Parameters of Rocket-Triggered Lightning

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Abstract—Various parameters of triggered lightning derived from measurements of current at the lightning channel base are reviewed. Correlations between parameters are examined. New insights into lightning termination on ground gained from triggered-lightning experiments are discussed.

Keywords—Rocket-triggered lightning, parameters, return-stroke peak current, current derivative, charge transfer,

I. INTRODUCTION

The rocket-and-wire technique has been used since the 1970s to artificially initiate (trigger) lightning from natural thunderclouds for purposes of research and testing. To date, approximately 1,000 lightning flashes were triggered using the rocket-and-wire technique, with over 300 of them at Camp Blanding, Florida. Leader/return stroke sequences in triggered lightning are similar in most (if not all) respects to subsequent leader/return stroke sequences in natural downward lightning and to all such sequences in object-initiated lightning. The initial processes in triggered lightning are similar to those in object-initiated (upward) lightning and are distinctly different from the first leader/return stroke sequence in natural downward lightning. The results of triggered-lightning experiments have provided considerable insight into natural lightning processes that would not have been possible from studies of natural lightning due to its random occurrence in space and time. Also, triggered-lightning experiments have contributed significantly to testing the validity of various lightning models and to providing ground-truth data for the U.S. National Lightning Detection Network (NLDN).

In this review paper, we discuss return-stroke current peak and current waveform parameters including current derivative peak (dI/dt), risetime, average rate of rise (steepness), and half-peak width. We will also consider correlations among the various parameters listed above.

II. RETURN-STROKE PEAK CURRENT AND CURRENT DERIVATIVE

Statistical characteristics of measured return-stroke currents, I, and derivatives of current with respect to time, dI/dt, were examined in detail by Schoene *et al.* (2003) [1]. They are presented in Tables 1 and 2, respectively. The geometric mean values of current peak range from about 12 to 15 kA. These values are similar to the median value of 12 kA reported by Anderson and Eriksson (1980) [2] for subsequent strokes in natural lightning. The geometric mean values of dI/dt peak based on data from two studies considered by Schoene *et al.* (2003) [1] are 73 and 97 kA μs^{-1}.

Fisher *et al.* (1993) [3] compared a number of return-stroke current parameters for classical triggered-lightning strokes from Florida and Alabama with the corresponding parameters for natural lightning in Switzerland reported by Berger *et al.* (1975) [4] and Anderson and Eriksson (1980) [2]. Distributions of peak currents are very similar, with median values being 13 and 12 kA for triggered and natural lightning, respectively. On the other hand, there appear to be appreciable differences between the triggered-lightning data of Fisher et al. (1993) [3] and the natural-lightning data of Berger *et al.* (1975) [4] and Anderson and Eriksson (1980) [2] in terms of current wavefront parameters, half-peak width, and stroke charge. The shorter risetime and higher average slope (steepness) in the triggered-lightning data may be explained by the better time resolution of the measuring systems used in the triggered-lightning studies.

III. CORRELATIONS BETWEEN PARAMETERS

Leteinturier *et al.* (1991) [5] presented scatter plots of dI/dt peak vs. I peak from the triggered lightning experiments in Florida (1985, 1987, and 1988) and in France (1986). Correlation coefficients are 0.87, 0.80, and 0.70 for the 1985, 1987, and 1988 Florida data, respectively, and 0.78 for the 1986 data from France. The largest measured value of dI/dt is 411 kA μs^{-1}, as reported from Florida (KSC) studies. The corresponding measured peak current is greater than 60 kA, the largest value of this parameter reported for summer triggered lightning to date.

Fisher *et al.* (1993) [3] studied relations among several return-stroke parameters (see Fig. 1). They found a relatively strong positive correlation between the 10-90 percent average steepness (S-10) and current peak (correlation coefficient = 0.71) and between the 30-90 percent average steepness (S-30) and current peak (correlation coefficient = 0.74). Essentially no linear correlation was found between current peak and 10-90 percent risetime.

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TABLE 1
CURRENT WAVEFORM PARAMETERS FOR NEGATIVE ROCKET-TRIGGERED LIGHTNING
ADAPTED FROM SCHOENE *ET AL.* (2003) [1]

Location/Year	n	Min.	Max.	Arithmetic Mean	σ	Geometric Mean	σ_{log}	Reference[b]
				Current Peak, kA				
Kennedy Space Center, Florida; 1985–1991	305	2.5	60.0	14.3	9.0	-	-	1
Saint-Privat d'Allier, France; 1986, 1990–1991	54	4.5	49.9	11.0	5.6	-	-	1
Kennedy Space Center, Florida and Fort McClellan, Alabama; 1990, 1991	45	-	-	-	-	12	0.28	2
Camp Blanding, Florida; 1993	37	5.3	44.4	15.1	-	13.3	0.23	3
Camp Blanding, Florida; 1997	11	5.3	22.6	12.8	5.6	11.7	0.20	4
Camp Blanding, Florida; 1998	25	5.9	33.2	14.8	7.0	13.5	0.19	5
present study	64	5	36.8	16.2	7.6	14.5	0.21	
				Current 10–90% Risetime, ns				
Kennedy Space Center, Florida and Fort McClellan, Alabama; 1990, 1991	43	-	-	-	-	370	0.29	2
Saint-Privat d'Allier, France; 1990–1991	37	250	4900	1140	1100	-	-	1
Camp Blanding, Florida; 1997	11	300	4000	900	1200	600	0.39	4
				Current 30–90% Risetime, ns				
Kennedy Space Center, Florida and Fort McClellan, Alabama; 1990, 1991	43	-	-	-	190	280	0.28	2
present study	65	54	1751	260	316	191	0.29	
				Current Half-Peak Width, μs				
Saint-Privat d'Allier, France; 1990–1991	24	14.7	103.2	49.8	22.4	-	-	1
Kennedy Space Center, Florida and Fort McClellan, Alabama; 1990, 1991	41	-	-	-	-	18	0.30	2
Camp Blanding, Florida; 1997	11	6.5	100	35.7	24.6	29.4	0.29	4
present study	64	2.4	37.2	13.2	8.5	10.5	0.32	

[a]The polarity of the peak values is ignored.
[b]References: 1, *Depasse* [1994a]; 2, *Fisher et al.* [1993]; 3, *Rakov et al.* [1998]; 4, *Crawford* [1998]; 5, *Uman et al.* [2000].

TABLE 2
CURRENT DERIVATIVE WAVEFORM PARAMETERS FOR NEGATIVE ROCKET-TRIGGERED LIGHTNING
ADAPTED FROM SCHOENE *ET AL.* (2003) [1]

Location/Year	n	Min.	Max.	Arithmetic Mean	σ	Geometric Mean	σ_{log}
				dI/dt Peak, kA/μs			
Kennedy Space Center, Florida; 1985–1991[b]	134	5	411	118	97	-	-
Saint-Privat d'Allier, France; 1986, 1990–1991[b]	47	13	139	43	25	-	-
Camp Blanding, Florida; 1998[c]	15	45	152	80	35	73	0.17
present study[d]	64	8	292	117	65	97	0.31
				dI/dt 30–90% Risetime, ns			
present study	29	17	69	32	13	30	0.16
				dI/dt 10–10% Width, ns			
Saint-Privat d'Allier, France; 1990–1991[b]	17	70	2010	400	210	-	-
				dI/dt Half-Peak Width, ns			
present study	29	49	149	92	25	89	0.12

[a]The polaritv of the peak values is ignored.
[b]*Depasse* [1994a].
[c]*Uman et al.* [2000].
[d]Fifteen dI/dt peaks obtained from differentiating I.

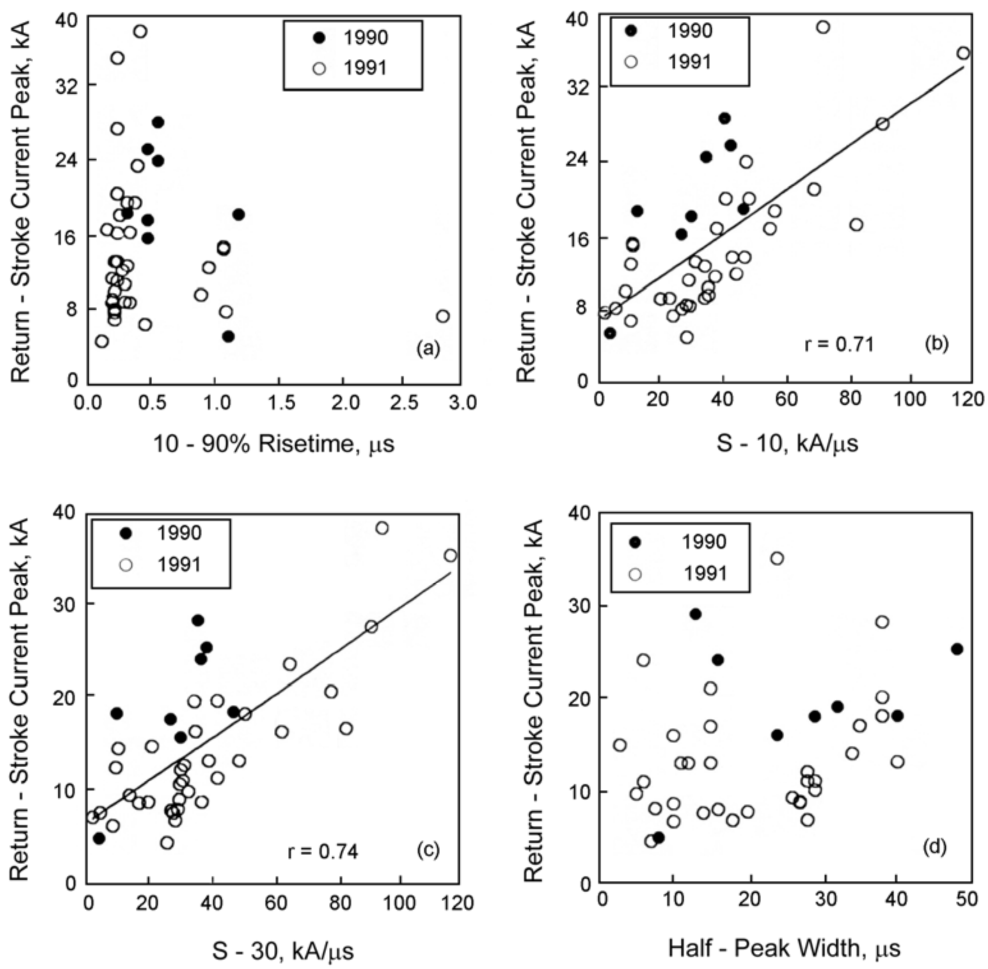

Fig. 1. Scatter plots relating various return stroke parameters. Solid circles represent 1990 data from KSC, Florida, and open circles represent 1991 data from Fort McClellan, Alabama. (a) Current peak versus 10-90 percent risetime; (b) current peak versus S-10; (c) current peak versus S-30; (d) current peak versus half-peak width. Regression lines and correlation coefficients (r) are given in (b) and (c). Adapted from Fisher *et al.* (1993) [3].

Schoene *et al.* (2009) [6] found significant correlation ($R^2 = 0.76$) between lightning return-stroke peak current and the corresponding charge transfer within 1 ms after return-stroke initiation. The dependence is surprisingly similar to that found by Berger and co-workers for the natural first return-stroke peak currents and 1-ms charge transfers.

IV. Return-Stroke Peak Current versus Grounding Conditions

Rakov *et al.* (1998) [7] reported that Camp Blanding measurements of lightning currents that entered sandy soil with a relatively poor conductivity of 2.5×10^{-4} S m^{-1} without any grounding electrode resulted in a value of the geometric mean return-stroke current peak, 13 kA, that is similar to the geometric mean value, 14 kA, estimated from measurements at KSC made in 1987 using a launcher of the same geometry which was much better grounded into salt water with a conductivity of 3-6 S m^{-1} via underwater braided metallic cables. Additionally, fairly similar geometric mean values were found from the Fort McClellan, Alabama, measurements using a poorly grounded launcher (10 kA) and the same launcher well grounded (11 kA) in 1993 and 1991, respectively. These results are summarized in Table 3.

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 the grounding impedance it initially encounters to a value that is always much lower than the equivalent impedance of the main channel. Rakov *et al.* (1998) [7] inferred that surface and underground plasma channels are important means of lowering the lightning grounding impedance, at least for the types of soil at the lightning triggering sites in Florida and Alabama (sand and clay, respectively). A photograph of ground surface arcing is shown in Fig. 2. Further, Bazelyan and Raizer (2000) [9] found from their laboratory experiments and modeling that surface arcs developing at a speed of 10^6 to 10^7 m s^{-1} is the most

TABLE 3
GEOMETRIC MEAN PEAK CURRENT VERSUS GROUNDING CONDITIONS FROM DIFFERENT TRIGGERED-LIGHTNING EXPERIMENTS
ADAPTED FROM RAKOV *ET AL.* (1998) [7]

Experiment	Reference	Trigger Threshold, kA	Sample Size	GM Peak Current, kA	Soil	Artificial Grounding	Grounding Resistance, Σ
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})	1.2x1.2 m square metal plane connected through three 0.5 m long wires at the four corners to salt water	0.1
Fort McClellan, Alabama, 1991	Fisher et al. (1993)	2 (two strokes below 2 kA from continuous tape record included)	37	11	clay (3×10^{-3} S m^{-1})	rebar framework of the munitions 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 (2.5×10^{-4} S m^{-1})	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	64×10^3 (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 (1.8×10^{-3} S m^{-1})	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 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.

Fig. 2. Photograph of surface arcing associated with the second stroke (current peak of 30 kA) of flash 9312 triggered at Fort McClellan, Alabama. Lightning channel is outside of field of view. One of the surface arcs approached the right edge of the photograph, a distance of 10 m from the rocket launcher. Adapted from Fisher *et al.* (1994) [8].

likely mechanism of grounding impedance reduction by lightning current. They stated that a voltage as low as 135 kV was required to bridge a 5 m long gap by such an arc. Since the arcs develop at a speed of 1 to 10 m μs^{-1}, some reduction of grounding impedance should occur before the current peak, particularly when the risetime is greater than 1 µs.

V. Influence of Electrical Properties of the Strike Object

Schoene *et al.* (2009) [6] recently presented a statistical analysis of the salient characteristics of current waveforms for 206 return strokes in 46 rocket-triggered lightning flashes. The flashes were triggered during a variety of experiments related to the interaction of lightning with power lines that were conducted from 1999 through 2004 at Camp Blanding, Florida. The return-stroke current was injected into either one of two test power lines or into the earth near a power line via a grounding system of the rocket launcher. The geometric mean return stroke peak current was found to be 12 kA, which is consistent with those reported from other triggered-lightning studies. Further, this parameter was found not to be much influenced by either strike-object geometry or level of man-made grounding, as previously reported by Rakov *et al.* (1998) [8]. Specifically, the peak current was about the same for the cases of current injection into an overhead power line conductor (impedance initially "seen" by lightning at its attachment point of about 200 ohm) and into a concentrated grounding system via a 8-m long down conductor. The means of the 10–90 percent current risetimes for strikes to the power line (geometric mean 1.2 µs) and for strikes to the ground nearby (geometric mean 0.4 µs) are significantly different (see Fig. 3), which indicates that the electrical properties of the strike object affect the risetime. This effect is likely related to the impedance seen by lightning at the strike point and/or to reflections at impedance discontinuities within the strike object, larger effective impedances apparently resulting in larger risetimes. A dependence of the return-stroke current half-peak width on the electrical properties of the strike object was not observed.

VI. Summary

1. Leader/return stroke sequences in rocket-triggered lightning are similar in most respects to subsequent leader/return stroke sequences in natural downward lightning and to all such sequences in object-initiated lightning.

2. Distributions of peak currents for triggered and natural (subsequent strokes only) lightning are similar. Median (or geometric mean) values are typically in the range of 10 to 15 kA.

3. The peak current is not much influenced by either strike-object geometry or level of man-made grounding.

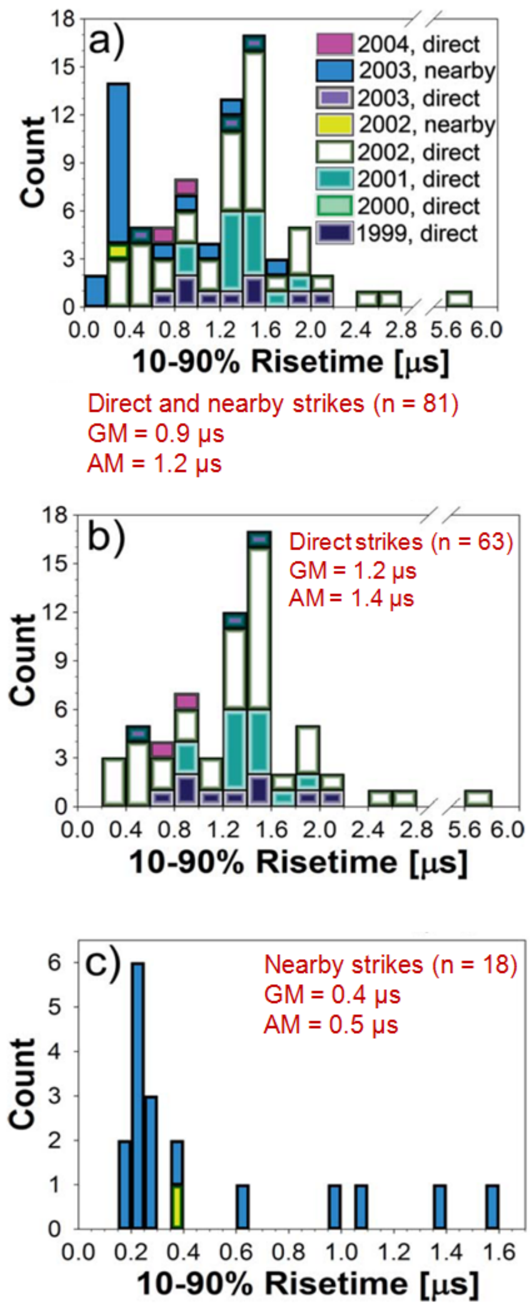

Fig. 3. Histograms of return stroke current 10-90 percent risetimes for 81 strokes in rocket-triggered flashes, Camp Blanding, Florida, 1999-2004, power-line experiments. a) Direct and nearby strikes, b) only direct strikes, and c) only nearby strikes. The horizontal scale in a) and b) is interrupted between 2.8 and 5.6 μs. The vertical and horizontal scales in c) are different from the scales in a) and b). Adapted from Schoene *et al.* (2009) [6].

4. The current risetime depends on the electrical properties of the strike object (1.2 μs for direct strikes to an overhead power line conductor versus 0.4 μs for nearby strikes to ground).

5. For triggered lightning, the current peak is essentially independent of current risetime.

6. Current wavefront parameters (in particular dI/dt peak) for triggered lightning are based on records acquired using better instrumentation than those for natural downward lightning.

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