linear correlation coefficients between the logarithms of the parameters. The logarithms were used because a better linear correlation was observed between the logarithms of the parameters than between the parameters themselves. This is indicative of a power (as opposed to a linear) relationship between the parameters. The correlation coefficients given on the scatterplots are based on a linear correlation between the logarithms of the parameters.

There is a relatively strong correlation (correlation coefficients from 0.74 to 0.95) between all time characteristics of M current pulses (see Figures 5-12). As the elapsed time from the return stroke or from the immediately preceding M pulse (the two are correlated to each other) increases, individual M current pulses appear to widen. There is a moderate correlation between the M current magnitude and M charge (correlation coefficient 0.67; Figure 13) and between the level of continuing current just prior to M current pulse and M interval (correlation coefficient -0.66; Figure 14). There is some negative correlation between the continuing current level and the time characteristics of the M current pulses (correlation coefficients from -0.50 to -0.58), indicating that there is a tendency for M pulses to be somewhat sharper as continuing current level increases. The latter observation is not in support of *Heckman*'s [1992] prediction that the higher-frequency components in the M current pulse should be more attenuated in higher-current channels than in lower-current ones. There is essentially no correlation between either M current magnitude or M charge and any of the time characteristics of M current pulses (see Figures 15-19). The M current magnitude and M charge also appear independent of the preceding continuing current level.

Summary and Conclusions

Overall, the M current pulse statistics from Florida and Alabama, as obtained from the measured channel base currents, are similar, except for the M current magnitude whose geometric mean value in Alabama is about twice the value for Florida. As demonstrated earlier, the latter

Table 2. Linear Correlation Coefficients Between Logarithms of M Component Parameters

	Magnitude	Rise Time	Duration	Half-Peak Width	Charge	CC Level	M Interval	Elapsed Time
Magnitude	1	-0.41	-0.32	-0.42	0.67	0.12	-0.23	-0.34
Rise time		1	0.92	0.95	0.29	-0.53	0.79	0.74
Duration			1	0.95	0.36	-0.50	0.77	0.74
Half-peak width				1	0.25	-0.58	0.83	0.76
Charge					1	-0.20	0.34	0.26
CC level						1	-0.66	-0.46
M interval							1	0.80
Elapsed time								1

difference is due, at least in part, to differences in saturation levels of the measuring systems used at the two sites. A typical M component is characterized by a more or less symmetrical current pulse having (1) an amplitude of 100-200 A (2 orders of magnitude lower than that for a return stroke [*Fisher et al.*, 1993]), (2) a rise time of 300-500 μs (3 orders of magnitude longer than that for a return stroke [*Fisher et al.*, 1993]), and (3) a charge transfer to ground of the order of 0.1 to 0.2 C (1 order of magnitude smaller than that for a subsequent return stroke pulse [*Berger et al.*, 1975]). About one third of M components, which outnumber return strokes 4 to 1, transferred charge greater than the minimum charge associated with negative subsequent leader-return stroke sequences (the so-called "impulse charge" reported by *Berger et al.* [1975]). M current pulses were observed when the continuing current at the channel bottom was greater than 30 A or so, with one exception of 140 cases, wherein that current was about 20 A. The first M component virtually always (one exception in 34 cases) occurs no later than 4 ms after the return stroke. There is essentially no correlation between either the M current magnitude or M charge transferred to ground and any other parameter considered herein, suggesting that these two parameters (moderately correlated with each other) are independent of the elapsed time from the return stroke or from the preceding M pulse, independent of the continuing current level, and independent of the shape of the M current pulse. M current pulses occurring later after the return stroke are separated by longer time intervals and tend to be wider.

Acknowledgments. This research was funded in part by NSF grants ATM 9014085 and ATM-9415507 (Program Director R. C. Taylor); by DOE contract DE-AC04-76DP00789; and by the Armament Research, Development and Engineering Center of the Department of the Army.

References

Berger, K., R. B. Anderson, and H. Kroninger, Parameters of lightning flashes, *Electra*, *80*, 23-37, 1975.

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

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.

Heckman, S., Why does a lightning flash have multiple strokes?, Ph.D. dissertation, Mass. Inst. of Technol., Cambridge, 1992.

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.*, this issue.

King, L. A., The voltage gradient of the free burning arc in air or nitrogen, in *Proceedings of the 5th International Conference on Ionization Phenomena in Gases*, pp. 871-877, North Holland, New York, 1962.

Krehbiel, P. R., An analysis of the electric field change produced by lightning, Ph.D. thesis, Inst. of Sci. and Technol., Univ. of Manchester, Manchester, England, 1981. (Available as *Rep. T-11*, *Geophys. Res. Cent.*, N. Mex. Inst. of Mining and Technol., Socorro, 1981.)

Krehbiel, P. R., M. Brook, and R. A. McCrory, An analysis of the charge structure of lightning discharges to ground, *J. Geophys. Res.*, *84*, 2432-2456, 1979.

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

Proctor, D. E., R. Uytenbogaardt, and B. M. Meredith, VHF radio pictures of lightning flashes to ground, *J. Geophys. Res.*, *93*, 12,683-12,727, 1988.

Rakov, V. A., M. A. Uman, D. M. Jordan, and C. A. Priore III, Ratio of leader to return stroke electric field change for first and subsequent lightning strokes, *J. Geophys. Res.*, *95*, 16,579-16,587, 1990.

Rakov, V. A., R. Thottappillil, M. A. Uman, and P. P. Barker, Mechanism of the lightning M component, *J. Geophys. Res.*, this issue.

Thottappillil, R., V. A. Rakov, and M. A. Uman, K and M changes in close lightning ground flashes in Florida, *J. Geophys. Res.*, *95*, 18,631-18,640, 1990.

J. D. Goldberg, V. A. Rakov (corresponding author) and M. A. Uman, Department of Electrical and Computer Engineering, University of Florida, 216 Larsen Hall, P.O. Box 1116200, Gainesville, FL 32611. (e-mail: rakov@admin.ee.ufl.edu; muman@admin.ee.ufl.edu)

R. J. Fisher and G. H. Schnetzer, Sandia National Laboratories, Albuquerque, NM 87185.

R. Thottappillil, Institute of High Voltage Research, Uppsala University, Husbyborg, S-752 28 Uppsala, Sweden. (e-mail: rajeev.thottapillil@hvi.uu.se)

(Received February 28, 1995; accepted August 22, 1995.)